博士論文

Carbon emission prediction and driving force analysis in construction industry on a city level

都市レベルにおける建設業の二酸化炭素排出量の予測と要因分析に関する研究

北九州市立大学国際環境工学研究科

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趙　秦楓

ZHAO QINFENG

Doctoral Thesis

CARBON EMISSION PREDICTION AND DRIVING FORCE ANALYSIS IN CONSTRUCTION INDUSTRY ON A CITY LEVEL

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ZHAO QINFENG
The University of Kitakyushu
Faculty of Environmental Engineering
Department of Architecture
Gao Laboratory

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Carbon Emission Prediction and Driving Force Analysis in Construction Industry on a City Level

ABSTRACT

Global warming and the climate crisis pose significant challenges worldwide. In response to the link between carbon emissions and climate change, governments globally have recognized the importance of mitigating carbon emissions to combat global warming, resulting in the establishment of carbon neutrality targets. The construction industry, a major contributor to carbon emissions, plays a vital role in achieving these targets. Carbon Emissions from the Construction Industry (CECI) primarily arise from the production of building materials, energy consumption during building construction and operation.

This study focuses on the materialization and demolition processes within the construction industry, examining carbon emission trajectory and key driving factors within a city scale. Specifically, representative cities at different stages of development, namely Hangzhou in China and Kitakyushu in Japan, are selected to explore the potential for decarbonizing the construction industry and achieving carbon neutrality. The study takes into account the synergistic decarbonization with upstream sectors and the synergistic carbon reduction with downstream waste recycling sectors, providing corresponding recommendations in light of these perspectives.

Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY, provides an overview of the current global climate change scenario, investigates the link between carbon emissions and global warming, and presents an analysis of the overall carbon emissions and building-related carbon emissions across different nations. The aim is to underscore the significance of CECI in attaining carbon neutrality. By examining the sources of CECI, it underscores the imperative of active support from upstream and downstream sectors in reducing carbon emissions in the construction industry. Lastly, it summarizes the climate actions and carbon neutrality objectives of various countries, underscoring the importance of studying CECI.

Chapter 2, LITERATURE REVIEW OF CARBON EMISSIONS FROM THE CONSTRUCTION INDUSTRY, aims to provide an overview of the existing research on CECI. Initially, a bibliometric analysis method is employed to examine the developmental trends and prominent topics. It is observed that research on CECI is still in its early stages, with current hot topics focusing on energy efficiency, sustainable development, green buildings, and policy evaluation. Subsequently, a manual review is conducted, focusing on aspects such as accounting scales, research objects, boundaries,

and methodologies. It is discovered that calculating CECI at the city scale remains a challenge, and differentiation between various types of buildings is often overlooked. Additionally, accounting for carbon emissions from the building demolition process and the disposal of C&D waste poses a significant challenge that requires attention. Finally, this chapter suggests potential directions for future CECI research.

Chapter 3, RESEARCH OBJECTS AND CARBON ACCOUNTING & ANALYSIS METHODS, focuses on the research objectives and methodological approaches. Firstly, an overview of the two research objects, Hangzhou in China and Kitakyushu in Japan, is provided, highlighting their comparative analysis potential due to their similar urban characteristics. The different stages of urban development in these cities enable a comprehensive analysis of carbon emission factors. Secondly, the carbon emission accounting methods and boundary definitions used in this study are explained. The foundation of this research is the carbon emission factor method. The top-down carbon emission accounting in Chapter 4 utilizes the input-output method, while the bottom-up carbon emission accounting in Chapters 5 and 6 incorporates life cycle assessment and carbon emission intensity methods. Furthermore, system dynamics and scenario analysis methods are introduced to construction area and forecast carbon emissions.

Chapter 4, CARBON EMISSION ACCOUNTING AND DRIVING FORCE ANALYSIS OF CONSTRUCTION INDUSTRY WITHIN A CITY SCALE, focuses on carbon emission accounting and driving force analysis of the construction industry within the city scale. The chapter simplifies the China city-level MRIO Table (2012) and establishes a framework for city-scale carbon emission accounting, the CECI of Hangzhou from 2005 to 2019 is quantitatively evaluated. The analysis tracks the sources of direct CECI and examines the trajectory of indirect CECI. Furthermore, the LMDI method decomposes the carbon emission increment into different factors, identifying the influences on CECI changes and reduction pathways. The carbon emission intensity method is applied to calculate the CECI of Kitakyushu and decompose the carbon emission reduction. By comparing the influencing factors between Hangzhou and Kitakyushu, the effects of various factors at different stages of urban development are validated. The research findings indicate that the construction industry in both cities has reached its carbon peak, with construction scale and energy efficiency being the main factors affecting carbon emissions.

Chapter 5, SYNERGISTIC DECARBONIZATION POTENTIAL OF THE CONSTRUCTION AND UPSTREAM SECTORS, explores the synergistic decarbonization potential of the construction industry and upstream sectors. Various factors that could impact future CECI, such as population growth, per capita floor area demand, material carbon intensity, and material demand intensity, are categorized into

two types: development mode and policy control. Each type has three development paths, resulting in nine scenarios. Using a system dynamics model, a building stock flow model is constructed to estimate building demand and new construction area under these scenarios. This allows for the calculation of material requirements, and a process-based life cycle assessment method is employed to calculate Materialization Stage Carbon Emissions (MSCE) in the construction industry. The carbon emission differences among different scenarios are then decomposed using the LMDI method to identify the core influencing factors of MSCE and explore the potential for decarbonization in the construction industry. The results reveal significant potential for collaborative emissions reduction between the upstream sector and the construction sector. However, to achieve carbon neutrality by 2060, Hangzhou's construction industry will require support from other industries.

Chapter 6, SYNERGISTIC DECARBONIZATION POTENTIAL OF THE CONSTRUCTION AND WASTE RECYCLING SECTOR, delves into the synergy between the construction and waste recycling sectors in decarbonization efforts. The chapter begins by examining the flow, disposal methods, and recycling techniques associated with the 11 types of C&D waste in Kitakyushu. Through a comprehensive analysis of the waste disposal and recycling processes, a meticulous assessment of the carbon emissions across the life cycle of C&D waste is conducted using both life cycle assessment and carbon emission factor methods. By comparing the carbon emission intensity of recycled materials to that of new materials, the carbon emission reduction attributable to Kitakyushu's waste recycling industry in 2019 is calculated. Additionally, a system dynamics approach is employed to model the building stock and flow, enabling predictions of C&D waste generation and its potential contribution to carbon emission reduction under three scenarios: baseline, large-scale, and long lifespan scenarios. The research findings demonstrate that recycling demolition waste can result in a notable 1.9-6.8% reduction in the CECI.

Chapter 7, CONCLUSION AND PROSPECT, provides a concise summary of the entire thesis and discusses the future work of research on CECI.

Keywords: Construction Industry; Carbon Trajectory; Synergistic Decarbonization; Driving Factor; Scenario Analysis; Building Stock and Flow

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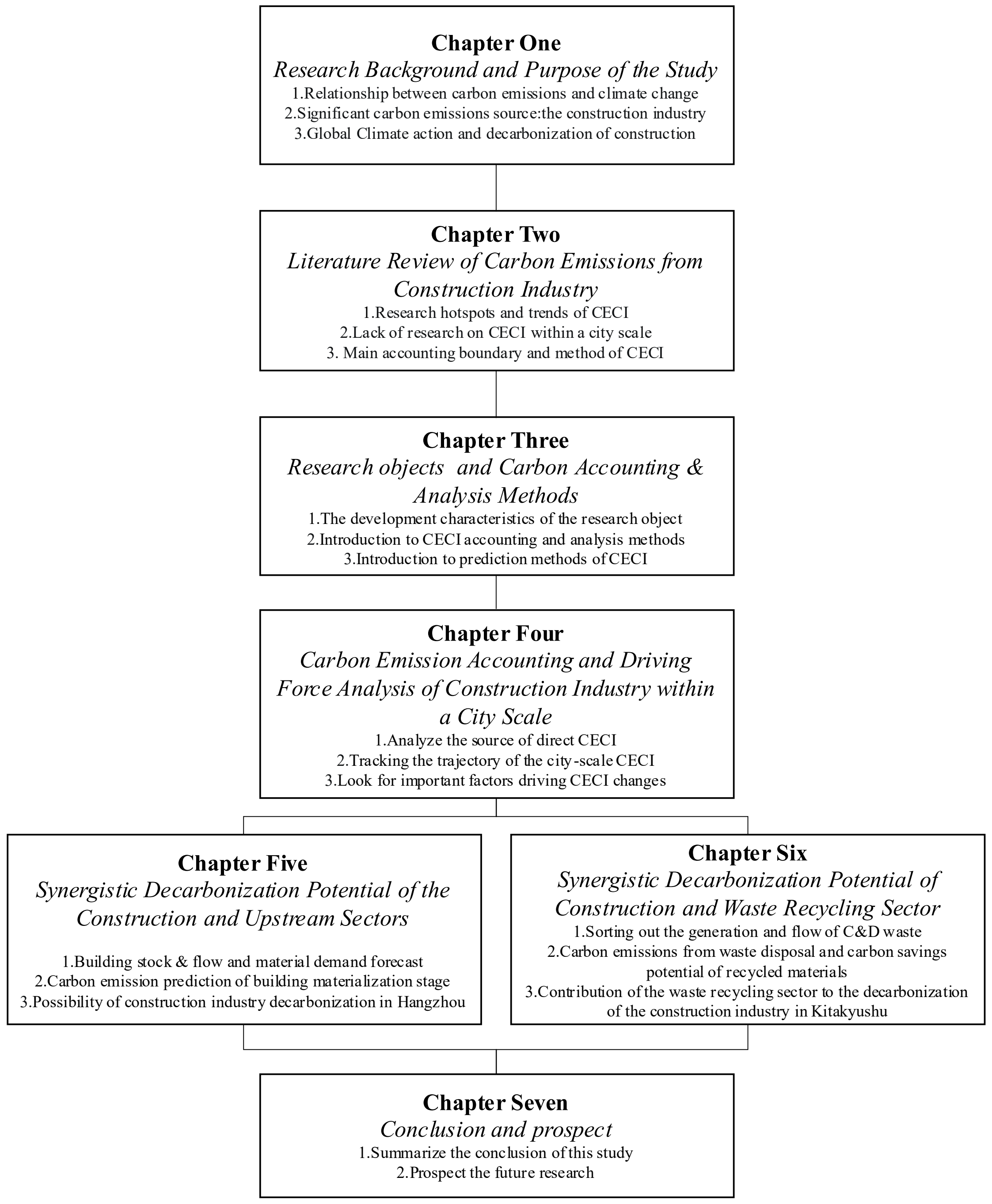
Carbon Emission Prediction and Driving Force Analysis in Construction Industry on a City Level



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Chapter 1

RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

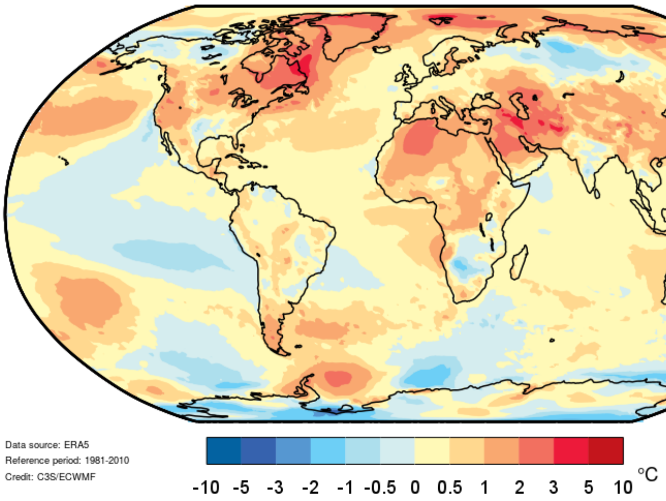
CHAPTER 1: RESEARCH BACKGROUND AND PURPOSE OF THE STUDY

Contents

1.1 Global warming

1.1.1 Climate change

Earth has become our home due to its habitable environment. However, in reality, it is not a gentle planet, but rather one that has been in a state suitable for human survival only in the last few hundred thousand years. The industrialization of human society has resulted in a significant increase in greenhouse gas emissions (GHG), which trap heat within the Earth's atmosphere and contribute to a rise in global temperatures, as shown in Figure 1-1. Climate change and global warming have become enormous challenges that humanity is facing worldwide. As such, it is imperative that we study and understand the root causes of these issues in order to find effective solutions.



Data source: ERA5
Reference period: 1981-2010
Credit: C3S/ECMWF

Fig.1-1 Temperature difference between Jan-Sept 2021 and 1981-2010
Source: C3S/ECMWF

Weather is a part of nature that exhibits variability during short periods of time. And when such weather states persist for longer periods of time, decades or even centuries, a climate is formed that covers larger scales of time and space. Since the formation of the Earth, the archaeological time, and geological records from different dimensions such as atmosphere, oceans, cryosphere, and sea level reveal that the climate has been in constant change (Petit et al., 1999). Global climate change has its own pattern of alternating hot and cold periods. In colder times, the global temperature is lower, called glacial state, and in warmer times, the global temperature is higher, called interglacial state.

The last ice age ended about 18,000 years ago, which indicates that the Earth is currently in an interglacial state (Sigman et al., 2010). It seems that even without human activity, the planet's natural cycles would periodically alternate between hot and cold and enter the glacial phase for natural cooling. However, the interval between past ice ages varies between about 40,000 and 100,000 years (Lisiecki & Raymo, 2005), which suggests that there may be at least another 40,000 years before the Earth cools naturally. In other words, the global climate is rapidly warming, and waiting for it to periodically adjust itself is not a viable solution. Since humans cannot influence the climate to enter ice ages or interglacial periods, the negative effects of global warming will persist and even worsen. Therefore, mankind must take action to address global warming, such as reducing greenhouse gas emissions and transitioning to renewable energy sources.

Global warming is having a tremendous impact on both nature and humanity, making the planet different than usual, as shown in Figure 1-2. In terms of water cycle, warming increases evaporation, changes regional precipitation and precipitation distribution patterns, intensifies the instability of water resources. In terms of ecosystems, natural ecosystems are unable to adapt to the changing environment, and human-occupied land limits the natural migration of ecosystems, resulting in the loss of species. Changes in sea water temperature and potential changes in some of its currents have affected changes in fish aggregation sites, causing some fishing grounds to disappear. In terms of agriculture, climate change increases the suitability of high-latitude regions for food production, and cause droughts and water shortages in mid- and low-latitude regions. This will exacerbate global food inequality and reduce global food production potential. In terms of human health, the increase in weather and climate extremes has disrupted human metabolism, accelerating the spread of disease vectors and the expansion of epidemic disease outbreaks.

Fig.1-2 Negative effects of climate change

Source: Intergovernmental Panel on Climate Change

1.1.2 Carbon emissions and global warming

The energy that brings temperature to the Earth is a dynamically balanced system, the main source of energy is the Sun, and the Earth gets energy from the Sun as well as radiating energy into space, with the in and out offsetting the dynamic balance. As shown in Figure 1-3, the sun provides power to the Earth’s climate, with $340\ \text{W/m}^2$ of energy reaching the Earth per second.

Of this, 50% of the energy is absorbed by the Earth's surface, 20% is absorbed by the atmosphere, and the rest is reflected back into space. To balance the absorbed solar radiation energy, the Earth itself must radiate long-wave radiation back out into space. Greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) absorb the long-wave heat radiation emitted by the Earth's surface and re-emit it in all directions. The presence of greenhouse gases means that the amount of long-wave radiation lost by the Earth is much less than the amount emitted by the Earth's surface, which contributes to an increase in the Earth's surface temperature. This is known as the greenhouse effect.

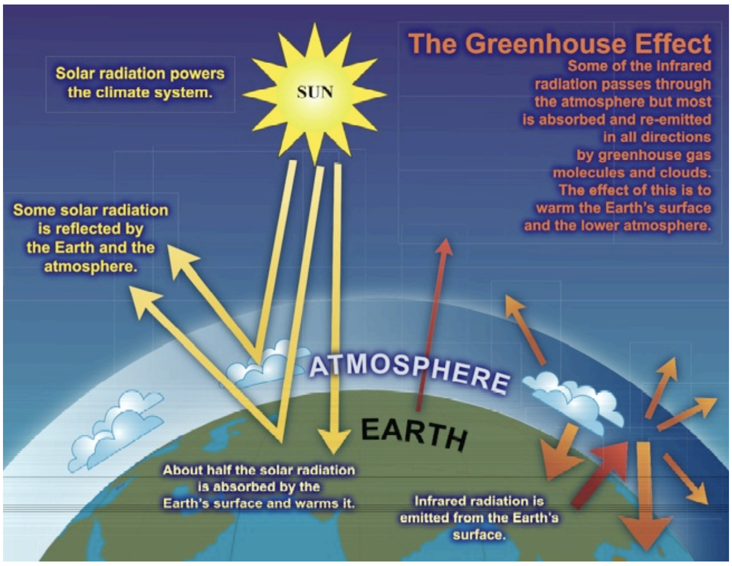


Fig.1-3 Greenhouse effect

Source: Intergovernmental Panel on Climate Change Working Group I

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization (WMO) in cooperation with the United Nations Environment Programme (UNEP) with the mandate to provide a comprehensive assessment of the state of scientific, technical, and socio-economic knowledge of climate change, its causes and response strategies to the world. Although the causes of climate warming are complex, the IPCC clearly pointed out in its Fifth Assessment Report (AR5) that the probability of warming due to increased greenhouse gas emissions such as CO_2 emissions from human activities is around 95%.

There is a strong relationship between carbon emissions and greenhouse gases. Greenhouse gases include substances such as CO_2, CH_4, N_2O and Freon. Carbon emissions are CO_2 and other carbon-based substances emitted by human activities. Carbon emissions is the most dominant of the greenhouse gases, and it is one of the main causes of climate change.

1.1.3 Global carbon emissions

Since the 1970s, there has been a basic positive correlation between global carbon emissions and global economic development. With the development of the global economy, carbon emissions have increased substantially. In terms of total emissions and growth rate, global carbon emissions have been rising in sync with the total economic output, but the growth rate has slowed down in recent years, as shown in Fig.1-4.

The reason for the synchronous growth of economic output and carbon emissions since the 1970s is that economic growth has increased the demand for energy sources such as electricity and fossil fuels like oil and natural gas, which all produce large amounts of carbon emissions. During periods of economic recession, energy consumption declines, and carbon emissions also experience periodic declines. For instance, the 2008 financial crisis and the 2020 COVID-19 pandemic both resulted in a temporary decrease in carbon emissions. In 2018, global carbon emissions reached a record high of 34.05 billion tons, triple the amount in 1965. In terms of growth rate, as climate change gradually becomes a global consensus, countries are taking measures to control carbon emissions, which has led to a slowdown in the growth rate of carbon emissions.

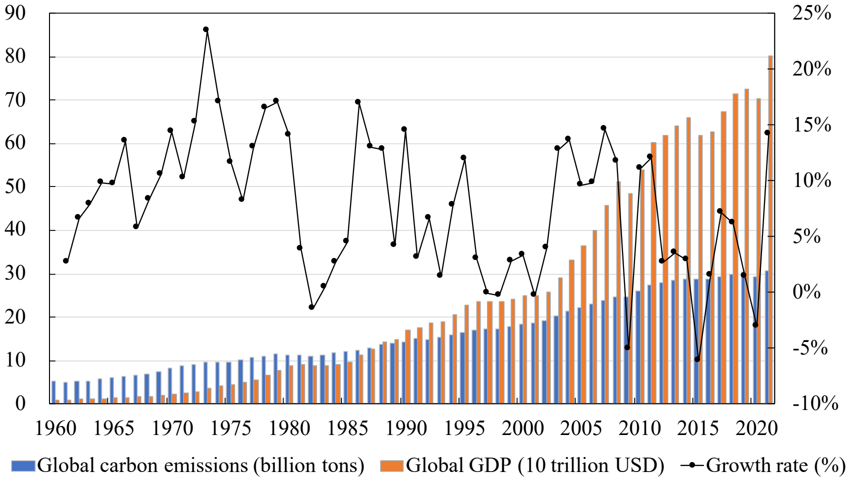


Fig.1-4 Global CO_2 emissions and GDP

From a regional perspective, Asia has become the world's largest carbon emission area due to the large-scale economic construction carried out by Asian countries since World War II. The driving force behind the rapid increase in carbon emissions mainly comes from the rapid economic development of countries such as China, Japan, South Korea, and India, which has led to a dramatic increase in demand for energy and industrial products. In contrast, the carbon emissions of North America and Europe have gradually decreased and entered the negative growth phase. Oceania, Africa, and Antarctica have lower carbon emissions due to their smaller carbon footprints.

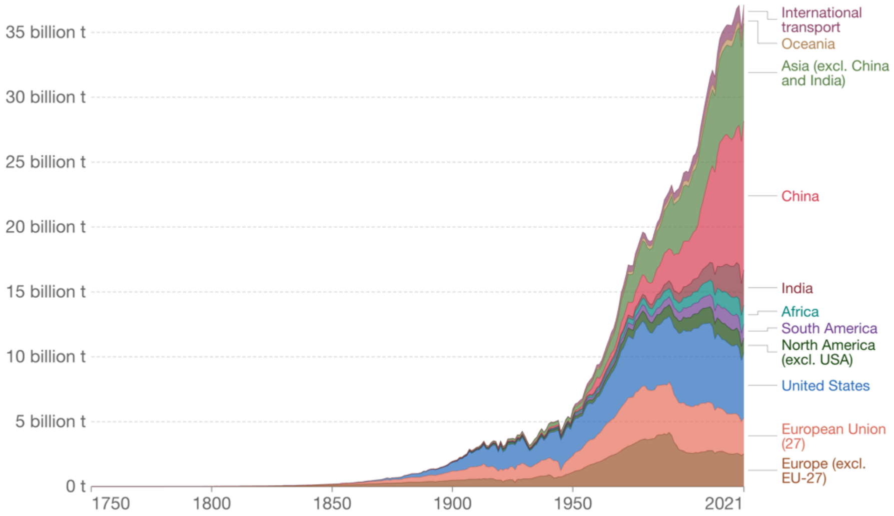


Fig.1-5 Annual CO_2 emissions by world region

Source: Our World in Data

As shown in Fig.1-5, Asia’s carbon emissions surpassed North America’s in 1985 and Europe’s in 1992, becoming the region with the highest carbon emissions in the world. Carbon emissions have increased by over 12 times from 1.6 billion tons in 1965 to 20.2 billion tons in 2019. In contrast, Europe and North America’s annual carbon emissions have generally decreased since around 2008. In terms of regional carbon emission growth rates, Asia maintained high growth rates before 2011, except for individual years. However, with countries gradually attaching importance to carbon emissions, growth rates began to slow down after 2011. In contrast, Europe’s carbon emission growth rates have been mostly negative since 1990, while North America’s growth rates have mostly been negatived since 2007.

From the perspective of emission sources, electricity and heat production activities, manufacturing industry and construction industry, and transportation industry are the main sources of carbon emissions, as shown in Fig.1-6. The power generation industry still relies heavily on the combustion of fossil fuels such as coal, oil, and natural gas as the main way of generating electricity. The heating industry also uses the combustion of fossil fuels as the main way of heating, which results in large amounts of carbon emissions.

In 2019, carbon emissions from major electricity and heat production activities worldwide reached 5.59 billion tons, accounting for 52.1% of the world’s total carbon emissions that year. The transportation industry is the world’s second largest source of carbon emissions. Land transportation, aviation, and shipping still rely heavily on fuel as the main power source, and the high demand for fuel also results in large amounts of carbon emissions.

The manufacturing industry and construction industry are another important source of carbon emissions, with carbon emissions reaching as high as 2.77 billion tons in 2019. Industries such as steel smelting, chemical manufacturing, mining, and construction have a large demand for energy, and the decomposition of raw materials during the production process also results in carbon emissions. In addition, building operations also emit 453.7 million tons of CO_2.

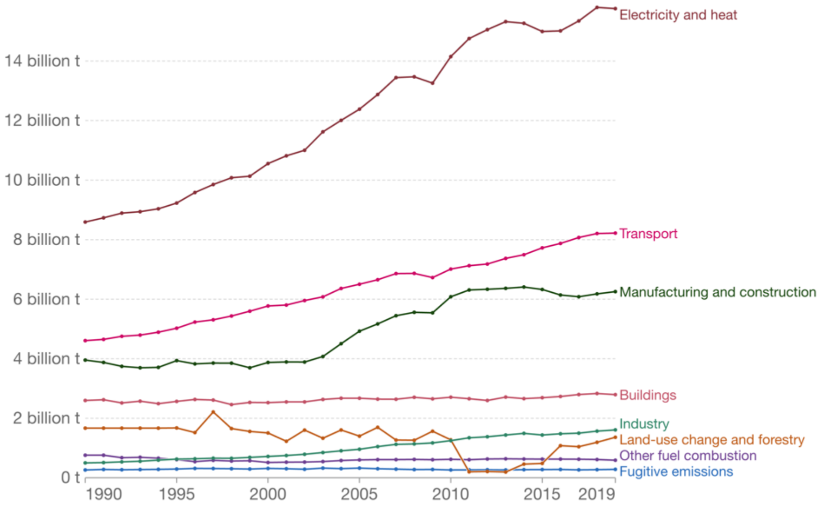


Fig.1-6 Global carbon emissions by sector

Source: Our World in Data

1.1.4 Carbon emissions by countries

According to the *Global Carbon Project* (Friedlingstein et al., 2022), the top ten countries with the highest carbon emissions in 2021 are ranked in Table 1-1. The top five global CO_2 emitters have remained the same since 1999: China, the United States, India, Russia, and Japan. The top 5 countries together account for 59.3% of the total global emissions.

Table 1-1 Global ranking of CO_2 emissions in 2021($MtCO_2$)

	Country	Level of development	Carbon emission	Share of global emissions
1	China	Developing	11472.4	30.9%
2	United States	Developed	5007.3	13.5%
3	India	Developing	2709.7	7.3%
4	Russia	Developing	1755.5	4.7%
5	Japan	Developed	1067.4	2.9%
6	Iran	Developed	748.9	2.0%
7	Germany	Developed	674.8	1.8%
8	Saudi Arabia	Developing	672.4	1.8%
9	Indonesia	Developing	619.3	1.7%
10	South Korea	Developed	616.1	1.7%

China is the world's largest emitter of carbon, accounting for about 30.9% of global emissions as of 2021. As one of the strongest driving forces of the world's economic growth over the past three decades, China's carbon emissions have shown a synchronous and rapid growth trend with its economic development. Rapid economic development requires a large amount of energy support, however, coal accounts for about 60% of China's total energy consumption, and the high dependence on coal in China's energy structure is one of the important reasons for its huge carbon emissions. As a developing country, China's urbanization and industrialization processes require a large amount of resource support, and the carbon emissions caused by the decomposition of minerals in the industrial production process is also one of the reasons for China's high carbon emissions. In addition, China is the countries with the largest population in the world, and its large population has also led to an increase in energy consumption and carbon emissions.

From the perspective of energy structure, Japan's high carbon emissions are similar to China's. Japan's energy is highly dependent on imports, with oil and natural gas being the main sources of energy, accounting for about 60% of Japan's total energy consumption. The high proportion of fossil fuels is one of the reasons for Japan's large carbon emissions. In addition, Japan's industrial structure is dominated by traditional high-energy-consuming manufacturing industries, which is a challenge for Japan in reducing carbon emissions. At the same time, Japan, as a developed country, has a highly developed public transportation system and urbanization level, and the energy consumption required to maintain a high standard of living for its people is also an important source of carbon emissions.

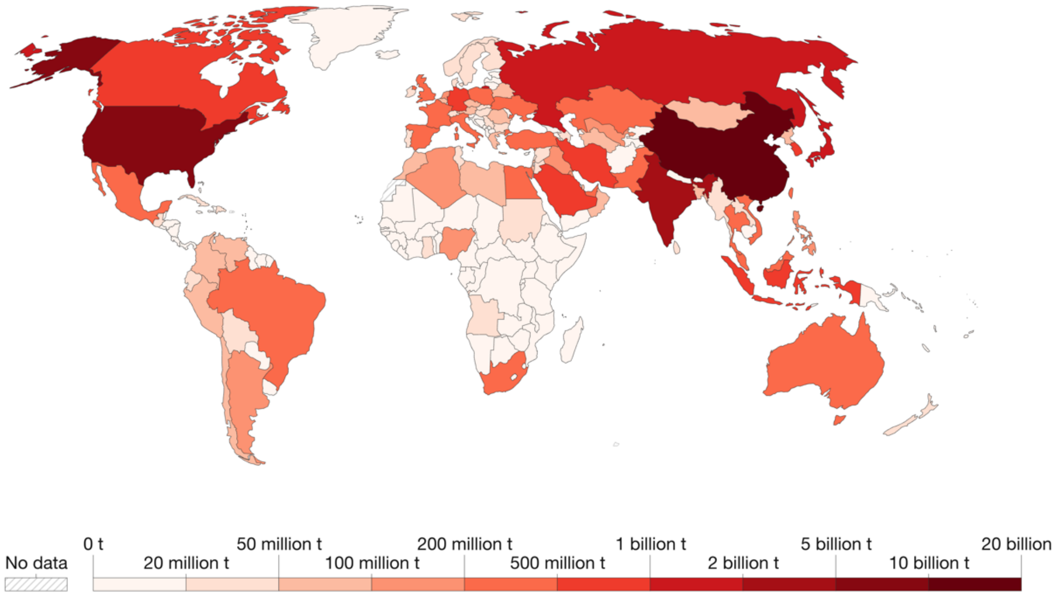


Fig.1-7 Carbon emissions by countries

Source: Our World in Data

The carbon emissions of other countries can be seen in Figure 1-7. It can be seen that global carbon emissions are unequal. Although carbon emissions are a global issue that affects everyone, some countries contribute more to carbon emissions than others and some are more vulnerable to the impacts of climate change.

The main contributors to global carbon emissions are developed countries that have rapidly developed through industrialization and urbanization. These countries have economies built on energy-intensive industrial bases that heavily rely on fossil fuels such as coal, oil, and natural gas. As a result, they have accumulated enormous carbon footprints over time, becoming the largest emitters of carbon dioxide and other greenhouse gases.

In contrast, developing and underdeveloped countries that are less industrialized and urbanized contribute much less to global carbon emissions. However, due to their limited resources and infrastructure, they are often the country’s most severely affected by climate change. Therefore, addressing the issue of carbon growth requires not only reducing carbon emissions in developed countries but also focusing on helping developing countries transition to cleaner and more sustainable forms of energy.

1.2 Carbon emission from construction industry (CECI)

1.2.1 The share of CECI in global emission

The IEA believes that construction industry is responsible for approximately 40% of global CO_2 emissions each year, as shown in Figure 1-8. Within this total, building operations account for 27% of emissions each year, while building materials and construction account for 13%. Today, sustainability or “green” has become a concept deeply rooted in the hearts of individuals. Building a clean, sustainable environment is essentially a long-term plan that must be maintained efficiently at the social, environmental, and economic levels. However, it has a high initial cost but has long-term advantages in building performance and low-cost maintenance and has positive impacts on the environment and building occupants.

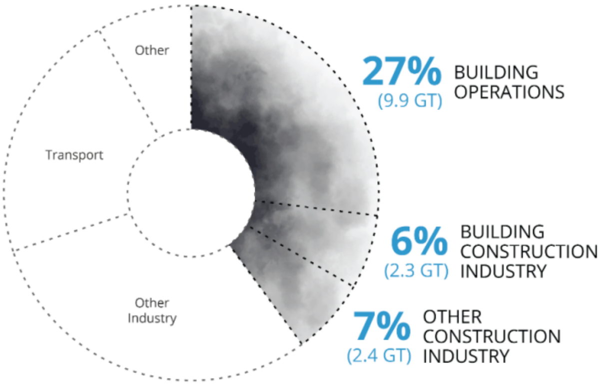


Fig.1-8 Annual global CO_2 emissions

Source: International Energy Agency (IEA)

Driven by a pick-up in construction activity in most major economies and increased use of fossil fuel gas in buildings in more emerging economies. As shown in Figure 1-9, the construction sector accounts for around 37% of energy and process-related CO_2 emissions and more than 34% of global energy demand in 2021.

Operational energy-related CO_2 emissions from the construction sector reach an all-time high of around 10 $GtCO_2$, with the increase in direct emissions occurring in developed and emerging economies, although this is largely driven by natural gas demand in emerging economies driven by economic growth, increasing by around 5% above 2020 levels and 2% above the pre-pandemic peak in 2019. If the approximately 3.6 billion tons of CO2 generated by the production of building materials (e.g., concrete, steel, aluminum, glass, and bricks) are included, the CO_2 emissions from buildings associated with building energy consumption and processes account for approximately 37% of total global carbon emissions in 2021.

Operational energy use in buildings increases from 115 EJ in 2010 to a record high of nearly 135 EJ in 2021, accounting for 30% of global final energy consumption. If energy use related to cement, steel, and aluminum production is included, this proportion increases to 34%. This is an increase of around 4% over 2020 and more than 3% above the 2019 peak, which is the largest annual increase in the last decade.

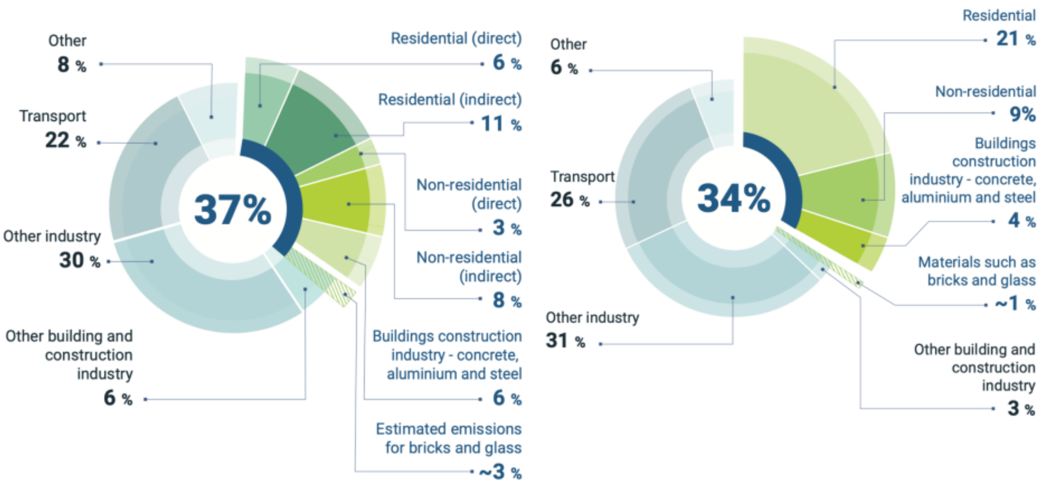


Fig.1-9 The share of building-related carbon emissions (left) and final energy demand (right) in global 2021

Source: The United Nations Environment Programme (UNEP)

According to the *2022 Global Status Report for Buildings and Construction* (UNEP, 2022), although investment in energy efficiency in the construction industry increased by 16% year-on-year to reach $237 billion in 2021, it still lags the expansion of new building area. From 2015 to 2021, the global increase in building area is equivalent to the total land area covered by buildings in Germany, France, Italy, and the Netherlands. In addition, the demand for energy for heating, cooling, lighting, and equipment in buildings also increased by about 4% and 3%

in 2021 compared to 2020 and 2019, respectively. Therefore, the report emphasizes that due to the trend of increasing building area continues, greater efforts must be made to reduce overall emissions and improve building energy efficiency.

In recent years, the growing and intertwined economic, energy, security, and climate crises have presented severe challenges to the global construction industry to increase resilience and achieve decarbonization goals. The United Nations Environment Programme (UNEP) states that the climate performance of the construction and building industry is getting farther away from the goal of decarbonization by 2050 and urgent, clear actions must be taken as soon as possible. The report proposes nine recommendations to address these challenges, including "national and local governments need to develop mandatory building energy codes and establish a performance-based path for their new building codes and standards, and achieve zero carbon as soon as possible over the building lifecycle", "the construction and real estate industries must develop and implement zero carbon strategies for new and existing buildings in all jurisdictions to effectively support government policies", "the building materials and construction industry must reduce carbon dioxide emissions throughout its entire value chain in accordance with the Paris Agreement and support government policies to achieve carbon-neutral building stock", and "emission regulations and assessments for governments aiming to achieve a net-zero carbon building environment need to adopt a whole-life approach to buildings, including consideration of embodied carbon and operational carbon emissions of materials".

The alarm for global decarbonization in the construction industry has sounded once again. Currently, there has been almost no structural change in the industry to reduce energy demand or carbon emissions (UNEP, 2022). Decarbonization in the construction industry must be put into practical action. It is necessary to prioritize decarbonization and sustainable transformation of the built environment and the production of building materials, in order to achieve zero-emission, efficient, and resilient construction and contribute to countries' carbon neutrality goals and global environmental targets to control temperature rise.

1.2.2 Sources of CECI

Defining the boundaries of carbon emissions calculation is crucial for identifying the sources of carbon emissions. Building carbon emissions can be divided into different stages of the building's life cycle, including building embodied carbon emissions, building operational carbon emissions, building demolition carbon emissions, etc.

Building embodied carbon emissions can be further subdivided into building construction carbon emissions, building materials carbon emissions, etc., which are all embedded in the building content carbon emissions (Scope 3). Building operational carbon emissions can be divided into direct and indirect carbon emissions according to the place of carbon emissions. Direct carbon emissions refer to the carbon emissions directly generated by the consumption of fossil energy during the building's operational stage, mainly from activities such as cooking, hot water, and decentralized heating (Scope 1). Indirect carbon emissions refer to the carbon emissions generated by the consumption of electricity and heat, which are the main sources of building operational carbon emissions (Scope 2).

(1) Carbon emissions in the building operation stage

Most studies believe that the contribution of the building operation stage to carbon emissions in each stage of the building's lifecycle is the largest. Nuri Cihat Onat et al.(Onat et al., 2014) used the economic input-output life cycle assessment (EIO-LCA) model to calculate the carbon emissions in each stage of the US building, and concluded that the carbon emissions in the building operation stage were the highest. Xiaocun Zhang et al. (X. Zhang & Wang, 2016) divided the building lifecycle into construction, operation, and disposal stages, calculated the carbon emissions in each stage based on the mixed input-output method, and found that the operation stage had the largest proportion of the total building carbon emissions. Andriel Evandro Fenner et al.(Fenner et al., 2018) and Shujie Zhao et al. (Zhao et al., 2019) calculated the carbon emissions of different stages of buildings using different methods and also concluded that the operation stage had the largest proportion of the total building carbon emissions. Peng Wu et al. (Wu et al., 2019) calculated the carbon emissions of China's building industry from the perspective of the building's lifecycle and found that the building operation stage was the main source of building carbon emissions. Xikai Mao et al. (Xikai et al., 2019) calculated the carbon emissions of 207 civil buildings in Tianjin based on the process analysis method, and found that the building operation stage accounted for 75% -87% of the total carbon emissions. Ma Jinwei et al. (Ma Jinwei et al., 2023)conducted a lifecycle carbon emissions evaluation of a museum building, quantitatively analyzed the carbon emissions characteristics of each stage of the building, and found that the carbon emissions in the operation stage accounted for 74.61% of the total, and the carbon emissions in the material production stage accounted for 20.34% of the total. Huang Beijia et al. (Huang Beijia et al., 2022) compared the carbon emissions of residential and non-residential buildings in Shanghai and found that the carbon emissions in the construction industry in Shanghai were increasing, and the production and operation stages of buildings were the two stages that contributed the most to the total carbon emissions.

(2) Carbon emissions from building materials

Carbon emissions from buildings are mainly derived from energy and material consumption, so the level of carbon emissions per unit of energy and material consumption is an essential data base for analysis and calculation. Other studies have concluded that the carbon emissions from the material production and transportation phases of building construction account for the largest share of total building carbon emissions. Chau et al. (Chau et al., 2015) analyzed the three perspectives of resource consumption, energy use and carbon emissions, with structural materials dominating. Feng et al. (Feng Guohui et al., 2022)conducted a study using a whole life volume calculation model, and the results showed that the material production and transportation phases and operation phases of the study case accounted for more than 98% of the total carbon emissions of the building. Yujie Lu et al. (Lu et al., 2016) used the emission factor method for calculation and found that the consumption of construction materials contributed the most to the carbon emissions of the building. Huang et al. (Huang Zhenhua, 2018)used the process analysis method to calculate the carbon emissions of construction in China and found that the highest carbon emissions were in the building construction phase, followed by the building operation phase. yang Zhang et al. (Y. Zhang et al., 2019) calculated the carbon emissions of the construction industry in China by using the China building construction model (CBCM) based on process life cycle assessment and also concluded that the material production phase accounted for the largest share. Cabeza (Cabeza et al., 2021) concluded that construction materials have a high carbon footprint as well as energy intensive activities. Taffese et al. (Taffese & Abegaz, 2019) through extensive survey data cement, HCB and steel reinforcement are the main energy consumers and major CO_2 emitters. They were found to generate 94% of the specific energy and 98% of the CO_2 emissions. They are the main source of construction waste in the Ethiopian construction industry and are also the main consumers of energy and the largest emitters of CO_2。

(3) Driving factors of the CECI

The factors driving the growth of CECI are mainly: factors of building energy consumption, including energy consumption of electricity, coal, oil, natural gas, and biomass energy; factors of urban construction level, including new buildings, building stock, urban plumbing penetration rate, central heating area in the north, etc.; factors of residents' living standard, including low-carbon awareness, environmental quality, per capita residential area, per capita income, per capita consumption level, etc.; research capability factors, including investment in science and technology, low-carbon technology, investment in education, etc.; population factors, including urban population, rural population, urbanization rate, ageing ratio, etc.; economic level factors, including GDP, total construction output value, etc.The most direct factors affecting the carbon emissions of buildings include building energy consumption, total population, GDP and GDP per capita.

Energy consumption in buildings includes energy consumption throughout the life cycle stages, with energy consumption for building operations accounting for the bulk of emissions. Specifically, it refers to the energy consumption generated by the different service functions provided to occupants or users in residential and public buildings. It is also the most significant and direct contributor to the carbon emissions of buildings. Population has many influences on carbon emissions. On the one hand, the continued increase in the number of people will accelerate the increase in demand for buildings, which in turn will lead to an increase in carbon emissions; on the other hand, with the rise of urbanization, the proportion of urban population has increased significantly, and energy consumption and carbon emissions have grown significantly. The level of economic development can be reflected by GDP and GDP per capita.

Rapidly developing economy, with a high demand for fossil-based energy, and carbon emissions from buildings will also increase with energy consumption.

1.2.3 China's CECI

(1) Total CECI trend

China's carbon dioxide emissions in 2020 reached 11.2 billion tons, divided into 4 billion tons of supply-side emissions and 7.2 billion tons of consumption-side emissions. The former is mainly attributed to electricity and fuel, with electricity accounting for around 36%. The latter includes industry, construction, and transportation, with industry contributing 44%, while construction and transportation contributed 10% each.

From 2005 to 2020, the national energy consumption for the entire construction process in China surged from 930 million to 2.2 billion ton of standard coal equivalent (tce), marking a 2.4-fold increase with an average annual growth rate of 6.0%. The annual growth rates were 5.9%, 8.3%, and 3.7% during the 11th, 12th, and 13th Five-Year Plans, respectively, as shown in Figure 1-10 (left).

The whole lifecycle carbon emissions of China's construction industry have been on the rise, as demonstrated in Figure 1-10 (right). The carbon emissions for the entire construction process surged from 2.2 to 5.1 billion tons CO_2, representing a 2.3-fold increase with an average annual growth rate of 5.6%. However, the growth rates of carbon emissions during different stages of construction have slowed notably, with average annual growth rates of 7.8%, 6.8%, and 2.3% during the 11th, 12th, and 13th Five-Year Plans, respectively. The carbon emissions fluctuation between 2010 and 2015 was caused by a significant change in carbon emissions from building material production. The trend of carbon emissions in different construction stages displays some differences.

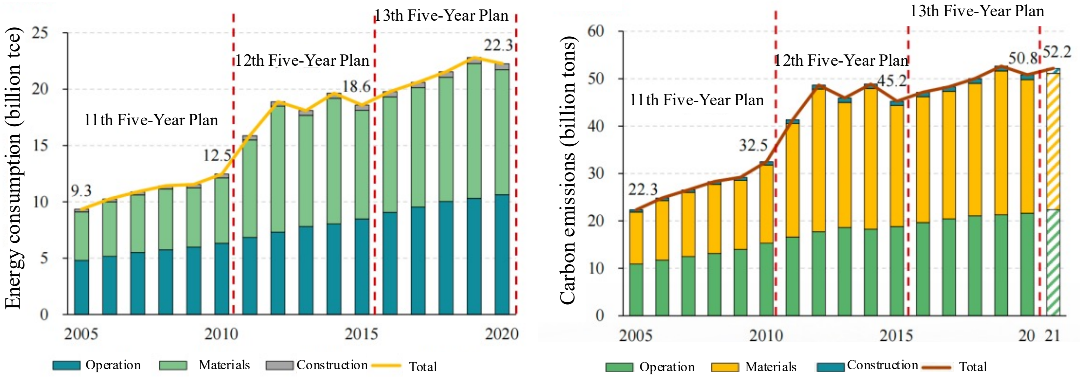


Fig.1-10 Trends in energy consumption (left) and carbon emissions (right) for the whole building process

Source: (CABEE, 2022)

(2) Carbon emission from material production stage

From the consumption side, the carbon emissions of building materials in completed residential buildings reached their peak in 2014, as shown in Figure 1-11. In 2020, the implied carbon emissions of building materials in completed residential buildings in China were 15.6 tons CO_2, a year-on-year decrease of 5.4%. During the 11th, 12th and 13th Five-Year Plan periods, the average annual growth rates were 10.6%, 7.7%, and -2.8%, respectively, and a downward trend has emerged since 2014. As residential demand increases, the proportion of carbon emissions from the production of building materials for residential buildings has been increasing year by year, from 51.0% in 2005 to 62.7% in 2020. Steel, cement, lime, and bricks are the main sources of emissions, accounting for over 90% of the total emissions.

From the production side, energy consumption and carbon emissions during the 12th Five-Year Plan period showed significant fluctuations. In 2020, China's energy consumption for building material production was 1.1 billion tce, with carbon emissions of 2.8 billion tons of CO_2, marking a year-on-year decrease of 7.1%. This decrease was mainly due to a significant reduction in the consumption of building materials, such as steel and cement, which decreased by approximately 100 million tons each. Despite the decrease, carbon emissions from building material production have been on an upward trend, rising from 1.1 billion tons of CO_2 in 2005 to 2.9 billion tons of CO_2 in 2020, with an average annual growth rate of 6.5%, which is consistent with the rise in energy consumption. During the 13th Five-Year Plan period, the average annual growth rate of carbon emissions from building material production was 2.0%, indicating a significant slowdown and entering a plateau phase.

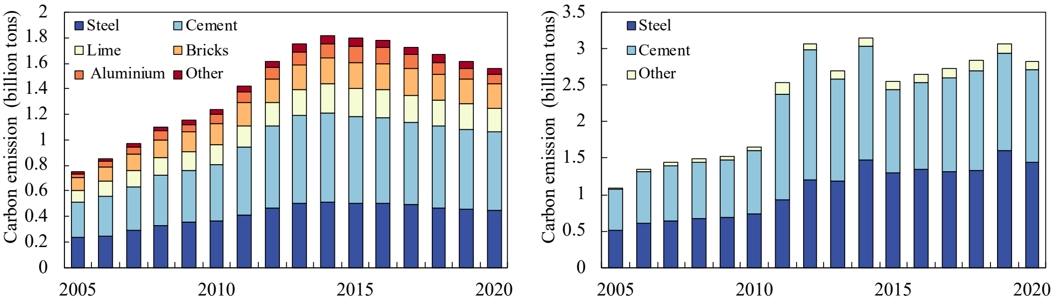


Fig.1-11 Carbon emissions from materials at consumption and production side

Data source: (CABEE, 2022)

(3) Carbon emission from construction stage

As shown in Figure 1-12, in 2020, the China CECI were 102 million tons of CO_2, a year-on-year decrease of 1.5%. This includes construction projects which including building and infrastructure construction, building renovations and demolitions. The average annual growth rates during the 11th, 12th and 13th Five-Year Plan periods were 7.9%, 4.9%, and 2.1%, respectively, showing a downward trend. The year 2013 was a turning point for the growth rate, with a significant change in the average annual growth rate, dropping from 8.1% to 1.4%. The significant increase in construction area is the main driving factor for the increase in CECI. From 2005 to 2020, the construction area in China increased from 3.5 billion m^2 to 14.9 billion m^2, more than three times, resulting in emissions of over 100 million tons of CO_2.

With the continuous strengthening of green and environmental protection requirements for construction, the deepening promotion of clean construction technology, and the continuous optimization of energy structure in the construction process, the carbon emissions per unit construction area and per unit value-added of the construction industry have significantly decreased. Over the past 15 years, the carbon emissions per unit construction area in China has decreased from 14.0 to 6.8 kgCO_2/m^2, a 51% decrease, and the carbon emissions per unit value-added of the construction industry has decreased from 4.8 to 1.4tons CO_2/ kilo CNY, a 70% decrease. The decrease in emission intensity is the main driving factor for carbon emission reduction in construction.

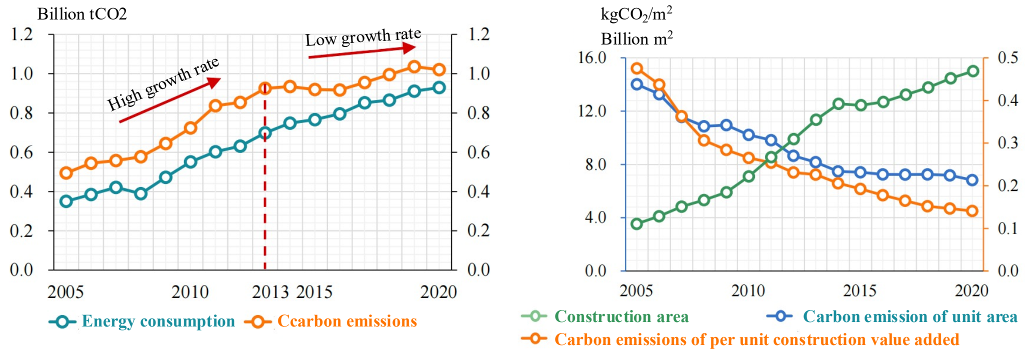


Fig.1-12 Trends in building construction carbon emissions and related indicators

Source: (CABEE, 2022)

(4) Carbon emission from building operation stage

From 2005 to 2020, energy consumption during the building operation stage increased by 580 million tce, with an average annual growth rate of 5.4%, resulting in a 1.07 billion tons carbon emissions increase, with an average annual growth rate of 4.7%. The growth rate of carbon emissions was lower than that of energy consumption, carbon emission intensity for building operation stage decreased from 2.3 tons CO_2/tce in 2005 to 2.0 tons CO_2/tce in 2020, indicating China's optimization of building energy structure (CESY, 2021).

As shown in Figure 1-13, direct carbon emissions from buildings were 550 million tons of CO_2 in 2020. Electricity carbon emissions were 1.15 billion tons of CO_2, accounting for 53% of total emissions. Heat carbon emissions were 470 million tons of CO_2. Direct carbon emissions from buildings peaked at 670 million tons of CO_2 in 2016 and have since shown a declining trend with an average annual decrease of 4.8%. The average annual growth rate of electricity carbon emissions in buildings during the 13th Five-Year Plan period was 7.1%, indicating not only a high total amount but also a strong growth trend. Heat carbon emissions increased every year, but the growth rate was slower, with an average annual growth rate of

2.0%. The share of direct carbon emissions from buildings stays around 34% from 2010 to 2017, then decreases to 25% in 2020. Electricity carbon emissions increase from 42% to 53%, and the share of thermal carbon emissions stays between 21% and 24%

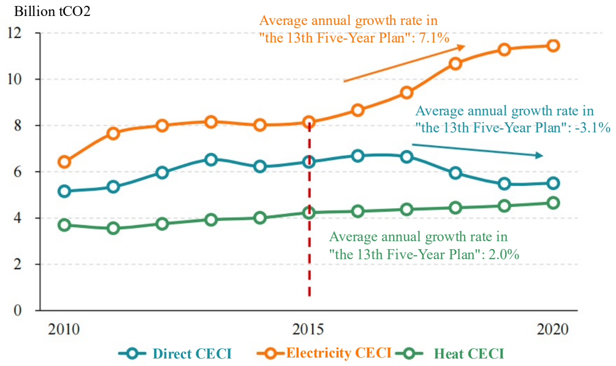


Fig.1-13 Trends in carbon emissions during the operational phase of a building
Source: (CABEE, 2022)

1.2.4 Japan's CECI

(1) CECI status in Japan

Japan's Ministry of Environment converts greenhouse gases to CO_2 mass in its greenhouse gas report. According to the characteristics of the construction industry, its greenhouse gas emissions are mainly caused by energy sources and non-energy sources, which result in direct CO2 emissions. Based on National Institute for Environmental Studies' data (NIES, 2022), Figure 1-14 shows the CO_2 emissions caused by energy and non-energy sectors after electricity and heat distribution, with the industry sector which include manufacturing and construction industry having the highest proportion, accounting for about 34.0% of the total, followed by commercial and related sectors, residential sectors, and transportation. The carbon emissions from the household and Business sectors can be considered as building operation carbon emissions, which account for 33.3% of the total emissions.

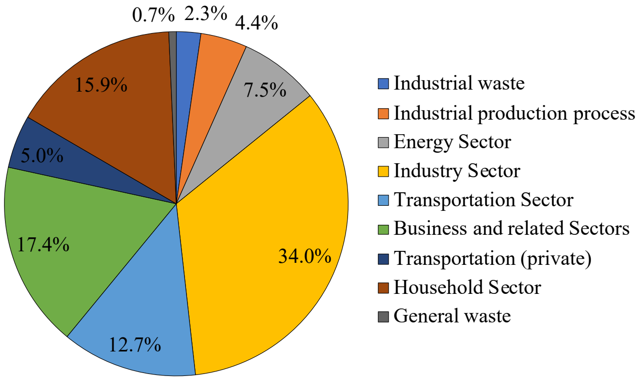


Fig.1-14 Japan's carbon emissions by sectors

Figure 1-15 (left) shows the proportion of each type of energy used in the construction phase based on 1149 buildings(JFCC, 2022), with diesel and electricity accounting for the largest proportions, approximately 76% and 22%, respectively, while kerosene and heavy oil account for a very small proportion. It should be emphasized that the construction stage in this data includes not only the construction of new buildings but also the electricity and kerosene consumed by the construction site of existing building renovations and demolition stages, as well as the carbon emissions generated by the fuel consumed by vehicles and equipment on the construction site, and the electricity and kerosene consumed by construction firms and the transportation of materials, equipment, and construction by-products.

Figure 1-15 (right) analyzes the carbon emissions caused by energy use in the operating stage of Japanese residential and commercial and related sectors (NIES, 2022), with the residential sector accounting for about 47% of the total carbon emissions in this stage and the commercial and related sectors accounting for about 53%. In terms of energy types, electricity, and natural gas account for the largest proportion, approximately 70% and 11%, respectively, followed by kerosene and liquefied petroleum gas (LPG), accounting for approximately 8% and 4%, respectively. Among the carbon emissions from the household sector, about 66% come from electricity use, about 13% from kerosene, and the carbon emissions from natural gas and LPG account for about 21%. For the carbon emissions of commercial and related sectors, about 72% come from electricity use, about 14% come from petroleum products, and carbon emissions from natural gas account for only about 9%, while other sources account for about 5%.

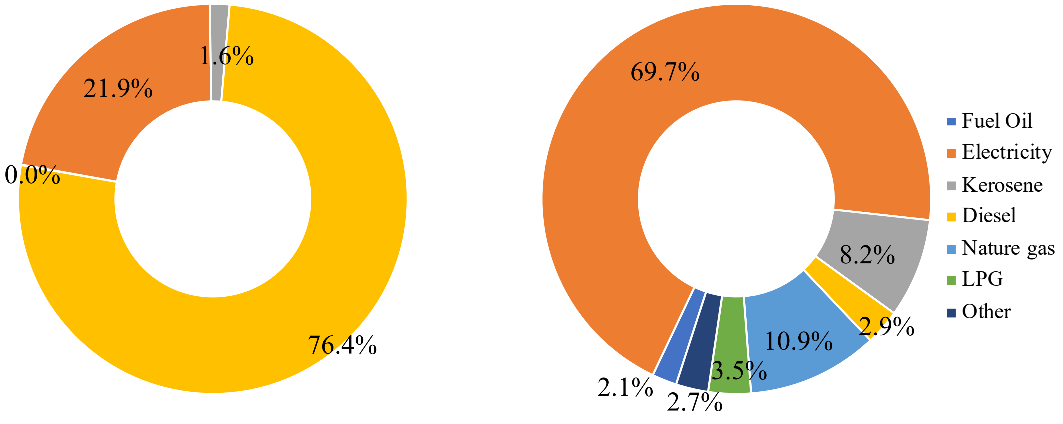


Fig.1-15 Sources of carbon emissions

(Left: Construction Stage; Right: Operation Stage)

According to statistics from the Japan Building Energy Management Technology Association, the average carbon emissions per unit area of buildings in 2019 was 79.3 kg/m^2, and the carbon emissions of various types of buildings are shown in Figure 1-16. The unit area carbon emissions of apartment buildings are lower than those of all public buildings, and hospitals have the highest carbon emissions, followed by hotels, department stores, and supermarkets.

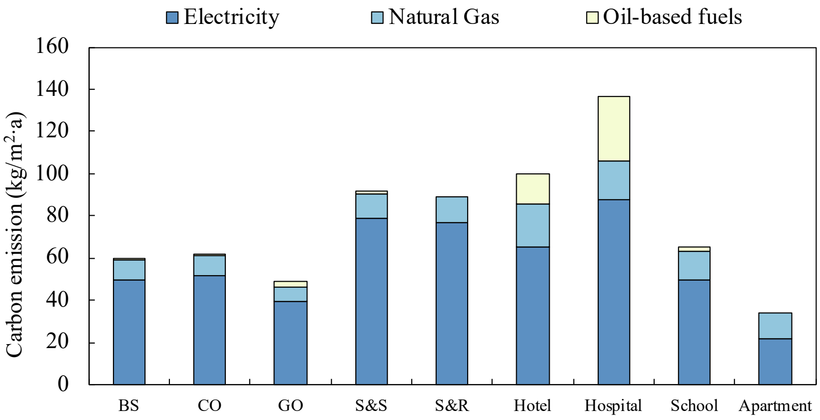


Fig.1-16 Carbon emissions from buildings in operation stage 2019

Note: BS means Business services building, CO means Civilian office building, GO means Government Office building, S&S means Store& Supermarket, S&R means Shop& Restaurant

(2) Carbon emissions from building construction and operation

Figure 1-17 shows the annual carbon emissions during the construction stage of buildings, based on surveys data (JFCC, 2022), covering new construction, building renovation, and demolition. The overall carbon emissions during the construction phase have decreased over the years, with a reduction of approximately 9.6% in 2020 compared to 2013 and a decrease of 2.3% compared to 2019. The overall decrease in carbon emissions is attributed to the increasing proportion of electricity in energy consumption and the decreasing proportion of diesel, which has optimized the energy structure of the construction phase. Additionally, the carbon emission factors of various types of energy have decreased year by year, leading to a reduction in total carbon emissions.

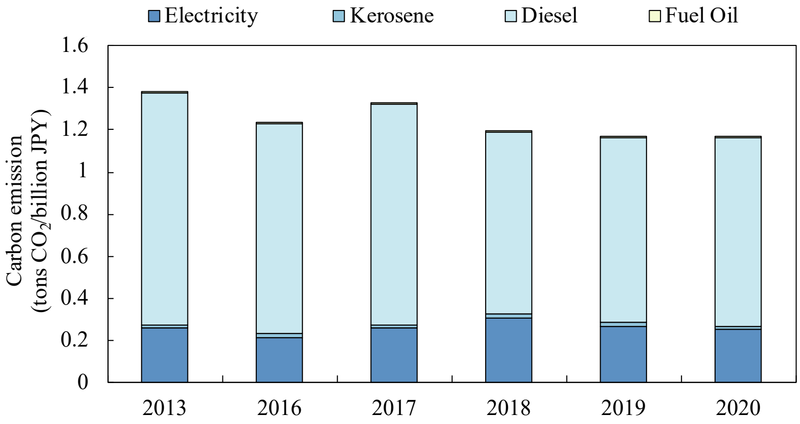


Fig.1-17 Trends in building construction stage carbon emissions

Figure 1-18 shows the annual carbon emissions during the operation phase of buildings in households, businesses, and related sectors (NIES, 2022), which have decreased year by year since 2013, with a reduction of approximately 22.1% in 2020 compared to 2013 and a decrease of approximately 1.4% compared to 2019. The reasons for the decrease include the adoption of energy-saving technologies, the impact of relevant laws and policies, and the introduction of renewable energy and a decrease in the proportion of fossil energy. Compared to 2013, renewable energy has increased by approximately 68.2% in 2020, with its power generation proportion increasing from 11% to 20%, while the proportion of oil-based power generation has decreased from 14% to 6%.

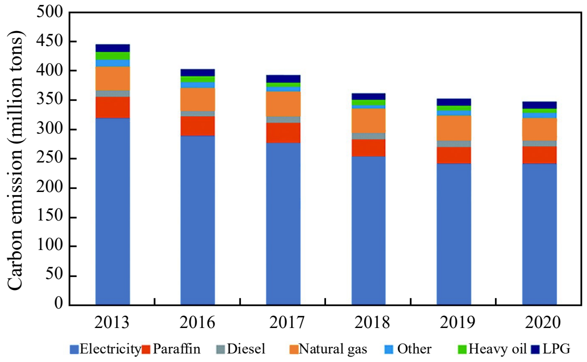


Fig.1-18 Trends in building operation stage carbon emissions

Source (Wang et al., 2022)

1.2.5 Other countries' CECI

According to data from the CAIT Climate Data Explorer, the top 10 countries with the highest carbon emissions from building operations are shown in Table 1-2, which is somewhat similar to the ranking of all carbon emissions. The United States is the country with the highest carbon emissions from building operations, emitting greenhouse gases equivalent to 550.6 million tons of CO_2 in 2019. China and Japan, the focus of this study, ranked 2nd and 7th respectively. Other countries with high carbon emissions from building operations include Russia, Iran, India, and Germany.

In terms of per capita carbon emissions, Canada has the highest per capita carbon emissions among these 10 countries, with 2.11 tons CO_2 e /per capita, ranking fifth among all countries. The per capita carbon emissions of developed countries such as the United States, Germany, the United Kingdom, and Italy are relatively high, all exceeding 1.0 ton CO_2 e /per capita, indicating that the driving force behind the carbon emissions from building operation in these high-income countries is mainly due to residents' pursuit of a comfortable living standard. The per capita carbon emissions from building operation in China are 0.31 CO_2 e /per capita, which is only about 1/5 of that of the United States and 1/3 of that of Japan, indicating that population is an important factor in the high carbon emissions from building operation in China, similar to India.

In addition, energy structure is also an important factor affecting carbon emissions from building operation. Developed countries such as France, Spain, and Sweden have lower per capita carbon emissions from building operation than China, because their energy structure is mainly based on low-carbon nuclear power. Although their building energy intensity is higher than China's, their carbon emission intensity is lower (BECRC, 2023). This also indicates that in the path towards carbon neutrality, not only energy efficiency and conservation in buildings should be emphasized, but also the transformation towards low-carbon energy systems and building energy structures should be achieved.

In terms of the building industry related sectors, China's carbon emissions in this accounting scope far exceed other countries, reaching 2774.5 million tons. However, this does not represent the carbon emissions of building materials and construction. The reason is that in this data, the carbon emissions from manufacturing are not distinguished between carbon emissions from the production of building materials and carbon emissions from the production of other products.

Table 1-2 Top 10 countries with the most carbon emissions from buildings in 2019

	Country	Buildings ($Mt\ CO_2\ e$)	Buildings (tons CO_2 e /per capita)	Manufacturing and construction ($Mt\ CO_2$ e)
1	United States	550.6	1.67	439.0
2	China	453.7	0.31	2774.5
3	Russia	220.5	1.51	280.5
4	Iran	129.3	1.56	100.5
5	India	122.3	0.09	572.5
6	Germany	121.0	1.45	93.6
7	Japan	109.1	0.86	189.3
8	United Kingdom	87.7	1.30	31.6
9	Canada	79.1	2.11	70.6
10	Italy	61.5	1.01	31.2

1.3 Global climate action

1.3.1 Global carbon reduction targets

Since the 21st century, global carbon emissions have grown rapidly. From 2000 to 2019, global CO_2 emissions increased by 40%. According to *the World Energy Statistics Yearbook* statistics released by British Petroleum (BP)(Dale, 2021), global carbon emissions have maintained a continuous growth since 2013, and in 2019, global carbon emissions reached a record high of 34.43 billion tons. The sheer volume of CO_2 emissions from human activities and the fact that some emissions remain in the atmosphere for hundreds to thousands of years makes CO_2 the biggest challenge to combat climate change climate change. Fig.1-19 shows how the net-zero carbon goal is performing in countries around the world. Climate change is a global challenge that transcends national boundaries. To solve it, requires coordination at all levels and international cooperation in the transition to a low-carbon economy.

Fig.1-19 Net-zero emissions target setting by countries/regions

Source:(Which Countries Have Set a Net-Zero Emissions Target?, 2021)

The Paris Agreement, which was adopted in 2015, aims to limit the global temperature rise to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C (*The Paris Agreement*, 2015). *The Paris Agreement* provides a durable framework that sets the direction for global efforts for decades to come, marking the beginning of a transition towards a net-zero emissions world. To achieve this goal, a UN report suggests that a rapid and comprehensive transformation of the global economy is needed, with a focus on transitioning to renewable energy, promoting energy efficiency, and reducing the use of fossil fuels. The report also emphasizes the importance of strengthening international cooperation, financing, and capacity building to support developing countries in mitigating and adapting to climate change. Countries have been implementing a series of climate actions, including setting more ambitious emission reduction targets, implementing carbon pricing mechanisms, promoting clean energy investments, and raising energy efficiency standards.

The Paris Agreement operates on a five-year cycle, driving increasingly ambitious climate action by countries. Every five years, each country must submit an updated national climate action plan, known as a Nationally Determined Contribution (NDC), which is central to achieving *the Paris Agreement* and its long-term goals. NDCs reflect the efforts of each country to reduce national emissions and adapt to the impacts of climate change. These climate actions collectively determine whether the world can achieve *the Paris Agreement's* long-term goals, including peaking global GHG emissions as soon as possible, followed by rapid reductions based on the best available science, to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of this century. In their submitted

NDCs, countries convey the actions they will take to reduce their greenhouse gas emissions to achieve *the Paris Agreement's* goals (*Climate Action*, 2023).

- Most of the contracting parties (90%) provided quantified mitigation targets, expressed as specific numerical targets, while the remaining 10% included strategies, policies, plans, and actions without quantified information as part of their nationally determined contributions (NDCs).
- The majority of contracting parties (80%) conveyed mitigation targets that covered all or almost all sectors defined in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, with an increasing number of them shifting towards absolute emissions reduction targets in their new or updated NDCs.
- For greenhouse gases, all NDCs covered carbon dioxide emissions, with most covering methane (91%) and nitrous oxide (89%) emissions. Many (53%) covered hydrofluorocarbon emissions, some covered perfluorocarbon and sulfur hexafluoride emissions (36%) and nitrogen trifluoride emissions (26%).
- Many contracting parties (50%) provided information on the synergies between their adaptation actions and/or economic diversification plans and the mitigation co-benefits generated, primarily when combined with other targets.
- Most of the contracting parties submitting new or updated NDCs (74%) have strengthened their commitments to reduce or limit greenhouse gas emissions by 2025 and/or 2030, indicating ambitious efforts to address climate change.
- Almost all contracting parties (92%) indicated that the implementation deadline for their NDCs is 2030, while a few (8%) specified implementation deadlines of 2025, 2035, 2040, or 2050. Many contracting parties (55%) identified 1 January 2021 as the start date for NDC implementation; some others (31%) indicated they began implementing their NDCs in 2020 or earlier; and a few contracting parties (3%) mentioned 2022 as the starting year.
- Almost all contracting parties (93%) provided quantified information on their mitigation targets and reference points. Among the contracting parties submitting new or updated NDCs, most (84%) updated the basis for defining their targets, including reference points and/or business-as-usual scenarios. Such updates led to higher-quality NDCs and, for some contracting parties, significant changes in estimated emissions levels for 2025 and 2030.

Considering the implementation of the NDCs, global GHG emissions are estimated to be around 53.4 (51.8-55.0) $GtCO_2e$ in 2025 and 52.4 (49.1-55.7) $GtCO_2e$ in 2030, as shown in Fig.1-20. These represent: 1) 53.7% increase from 1990 levels (34.7 GtCO2e) by 2025, a 12.6% increase from 2010 levels (47.4 GtCO2e), and a 1.6% increase from 2019 levels (52.6 GtCO2e); 2) 50.8% increase from 1990 levels by 2030, a 10.6% increase from 2010 levels, a 0.3%

decrease from 2019 levels, and a 1.9% decrease from the estimated emissions in 2025, indicating a possible peak in global emissions before 2030.

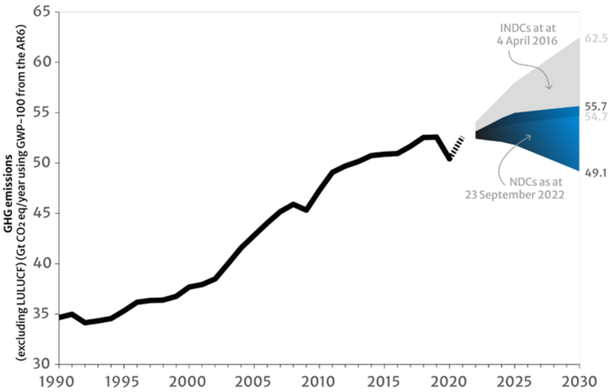


Fig.1-20 Projected range and progression of emission levels according to nationally determined contributions

Source: Climate action

Since 2007, China has become the country with the highest CO_2 emissions in the world. China has actively implemented *the Paris Agreement*, further increased its national voluntary contributions, and effectively promoted key work around carbon peaking and carbon neutrality goals in an orderly and effective manner, achieving remarkable results. China has established a policy system for carbon peaking and carbon neutrality, known as the “1+N” policy system (CPBA, 2021), formulated medium to long-term greenhouse gas emissions control strategies, promoted the development of a national carbon emissions trading market, and implemented a national adaptation strategy for climate change.

As the second-largest emitter in the world, the United States has taken decisive action to make corresponding contributions to the global emission reduction targets that need to be achieved in the next decade. *The U.S. climate plan* commits to achieving carbon neutrality by 2050 and will soon announce its emission reduction targets for 2030. The plan envisions the establishment of stricter energy efficiency standards, the provision of clean technology subsidies, and support for key technologies such as clean energy infrastructure and green hydrogen. Japan’s mid-term goal is to “reduce greenhouse gas emissions by 26% by 2030”, with long-term goals of “reducing greenhouse gas emissions by 80% by 2050” and “achieving a decarbonized society around 2050 if possible” (Someno, 2021).

In 2021, the European Commission launched *the European Climate Law* (EEAS, 2021), which incorporated the EU’s climate neutrality commitment and the mid-term target of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels into binding legislation, fundamentally changing Europe’s economy and society to achieve a fair, green, and prosperous future. India set an overall emissions reduction target, aiming to reduce its carbon intensity by 45% from its economic activities by 2030, which is a more ambitious target than the previous goal of reducing carbon intensity by 33-35% compared to 2005 levels by 2030(Abhimanyu Sharma, 2023). The Canadian government has introduced green policies, such as developing clean energy and public transportation systems, while setting an ambitious target to reduce greenhouse gas emissions by 40%-45% below 2005 levels by 2030 (MECC, 2022).

Table 1-3 further illustrates the main contents of the NDC discussions of some developing countries from 2020 to 2021(UNCC, 2022).

Table 1-3 Targets of NDCs in some developing countries

Country	Main Content
Chile	Chile plans to achieve carbon neutrality before 2025. The country plans to work closely with the private sector and adopt tools such as carbon budgeting to implement comprehensive emissions reductions in the economy. Due to its long coastline, Chile will gradually protect its oceans and move towards a waste-free circular economy.
Colombia	Carbon neutrality by 2050 and will achieve this goal using the country's *National Autonomous Contribution program* (NAC), which plans to be more than halfway to net zero emissions by 2030. The country will decarbonize its energy system by signing NDC implementation agreements with the energy, agriculture and industry sectors. Increasingly, climate change adaptation commitments are reflected in the overall progress indicators and have been incorporated into national monitoring.
Panama	The goal is to restore 50,000 hectares of national forest and increase the country's emissions reduction target by 11.5 % by 2030. Risk mitigation improves the protection of communities, health and infrastructure.
Vietnam	Implementation steps were identified for energy, agriculture, waste, land use, land-use change and forestry, and industry. Its projected emission reductions represent a 34% increase over the first program.
Rwanda	Rwanda is the first country in Africa to revise its first nationally owned contribution program, which aims to reduce emissions by 38 % by 2030. It will reduce emissions in all key sectors of the country's economy and has established a system of indicators to track and record climate change adaptation in water, agriculture, land and forestry, human settlements, health, transport and mining.

1.3.2 Industry-wide decarbonization

The low-carbon economy triggered by carbon neutrality actions will reshape people's production and lifestyle. All sectors of society need to continue to carry out low-carbon technology research and development and standardization to guide the low-carbon transformation of the economy and society. To achieve a decarbonized society, the world is taking active action, and its impact may cover all areas, including government administrative agencies, businesses, and citizens. Businesses have a significant amount of CO_2 emissions, so it is unquestionable that industries such as mining, construction, manufacturing, and transportation need to adopt environmental protection measures. Against this background, the industrial sector is accelerating equipment technology innovation to promote energy-saving and high-efficiency goals for industrial products and systems.

(1) China's industry-wide decarbonization

China has the largest population in the world, and is the top emitter of greenhouse gases, with a combined CO_2 emissions share of 30.7%. To address this issue, the region needs to take urgent action to reduce emissions and shift towards a low-carbon economy.

Carbon neutrality efforts are not only a global climate change issue but also involve the transformation of production and lifestyle, national energy security, and scientific and technological revolution, which will bring about an important strategic opportunity for China's economic and social development. So far, the specific goals of China's 14th Five-Year Plan, announced include reducing carbon intensity by 18% and unit GDP energy consumption by 13.5% from 2021 to 2025. There is also a non-binding target of increasing the proportion of non-fossil energy in the total energy consumption to 20% by 2025 (approximately 16% in 2020). Achieving the peak of carbon dioxide emissions before 2030 depends on progress in three key areas: improving energy efficiency, developing renewable energy, and reducing coal consumption(IEA, n.d.).

Although the total amount of CO_2 emissions in China is high, it has also made positive progress in controlling carbon emissions and achieving green development. On the one hand, the growth rate of CO_2 emissions has slowed down significantly. the average annual growth rate of CO_2 emissions reached about 8% in 2005-2010, declined to 3% in 2011-2015, and further decreased to about 1.9% in 2016-2019. On the other hand, the intensity of CO_2 emissions per unit of GDP is gradually decreasing. As measured by data published by the IEA, China's CO_2 emissions per unit of GDP have gradually declined from 29 tons/ kilo CNY in 2005 to 10 tons/ kilo CNY in 2019, a reduction of about 60%. These advances have benefited to a large extent from the continuous adjustment of the energy structure.

(2) Japan's Decarbonization Path

Although Japan's share of global CO_2 emissions in 2020 is only about 2.8%, its per capita emissions are higher than those of China, the EU, and India. After the 2011 Great East Japan Earthquake, nuclear power was shut down, while some thermal power plants were also affected and shut down. The increased use of fossil fuels has led to a rapid upward trend in Japan's carbon emissions. Given that Japan's energy structure is constrained by its heavy dependence on overseas fossil energy sources, policy bottlenecks are difficult to break through, and the technological transformation of energy and its industries faces real difficulties.

Japan's early initiation of low-carbon development strategy can be traced back to 1998, when *the Act on Promotion of Global Warming Countermeasures* was enacted. The implementation of carbon tax began in 2007, followed by the launch of *the Low Carbon Society Action Plan* in 2008. Over the past two decades, despite slow economic growth, Japan has achieved significant improvements in energy efficiency, resource utilization efficiency, and carbon productivity per unit of output. Moreover, it has essentially achieved the decoupling of energy consumption, electricity consumption, and economic growth.

The 2050 Carbon Neutral Green Growth Strategy (Shen et al., 2022) of Japan identifies the energy sector, which accounts for more than 80% of greenhouse gas emissions, as the key area for reform, with electrification of the energy system as the main development focus and proposes that decarbonization of the power sector is an important precondition for achieving the carbon neutral target. Effective implementation of emission reduction measures in this sector is crucial for Japan to achieve its greenhouse gas reduction targets. According to data from *Low Carbon Power* (*https://lowcarbonpower.org)*, approximately 29% of Japan's electricity will come from low-carbon sources in 2022.

The Japanese government has set more detailed targets for different sectors. On the one hand, it aims to significantly increase the share of zero-emission sources in the power sector, which is the main CO_2 emitting sector, accounting for about 37% of total emissions. Japan plans to raise the target share of non-fossil fuel power sources in the entire electricity generation capacity from the previous target of 44% to 59% by 2030. This involves two main aspects: significantly increasing the share of renewable energy sources, and vigorously developing hydrogen and ammonia-based power generation to reach a share of about 1%, with a further increase to 10% by 2050. Another aspect is to revive the nuclear power industry and accelerate the restart of nuclear power units, while reducing the share of fossil fuel power sources, with the proportion of LNG-based power generation reduced from 27% to 20%, coal-based power generation reduced from 26% to 19%, and oil-based power generation further reduced from 3% to 2%.

(3) Carbon neutral strategies for other major economies

The carbon neutral strategies of the United States, United Kingdom, and France all include two levels: specific timeframes and carbon reduction targets for key industries to achieve carbon neutrality, and the corresponding technological innovations, funding, employment arrangements, and economic growth goals that align with these targets(*CLEAN Future Act*, 2021). Both the U.S. and UK focus on major carbon reduction industries and emphasize industrial technological development to achieve carbon reduction targets. The French government is using carbon reduction targets to force key industries to push forward with the carbon reduction process.

The Long-Term Strategy of the United States Pathway to Net-Zero Greenhouse Gas Emissions by 2050 states that the country will reduce greenhouse gas emissions by 50% to 52% by 2030, establish a 100% clean power system by 2035, and achieve net-zero emissions by 2050(U.S. Department of State, 2021). The main measures are:

- Proposed 5 key shifts: zero carbon power system, promotion of clean fuels, reducing energy consumption, reducing greenhouse gas emissions, and increasing CO_2 removal efforts.
- Reducing pollution emissions from power plants, developing photovoltaic and wind power industries.
- Accelerating the deployment of clean fuels, promoting zero emission vehicles, investing in clean transportation infrastructure.
- Promoting the electrification of end-use equipment by improving energy efficiency, improving industrial production process.

The UK's *Energy White Paper* aims to reduce CO_2 emissions by 230 million tons by 2032 which approximately 50.9% of the total carbon emissions in 2018, create 250,000 jobs, and become a world leader in green technology (*Energy White Paper*, 2020). The UK has identified 10 key industries: offshore wind power, low-carbon hydrogen energy, advanced nuclear energy, net-zero vehicles, green public transportation, net-zero aviation and green shipping, green buildings, carbon capture and storage, environmental protection, green finance, and innovation. The UK has set some specific targets, such as producing 5GW of low-carbon hydrogen energy and building a gas-energy town by 2030, phasing out fossil fuel boilers for heating by 2035, and installing 600,000 sets of heat pumps annually by 2028.

France's *National Low-Carbon Strategy* sets a goal of reducing greenhouse gas emissions by 40% compared to 1990 levels by 2030, and plans to achieve complete decarbonization of energy supply by 2050 (France, 2021). France will achieve their set goals through the following methods. The main measures are:

- Propose three basic principles: Future market competitiveness, provision of necessary goods and services, and adaptation to low-carbon social development.
- Clarify three research directions: decarbonization of the energy source sector, energy use efficiency, and carbon capture and sequestration.
- Systematically quantify greenhouse gas emissions and control the carbon content of imported and exported products.
- Clarify the additional short- and medium-term investments needed for a low-carbon transition and divert funds away from climate-unfriendly investments.
- Set the evolutionary process for zero-carbon trajectory expertise in urban planning.

With the increasing attention of countries to climate issues, it has become a global consensus to jointly decarbonize. Currently, more than 123 countries or regions have proposed carbon neutrality schedules or roadmaps in different forms. Among them, 18 countries including Germany, Switzerland, and Japan have already set carbon neutrality target years through legislation. The development of policy documents and promotion of carbon neutrality targets are the most common forms, with 46 countries including the United States, Finland, and Iceland setting carbon neutrality target years through this approach. 15 countries such as

Malaysia, India, and South Africa have made carbon neutrality commitments. In addition, some countries have already proposed schedules and are making final decisions. According to the schedule, national-level carbon neutrality will be achieved as early as 2030, for example in Barbados and Maldives. Most countries have set their carbon neutrality target years for 2050, with India and Ghana being the latest for 2070.

1.3.3 Decarbonization in the construction industry

(1) Global construction industry decarbonization

With the continuous advancement of urbanization, the construction industry has gradually become a major emitter of carbon, it faces a daunting task of energy conservation and emissions reduction. According to the latest report by the United Nations Environment Programme (Life, 2004), despite the construction industry's strong investment in energy efficiency and reduction of its energy intensity, the energy consumption and carbon dioxide emissions caused by buildings and construction still exceed the pre-COVID-19 outbreak levels, reaching a historic high. The data shows that in 2021, buildings and the construction industry accounted for more than 34% of global energy demand, and their proportion in carbon dioxide emissions related to energy consumption and production processes reached about 37%. The operational emissions related to buildings and the construction industry reached 10 billion tons of carbon dioxide equivalent, which was 5% higher than the level in 2020.

The strategy to achieve net-zero energy consumption and zero carbon emissions in buildings is a key component of global decarbonization efforts, and it must become the primary form of achieving net-zero emissions for all economies in the building construction industry by 2050. In 2021, 42% of countries that are signatories to the Paris Agreement have established building energy regulations. 158 countries mention buildings in their Nationally Determined Contributions (NDCs), with 118 countries including energy efficiency as part of their emission reduction strategies.

Achieving decarbonization of buildings over their entire life cycle requires a transformation of the building and construction industry. Net-zero operation and embodied carbon emissions in buildings are possible but require ambitious policy signals to drive a range of measures. *The 2022 Global Status Report for Buildings and Construction* released critical recommendations for decision-makers, including the establishment of a national stakeholder alliance to set goals and strategies for sustainable, zero-carbon, and resilient buildings and construction industry through building roadmaps. National and local governments must enact mandatory building energy regulations and establish a pathway for their building codes and standards to achieve net-zero emissions as soon as possible. Governments and non-state actors must increase investments in energy efficiency. The building and real estate industry must implement zero-carbon strategies for new and existing buildings. The building materials and construction industry must strive to reduce their carbon emissions throughout their entire value chain. Governments, especially cities, need to implement policies that promote the transition to a circular economy. Rapidly developing countries and economies need to invest in capacity building and supply chain to promote energy-efficient design, low-carbon, and sustainable construction(UNEP, 2022). Figure 1-21 shows the emission reduction paths provided in the report.

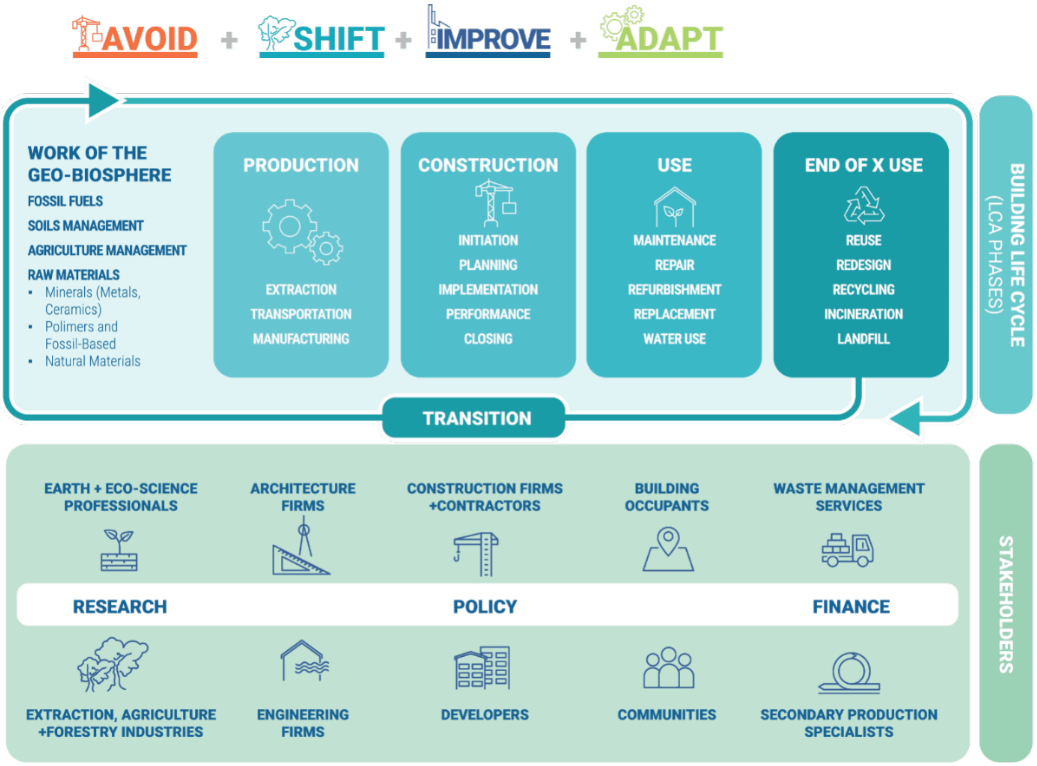


Fig.1-21 Decarbonization pathways in the construction industry

Source: UNEP

(2) Decarbonization in the construction industry of China

The carbon dioxide emissions from the entire building industry chain in China is about 5 billion tons, accounting for over 50% of the country's total emissions. The low-carbon transformation of the building industry is crucial for China to achieve its "dual carbon" goals and is also important for achieving net-zero emissions worldwide. According to *The Opinions on Accelerating Ecological Civilization Construction*, the construction industry has become a key industry that requires attention for national green development and ecological civilization construction. Table 1-4 summarizes the policies related to the decarbonization of China's construction industry.

Table 1-4 Policies related to decarbonization of construction industry in China

Implementation time	Policy
2019.6	Action Plan for Green and Efficient Refrigeration
2020.4	General Specification for Building Energy Efficiency and Utilization of Renewable Energy
2020.7	Action Plan for Creating Green Buildings
2021.10	Opinions on Promoting Green Development of Urban and Rural Construction
2021.10	Opinions of the Central Committee of the Communist Party of China and the State Council on Fully Implementing the New Development Concept and Doing a Good Job in Carbon Peak and Carbon Neutrality
2021.10	Action Plan for Carbon Peak by 2030

To decarbonize the Chinese construction industry, four aspects should be addressed. The first is to improve building energy efficiency. The second is to promote the use of renewable energy in buildings and develop green energy heating technology on a large scale. The third is to coordinate with the power sector to promote building electrification, improving the interaction between building electricity and the power grid. The fourth is to increase urban greening and green space area, improving carbon sequestration and carbon sink capabilities (DUAN et al., 2020).

When it comes to specific actions, decarbonization actions can be summarized into the following three aspects: low-carbon building materials and green construction, the operational phase of building projects, and zero-carbon operation of buildings.

In terms of low-carbon building materials and green construction, the carbon emissions from the construction industry account for more than half of the total national emissions, with carbon emissions from cement and concrete structures accounting for as much as 20%. To achieve the goal of carbon neutrality in construction, it is necessary to promote the low-carbon development of cement and concrete materials, develop recycled concrete, adopt new green construction methods and green building materials, and vigorously promote nearly zero-energy buildings. Starting from the perspective of the entire life cycle, the concept of green and low-carbon development should be integrated throughout the entire process of construction and the upstream and downstream industrial chains to significantly reduce the on-site emission of construction waste, and to achieve green and low-carbon development in the entire industry chain of construction.

In terms of the operation stage of building engineering, the goal of the building energy revolution is to achieve electrification based on green electricity and completely eliminate the use of fossil fuels in building engineering. Building engineering will transform from a simple electricity consumption end to a “production, storage, and consumption” integrated system, realizing the unity of energy-saving requirements and the pursuit of a better life through energy-saving design for new buildings and energy-saving retrofitting for existing buildings. The realization of electrification depends on the development of new energy sources, including the increase in the proportion of wind power and photovoltaic power generation, as well as the construction of building projects that connect charging piles and the power grid as a bridge for new energy vehicle charging and power consumption. The transformation of the terminal energy unit from a traditional rigid load to a new flexible load also helps to regulate the power system.

In terms of zero-carbon operation of buildings, the zero-carbon path focuses on energy-saving, achieving green electrification, no longer using fossil fuels, and achieving zero-carbon power supply and zero-carbonization of heating systems. This is also the goal that the future urban energy supply system must achieve. The energy consumption of urban buildings should first consider the installation space of wind and solar power and relieve the lack of coordination between the power generation side and the power consumption side through building energy storage, charging piles, and other measures. The future zero-carbon power system will integrate the functions of power generation, consumption, storage, and regulation in buildings. In addition, rural areas in China have sufficient roof areas that can be converted into potential photovoltaic power generation.

(3) Decarbonization in the construction industry of Japan

In April 2021, Japan established the *Regional Decarbonization Roadmap* at the Decarbonization Conference. Based on the idea that regional decarbonization will solve regional issues and improve the attractiveness and quality of the region, the roadmap focuses on measures and actions to turn the region into a vibrant society by 2030. It presents specific measures for decarbonization processes and regions, as shown in Fig.1-22.

The national government will provide sustained and comprehensive support in human resources, information, funds, and other aspects to establish at least 100 “Decarbonization Preceding Region” that lead the way in decarbonization by 2030(TOMOYA TANIGUCHI, 2022). Local stakeholders, such as local governments, local businesses, and citizens, will play a leading role in maximizing the use of local resources such as renewable energy, promoting a circular economy, improving disaster prevention and reduction measures, and enhancing the quality of life. Decarbonization advanced zones are regions that achieve almost zero carbon dioxide emissions related to electricity consumption in the residential sector (residential and commercial and other sectors) to achieve carbon neutrality by 2050, including the transportation sector and thermal use. In terms of greenhouse gas emissions reduction, the region will achieve a reduction in emissions consistent with Japan’s overall 2030 target, and become a model for implementing the “decarbonization domino effect” to achieve regional-specific emission reduction targets(Ministry of the Environment, n.d.).

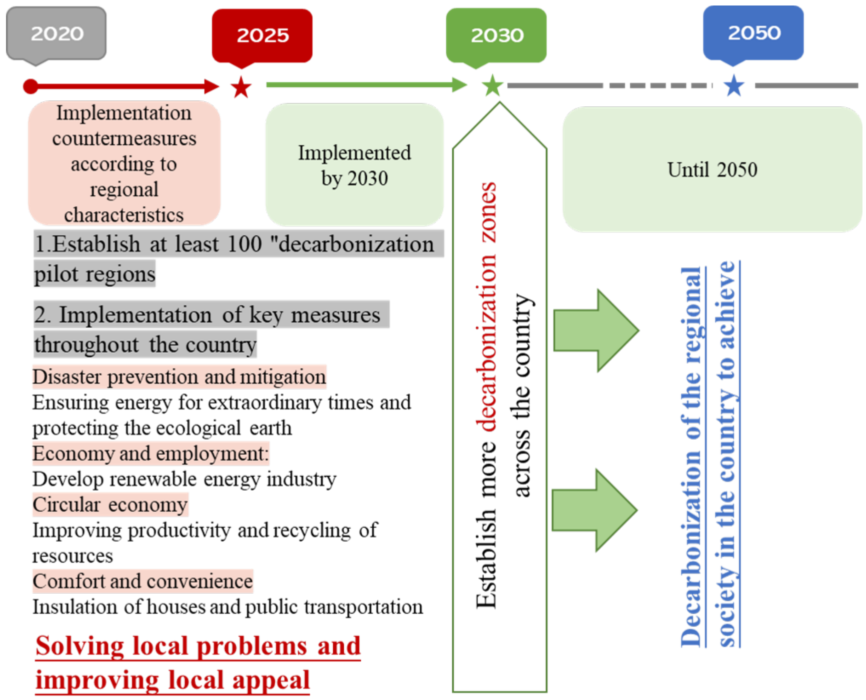


Fig.1-22 Decarbonizing Domino

Sources: Ministry of the Environment

The industry, housing, and construction industries are key areas for carbon neutrality in Japan. The control of emissions from the next generation of housing/buildings will be an important component of carbon emissions. According to the strategic plan, the emission reduction target of “zero energy consumption for new housing/buildings by 2030 and zero energy consumption for existing housing/buildings after 2050” has been proposed. To achieve this goal, the Japanese government has also established a series of institutional requirements and incentive measures(ES, 2021), mainly reflected in the reform of energy management system technology, the popularization of high-performance housing, and the promotion of high-performance wood structures such as CLT. In terms of building materials and equipment, equipment performance is improved through the “leadership” program, standards are revised, and the market placement of clean energy such as solar energy is further promoted.

(4) Decarbonization in the construction industry of other major economies

Residential and commercial buildings accounted for 19% and 16% of US sectoral energy-related CO_2 emissions in 2021, respectively. Electricity is the primary energy source consumed in residential and commercial sectors, accounting for 43% and 50%, respectively, followed by natural gas, accounting for 42% and 37%, respectively. Renewable energy accounts for a small portion only 7% and 3%, respectively. Buildings play an important role in supporting decarbonization as energy-intensive consumers.

Fig.1-23 shows the main theories of US building decarbonization research. Altering energy use patterns could change CO_2 emissions in buildings, making them critical to decarbonization efforts. Additionally, using electricity generated by user-side distributed energy will further support decarbonization. Rapid deployment of decarbonization will pose significant technological and economic challenges to the grid and its consumers, and policymakers, stakeholders, and industry leaders should develop feasible pathways to achieve clean power objectives.

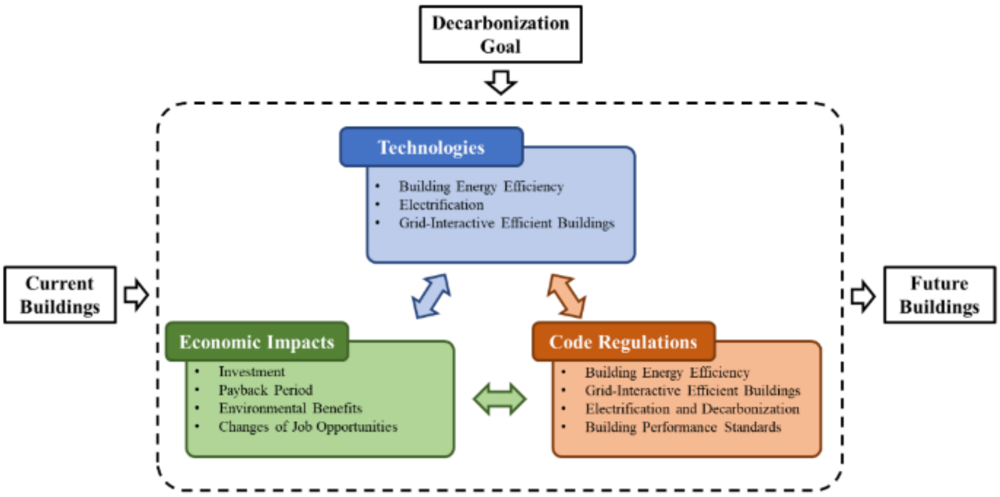


Fig.1-23 Major theories of building decarbonization research in the United States

Source：(Ye et al., 2023)

The construction industry is one of the key industries for GHG mitigation measures in Germany’s 2050 Climate Action Plan. Currently, the construction industry accounts for approximately 30% of Germany’s total carbon emissions and about 40% of total energy consumption. The goal of the German construction industry is to reduce emissions by 40% compared to 1990 levels by 2020, 67% by 2030, and achieve full carbon neutrality by 2050. Therefore, retrofitting existing buildings for insulation and setting higher construction standards for new buildings plays a crucial role in achieving Germany’s climate targets(*Energy Efficiency in Buildings and Neighborhoods in Urban Renewal*, 2021).

Improving the energy performance of existing buildings in Germany mainly focuses on two main strategies: first, reducing primary energy demand by increasing energy efficiency; and second, increasing the share of renewable energy in the overall energy mix. These aspects are also at the core of Germany’s energy transition. Germany has developed a new *Building Energy Act (GEG)*, which aims to consolidate existing *Energy Conservation Regulations (EnEV)*, *Energy Saving Act (EnEG)*, and *Renewable Energies Heat Act (EEWrmeG)* into one regulation and implement *Nearly Zero Energy Buildings standard (nZEB standard)* in line with the requirements of the *EU Energy Performance of Buildings Directive* (EPBD2010). By 2019, the Building Energy Act (GEG) and the *nZEB standard* will become the new mandatory standards for public buildings, and from 2021, they will be mandatory for new private buildings as well.

Over the past two decades, the UK government has made the efficiency and productivity of the construction industry a key objective in various initiatives, including *Construction 2025* and *Construction Sector Deal*. Recently, the Construction Leadership Council (CLC) has released an *Roadmap to Recovery* for the construction industry, highlighting the urgent need for transformation, and has published a *Climate Action Plan for Zero Carbon* outlining the actions needed for the industry to decarbonize (*Decarbonising-Construction-Mandarin*, n.d.).

France plans to invest significant funds in improving the energy efficiency of buildings and has also released *Environmental Regulation 2020 (RE2020)* to encourage construction companies to use a mix of building materials(France, 2021). This regulation aims to establish a policy framework for the decarbonization of the construction industry by promoting carbon storage and emphasizing the use of wood and other bio-based construction materials.

1.4 Research purpose and logical framework

1.4.1 Research purpose and core content

With the proposal of carbon neutrality goals and increasing strictness in carbon emissions management, cities have become the basic unit for assessing carbon neutrality progress. However, research on carbon emissions at the urban level is still insufficient. The construction industry is a high-energy-consuming and high-carbon-emitting industry, and decarbonization of this industry has become a key focus for achieving global carbon neutrality goals. Therefore, this study is dedicated to researching carbon emissions from the construction industry at the urban level, with the aim of exploring the possibility of decarbonization in this industry.

This paper conducts a comparative analysis of carbon emissions from the building industry in Hangzhou, China and Kitakyushu, Japan, two cities in different stages of urban development, in order to gain a deep understanding of the driving factors behind changes in carbon emissions from the building industry in each city. Based on this analysis, the article selects the building materialization phase in Hangzhou and the demolition phase in Kitakyushu as representatives of carbon reduction in the building industry. It explores the potential for decarbonization in both cities through different means and provides decarbonization predictions.

The purposes of this paper are as follows:

（1） Accounting for CECI trajectory within a city scale.

Carbon accounting is an emerging field of research, and currently research on CECI mainly focuses on the national scale, provincial scale, or the scale of individual buildings. This paper adopts a top-down accounting method to calculate CECI at the city scale, analyzing the sources of direct carbon emissions and the trajectory of indirect carbon emissions to determine the spillover of carbon emissions.

（2） Analysis of the driving forces of CECI changes.

Based on the accounting of CECI, explore the main factors that affect CECI. Select two typical cities in different stages of development, use the LMDI method to decompose the CECI increment, and determine the driving effect of each influencing factor on CECI growth, providing a basis for decarbonization.

（3） Projection of the possibility of decarbonization in the construction industry

Based on the driving force analysis, this study explores different decarbonization perspectives in the materialization and demolition stages of buildings for two cities. Multiple development paths and scenarios are established to examine the contributions of upstream sectors and C&D Waste recycling sectors to decarbonization of the construction industry and to analyze the possibility of carbon neutrality. The carbon accounting for the materialization and demolition stages of buildings is carried out from bottom up.

The research framework of this paper is shown in Figure 1-24, which also expresses the research logic of this paper.

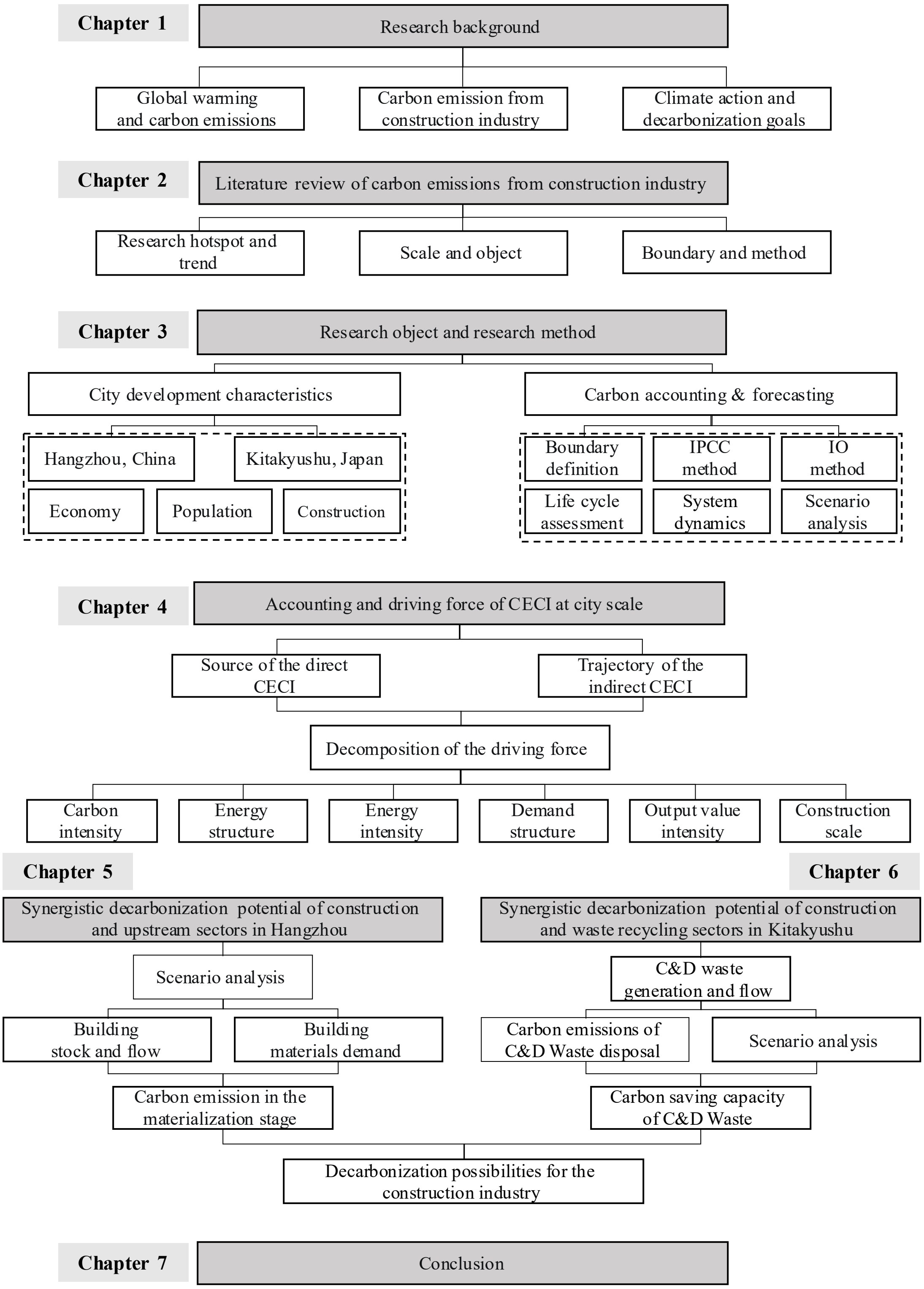


Fig.1-24 Research framework

1.4.2 Chapter content overview and related instructions

The chapter names and basic structure of this study are shown in Figure 1-25, and the details of the study are described below.

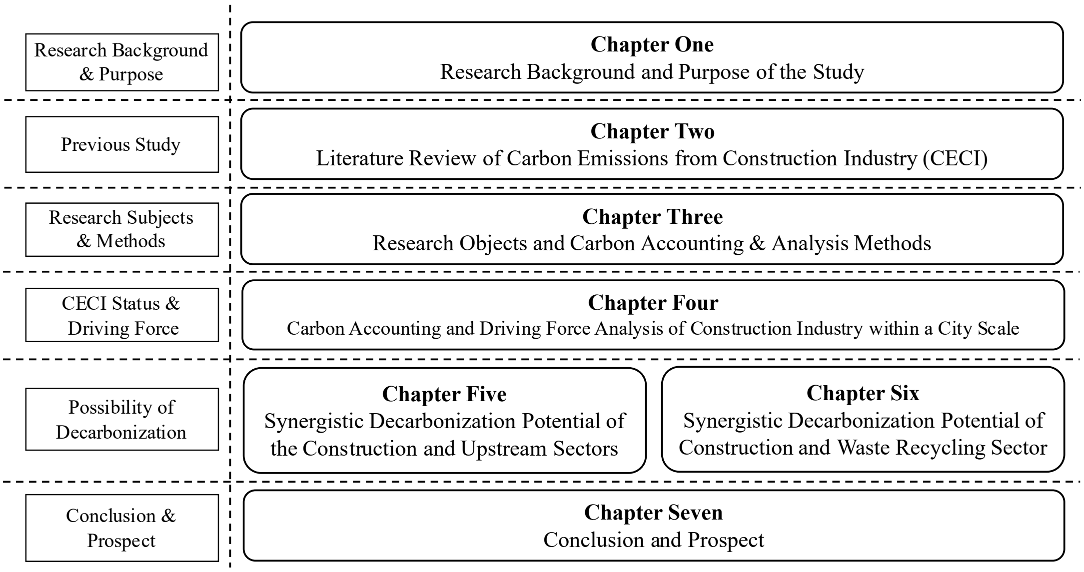


Fig.1-25 Chapter names and basic structure of this paper

In Chapter 1, Research Background and Purpose of the Study:

Carbon emissions are one of the important factors contributing to global climate change, and the carbon emissions from the construction industry account for a large proportion of global emissions. Therefore, decarbonizing the construction industry is crucial for achieving global climate goals and each country's commitment to carbon neutrality. Chapter One aims to introduce the current state of global climate change, explore the relationship between carbon emissions and climate warming, and briefly outline the status of carbon emissions in various countries, emphasizing the urgency of curbing carbon emissions growth. Then, it details the sources of carbon emissions in the construction industry, as well as the carbon emissions situation in the construction industry of China and Japan. Next, it introduces the climate actions and carbon neutrality goals of various countries, demonstrating that carbon emissions reduction in the construction industry has become a global consensus. Finally, the research objectives and article structure are presented.

In Chapter 2, Literature Review of Carbon Emissions from Construction Industry:

Carbon emissions research is an emerging field. Chapter two adopts a bibliometric analysis method based on 282 relevant research papers collected from the SCIE and SSCI in Web of Science to analyze the development trends and hotspots of carbon emissions research in the construction industry. The analysis finds that building energy efficiency, sustainable development, green buildings, and policy evaluation have become popular topics in the field of carbon emissions research in the construction industry (CECI). Currently, research is focused on macro and micro scales such as national and building scales, while CECI accounting at the city scale remains a challenge. Carbon emissions accounting for building demolition or the treatment and recycling of building waste is a challenge that needs to be addressed. The review summarizes the value and information of important literature and scholars to understand the latest progress and future challenges in carbon emissions accounting and environmental impact in the construction industry.

In Chapter 3, Research Objects and Carbon Accounting & Analysis Methods:

Chapter three mainly introduces the reasons for choosing Hangzhou in China and Kitakyushu in Japan as the research objects, as well as the concepts and methodology related to the research. The two research objects have similar geographic locations and urban status but differ in their stages of urban development. Hangzhou is in a period of rapid development with a rapidly increasing building stock, while Kitakyushu is in a stage of urban contraction with a large number of vacant buildings. Then, this chapter defines the boundary of CECI in the research and elaborates on the carbon emissions factor method, which is a commonly used method based on energy consumption data to estimate carbon emissions. In addition, other methods are introduced, including input-output models, life cycle assessment, system dynamics theory, and scenario analysis. These methods can be used to analyze the sources and influencing factors of CECI, help understand the complexity of CECI and propose corresponding countermeasures.

In Chapter 4, Carbon Accounting and Driving Force Analysis of Construction Industry within a City Scale:

Assessing city-scale carbon emissions and their sources from the construction industry is a significant problem. Chapter four focuses on the carbon emissions accounting of Hangzhou city within the city scale, exploring the CECI trajectory through the establishment of a new accounting framework, analyzing the sources of direct CECI, and highlighting the upstream indirect CECI in different regions, particularly the problem of carbon emissions spillover in Hangzhou city. Subsequently, the Logarithmic Mean Division Index (LMDI) method is used to decompose the differences in carbon emissions, elucidating the driving forces behind typical cities CECI changes, which is helpful for the subsequent two chapters to predict decarbonization from different perspectives on city development characteristics. Finally, the reasons for changes in direct and indirect CECI are discussed from a policy perspective. This chapter’s research has a certain reference value for CECI reduction and provides a basis for the development and optimization of carbon emissions reduction policies.

In Chapter 5, Synergistic Decarbonization Potential of the Construction and Upstream Sectors:

Hangzhou is in a period of rapid development, with a large number of buildings being constructed. Meanwhile, indirect emissions from upstream sectors of the construction industry account for approximately 97% of Hangzhou’s CECI. Studying the collaborative decarbonization potential and emission reduction pathways between the construction industry and upstream sectors can help guide the sustainable development of Hangzhou. Chapter five proposes a bottom-up CECI accounting model based on system dynamics and process-based life cycle assessment. Based on possible development paths, nine future scenarios are established. The accounting model simulated the carbon emissions of Hangzhou's construction industry in the materialization stage under different scenarios until 2060 and explored the emission reduction potential of various factors using the LMDI decomposition method. The results show that the cumulative emission reduction potential in the next 40 years can reach 366.1 million tons, but 3.7 million tons of CO_2 still need to be compensated through carbon trading or carbon removal methods by 2060. Controlling construction scale and reducing material CECI will be key strategies for the decarbonization of the construction industry in Hangzhou.

In Chapter 6, Synergistic Decarbonization Potential of Construction and Waste Recycling Sector:

Kitakyushu is currently experiencing urban shrinkage, and the peak period of building demolition is expected to arrive soon. Studying the synergistic decarbonization potential and emission reduction contribution of the construction industry and waste recycling industry can help Kitakyushu develop more reasonable renewal plans. Chapter 6 clarifies the flow of C&D Waste in Kitakyushu and explains the carbon emissions of C&D Waste treatment through life cycle assessment and IPCC methods. By comparing the carbon emissions of waste recycling with those of new material production, the contribution of C&D Waste recycling to CECI reduction has been confirmed. Finally, by modeling the building stock flow, the decarbonization contribution of recycled materials to the construction industry in Kitakyushu under different future scenarios was predicted. The results show that in Kitakyushu, a pioneer region in decarbonization, the recycled products of C&D Waste in 2019 could reduce emissions in the construction industry by 7,845 tons. The carbon emissions from the recycling process mainly come from the disposal of concrete and steel, and steel recycling and utilization is the biggest driver of emission reduction. In the future, material recycling can contribute to decarbonization in Kitakyushu's construction industry by 1.9-6.8%.

In Chapter 7, Conclusion and Prospect

This chapter summarized the conclusions obtained from previous chapters and prospected the further research of carbon emissions in the construction industry.

Reference

Abhimanyu Sharma. (2023). *Economic Survey 2023: India aims 45% reduction in emission intensity of its GDP by 2030 from 2005 levels*. https://www.cnbctv18.com/

CABEE. (2022). *Research Report on Energy Consumption and Carbon Emissions of Buildings in China*. China Association of Building Energy Efficiency Special Committee on Building Energy Consumption and Carbon Emission Data.

Cabeza, L. F., Boquera, L., Chàfer, M., & Vérez, D. (2021). Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis. *Energy and Buildings*, *231*, 110612. https://doi.org/10.1016/j.enbuild.2020.110612

CESY. (2021). *China Energy Statistical Yearbook 2021*.

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Applied Energy*, *143*, 395–413. https://doi.org/10.1016/j.apenergy.2015.01.023

CLEAN Future Act. (2021). 117th Congress. https://www.congress.gov/

Climate Action. (2023). United Nation. https://www.un.org/en/climatechange

CPBA. (2021). *China Building Energy Efficiency Annual Development Research Report 2021*. China Architecture & Building Press.

Dale, S. (2021). BP statistical review of world energy. *BP Plc: London, UK*, 14–16.

Decarbonising-construction-mandarin. (n.d.). Poyal Academy of Engineering. https://nepc.raeng.org.uk/

DUAN, H., CHEN, S., & LIU, Y. (2020). Characteristics of reginal energy consumption of China's construction industry from theperspective of life cycle. *China Population , Resources and Environment*, *30*(7), 57–65.

EEAS. (2021). *New Green Deal for Europe*. https://www.eeas.europa.eu/

Energy efficiency in buildings and neighborhoods in urban renewal. (2021). BUROHAPPOLD ENGINEERING. https://transition-china.org/

Energy White Paper. (2020). GLOBAL CCS INSTITUTE.

ES. (2021). *Japan's Road to Carbon Reduction: Options for Resource-Constrained Countries*. EVERBRIGHT SECURITIES. https://pdf.dfcfw.com/

Feng Guohui, Cui Hang, Chang Shasha, Huang Kailiang, & Wang Xiru. (2022). Analysis of Carbon Emissions and Influencing Factors of Near-Zero Energy Buildings. *Advances in Climate Change Research*, *18*(2), 205.

Fenner, A. E., Kibert, C. J., Woo, J., Morque, S., Razkenari, M., Hakim, H., & Lu, X. (2018). The carbon footprint of buildings: A review of methodologies and applications. *Renewable and Sustainable Energy Reviews*, *94*, 1142–1152. https://doi.org/10.1016/j.rser.2018.07.012

France. (2021). *Revised national low carbon strategy of France*. SNBC. https://www.ecologie.gouv.fr/

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., … Zheng, B. (2022). Global Carbon Budget 2022. *Earth System Science Data*, *14*(11), 4811–4900. https://doi.org/10.5194/essd-14-4811-2022

Huang Beijia, Cui Hang, Song Jialing, & Yu Haiyong. (2022). Study on the Accounting of Carbon Emissions from Buildings in Shanghai. *Journal of Shanghai University of Technology*, *44*(4), 343–350.

Huang Zhenhua. (2018). Study on the influencing factors of carbon emission of buildings in Chongqing based on STIRPAT model. *Project Management Technology*, *16*(5), 9.

IEA. (n.d.). *An energy sector roadmap to carbon neutrality in China*. International Energy Agency.

JFCC. (2022). *CO2 Emissions Survey Report 2020*. Japan Federation of Construction Contractors.

Life, null. (2004). *United Nations Environment Programme: Paris* (Vol. 2004).

Lisiecki, L. E., & Raymo, M. E. (2005). A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. *Paleoceanography*, *20*(1).

Lu, Y., Cui, P., & Li, D. (2016). Carbon emissions and policies in China's building and construction industry: Evidence from 1994 to 2012. *Building and Environment*, *95*, 94–103. https://doi.org/10.1016/j.buildenv.2015.09.011

Ma Jinwei, Ouyang Linhao, & Chen Xixi. (2023). Analysis of the whole life cycle carbon emission accounting of a typical museum building. *Journal of Anhui University of Architecture*, *31*(1), 50–55.

MECC. (2022). *2030 Emissions Reduction Plan: Clean Air, Strong Economy*. Minister of Environment and Climate Change. https://www.canada.ca/en/

Ministry of the Environment. (n.d.). *Climate Actions towards net-zero by 2050*. Ministry of the Environment, Government of Japan. https://www.env.go.jp/earth/

NIES. (2022, April 15). *Greenhouse Gas Emissions in FY2020 (FY2020)*. https://www.nies.go.jp/whatsnew/20220415/20220415-2.html

Onat, N. C., Kucukvar, M., & Tatari, O. (2014). Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input–output hybrid life cycle assessment approach. *Building and Environment*, *72*, 53–62. https://doi.org/10.1016/j.buildenv.2013.10.009

Petit, J.-R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., & Delaygue, G. (1999). Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, *399*(6735), 429–

436.

Sigman, D. M., Hain, M. P., & Haug, G. H. (2010). The polar ocean and glacial cycles in atmospheric CO2 concentration. *Nature*, *466*(7302), 47–55.

Someno, K. (2021). *Japan's policies and moves to create a decarbonized society by 2050*.

Taffese, W. Z., & Abegaz, K. A. (2019). Embodied Energy and CO2 Emissions of Widely Used Building Materials: The Ethiopian Context. *Buildings*, *9*(6), 136. https://doi.org/10.3390/buildings9060136

The Paris Agreement. (2015). United Nation. https://www.un.org/

TOMOYA TANIGUCHI. (2022). *Japan aims to create 100 or more Decarbonization Leading Areas by 2030*. https://talkofthecities.iclei.org/decarbonization-leading-areas-as-advanced-japan-models-for-achieving-carbon-neutrality/

UNCC. (2022). *2022 NDC Synthesis Report*. United Nation Climate Change. https://unfccc.int/ndc

UNEP. (2022). *2022 Global Status Report for Buildings and Construction*. UNEP.

U.S. Department of State. (2021). *The Long-Term Strategy of the United States Pathway to Net-Zero Greenhouse Gas Emissions by 2050*. the United States Department of State.

Wang, H., Zhang, Y., Yang, Y., & Gao, W. (2022). Development and strategy of building carbon neutrality in Japan. *Heating Ventilating & Air Conditioning*, *11*, 35–41. https://doi.org/10.19991/j.hvac1971.2022.11.04

Which countries have set a net-zero emissions target? (2021). Net Zero Tracker. Energy and Climate Intelligence Unit, Data-Driven EnviroLab, NewClimate Institute, Oxford Net Zero. https://eciu.net/netzerotracker/map

Wu, P., Song, Y., Zhu, J., & Chang, R. (2019). Analyzing the influence factors of the carbon emissions from China's building and construction industry from 2000 to 2015. *Journal of Cleaner Production*, *221*, 552–566. https://doi.org/10.1016/j.jclepro.2019.02.200

Xikai, M., Lixiong, W., Jiwei, L., Xiaoli, Q., & Tongyao, W. (2019). Comparison of regression models for estimation of carbon emissions during building's lifecycle using designing factors: A case study of residential buildings in Tianjin, China. *Energy and Buildings*, *204*, 109519. https://doi.org/10.1016/j.enbuild.2019.109519

Ye, Y., Dehwah, A. H. A., Faulkner, C. A., Sathyanarayanan, H., & Lei, X. (2023). A Perspective of Decarbonization Pathways in Future Buildings in the United States. *Buildings*, *13*(4). https://doi.org/10.3390/buildings13041003

Zhang, X., & Wang, F. (2016). Hybrid input-output analysis for life-cycle energy consumption and carbon emissions of China's building sector. *Building and Environment*, *104*, 188–197. https://doi.org/10.1016/j.buildenv.2016.05.018

Zhang, Y., Yan, D., Hu, S., & Guo, S. (2019). Modelling of energy consumption and carbon emission from the building construction sector in China, a process-based LCA approach. *Energy Policy*, *134*, 110949. https://doi.org/10.1016/j.enpol.2019.110949

Zhao, S., Song, Q., Duan, H., Wen, Z., & Wang, C. (2019). Uncovering the lifecycle GHG emissions and its reduction opportunities from the urban buildings: A case study of Macau. *Resources, Conservation and Recycling*, *147*, 214–226. https://doi.org/10.1016/j.resconrec.2019.04.030

Chapter 2

LITERATURE REVIEW OF CARBON EMISSIONS FROM CONSTRUCTION INDUSTRY

CHAPTER 2: LITERATURE REVIEW OF CARBON EMISSIONS FROM CONSTRUCTION INDUSTRY

Contents

2.1 Contents

The construction industry is a high-energy-consuming and high-carbon-emitting industry, with great potential for carbon reduction, which is a key to achieving carbon neutrality goals. This Chapter employs bibliometric analysis to investigate the development trends and hot topics in research on Carbon Emissions from the Construction Industry (CECI), based on 282 articles included in the SCIE and SSCI in Web of Science from 1992 to 2022. Through manual review, the challenges and possibility about CECI are examined, with a focus on the accounting scales, objects, boundaries, and methods. It was found that (1) From 2015, CECI became a hot topic, with a focus on energy efficiency, sustainable development, green buildings, and policy evaluation. (2) 80.7% of the research focuses on macro and micro scales such as national and building scales, and CECI accounting at the city scale remains a challenge with only 13 articles. (3) For research object, 74.8% of the studies do not differentiate between different types of buildings, and there is a need for more detailed research on rural residential, educational, and office buildings. (4) Only 18 articles considered carbon emissions during the demolition stage of buildings or the disposal and recycling of construction waste. How to fill this research gap is the challenge to be addressed. (5) The CECI accounting relies heavily on the carbon emission factor method, some accounting processes have assumptions, and how to enhance the accuracy of carbon accounting is currently the biggest challenge. This review summarizes the value and information of important literatures and scholars, can help the researcher in this area to understand state-of-the-art and future challenge in carbon accounting and environmental impact in the construction industry.

2.2. Literature Searching and Bibliometric Methods

Bibliometric refers to the study and use of statistical and mathematical methods to analyze and evaluate scientific and scholarly publications, such as articles, books, and conference papers. Bibliometrics can be used for various purposes, including measuring research productivity and impact, determining the distribution of funding and resources, and assessing the quality and relevance of scientific and scholarly outputs. The bibliometric approach has now become an important method for literature reviews.

2.2.1 The literature retrieved

Web of Science (WOS) is the world’s leading citation database, which contains a large number of influential journals. The database is updated daily and has high recognition worldwide. The data sources and retrieval strategies in this study are based on Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI) in the WOS Core collection.

These two indexes are regarded as important data sources for bibliometric research, with a collection of more than 12,600 journals from 178 scientific disciplines and 58 social disciplines.

Fig.2-1 shows the process of literature retrieval. Firstly, define the search terms and criteria to be used for retrieving the relevant publications, including the keywords, author names, publication years, and publication types.

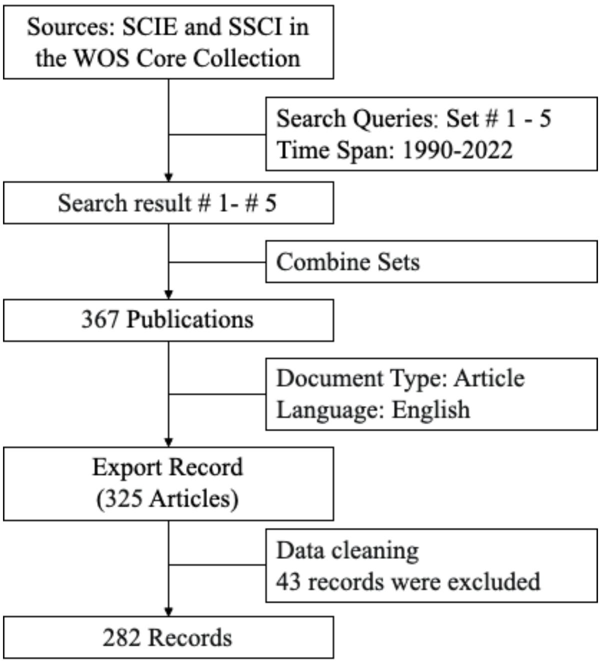


Fig.2-1 Literature retrieval process

The publication period of the search literature is set to be 1990-2022, as research on carbon emissions has developed since 1992, when the United Nations Framework Convention on Climate Change was adopted. Different search terms were used to search the literature on construction industry and carbon emissions. Set #1 and Set #2 in Table 2-1 shows the search results for the topic of carbon emissions. Set #3, Set #4 and Set #5 show the search results of related research on the construction industry. According to WOS search rules, “TS” represents the topic of the article, “TI” represents the title of the article, “KP” represents the keyword of the article, and “*” represents fuzzy search.

According to the function of the “Combine Sets” in WOS, different sets are combined using the "AND" or "OR" operators to obtain the search results, a total of 367 publications such as Set #6 to Set #14. Among them, Set #3 can obtain many irrelevant literatures, which is not conducive to the bibliometric research. so Set #4 and Set #5 are used instead of Set #3 to narrow the scope of search and increase the accuracy of search.

Journal articles can provide better quality information than other articles, and research papers are better than review papers at showing which research topic was hot at the time of publication. Therefore, research articles are selected for bibliometric analysis. 39 review papers and 3 other types of papers were excluded. Non-English literature was also excluded. 325

records of research papers were exported from the WOS database, with each record including Author, Institution, Country/Region, Publication time, Source journal, Title, Abstract and Keywords.

The exported records are also subject to data cleaning, which aims to exclude duplicate articles and articles that are not relevant to the topic. By manually reviewing the titles and abstracts of the articles one by one, 43 articles were excluded. Records of the final 282 research papers were obtained.

Table 2-1 Search queries used in data collection

No.	Search Queries	Publication	Article	Reviews	Other
#1	TS = ("carbon emission* " OR "carbon peak" OR "carbon neutral*" OR "carbon footprint")	40944	36878	3115	951
#2	TS = ("CO2 emission* " OR "CO2 peak" OR "CO2 neutral*" OR "CO2 footprint")	48390	45058	2794	538
#3	TS = ("building sector" OR "construction sector" OR "building industry" OR "construction industry")	17842	16051	1448	343
#4	TI = ("building sector" OR "construction sector" OR "building industry" OR "construction industry")	2815	2339	217	259
#5	KP = ("building sector" OR "construction sector" OR "building industry" OR "construction industry")	718	633	83	2
#6	#1 AND #3	977	856	117	4
#7	#2 AND #3	934	821	109	4
#8	#1 AND #4	189	170	17	2
#9	#1 AND #5	89	77	12	0
#10	#2 AND #4	181	162	18	1
#11	#2 AND #5	86	80	6	0
#12	#8 OR #9	265	235	28	2
#13	#10 OR #11	255	230	24	1
#14	#12 OR #13	367	325	39	3

2.2.2 Bibliometric tool

With the development of bibliometrics, many different types of knowledge mapping tools have been developed. VOSviewer, Publish or Perish, CiteSpace, HistCite etc. are commonly used analysis tools, which have different characteristics and limitations(Sun et al., 2022).

Many literature databases have developed their own literature statistics systems relying on the huge literature foundation such as Scopus, Google Scholar, and WOS. Users can obtain analysis results through simple operations while sub-searching literature, which is convenient and fast. These web tools can only provide some simple bibliometric analysis, often only classifying the literature by publication date, publication, author or type.

The development of AI technology has also brought convenience to bibliometrics. Several AI technology-based web platforms have developed bibliometric tools. Such as “AMiner” and “wisdom.ai”, which can automatically search the literature and generate analysis charts by simply entering keywords. However, these tools suffer from small literature databases and unclear data sources. There are also platforms that are similar to traditional bibliometric software and use records from literature databases to analyze the literature, such as “bibliometric.com”.

Compared to emerging bibliometric platforms, traditional bibliometric software is complex to operate but has more powerful features. VOSview, invented at Leiden University in the Netherlands, has good performance in the visualization of contributions and collaborations(Y. Hu et al., 2022), so this chapter uses this software to analyze the contributions and collaborations of institutions and authors. The CiteSpace software invented by Prof. Chaomei Chen is characterized by co-occurrence and co-citation analysis, which is advantageous in trend detection(C. Chen, 2020). Therefore, this software is used in this chapter for co-occurrence of keywords and topics and co-citation analysis of journals and authors.

2.3. Results of bibliometric analysis

2.3.1 The publication trends

The publication time distribution of research articles related to carbon emissions in construction industry reflects the development speed and knowledge accumulation in this field. Figure 2-2 shows the publication time distribution of 282 research articles obtained from WOS according to search queries #14.

In the literature retrieved, the research on carbon emissions from the construction industry began in 1998 and showed an increasing trend after 2006. Related publications grew rapidly after the Paris Climate Conference in 2015. The Paris Agreement has a huge impact on the energy policies of all countries, and the carbon emission of the construction industry has gradually become a hot topic.

Figure 2-2 also shows publishing trends in 12 countries with more than 5 publications. China had the largest number of published papers, 168, more than half of the total, and the annual number of published papers increased steadily. The trend of growth is consistent with the policy direction of the Chinese government. The “13th Five-Year Plan for controlling greenhouse gas emissions” in 2016(H. Chen & Chen, 2019b) and the “Dual Carbon” Target in 2020 (Ding, 2021) are the driving forces behind the rapid growth. England, the United States and Australia are also big contributors, and the number of publications is on the rise.

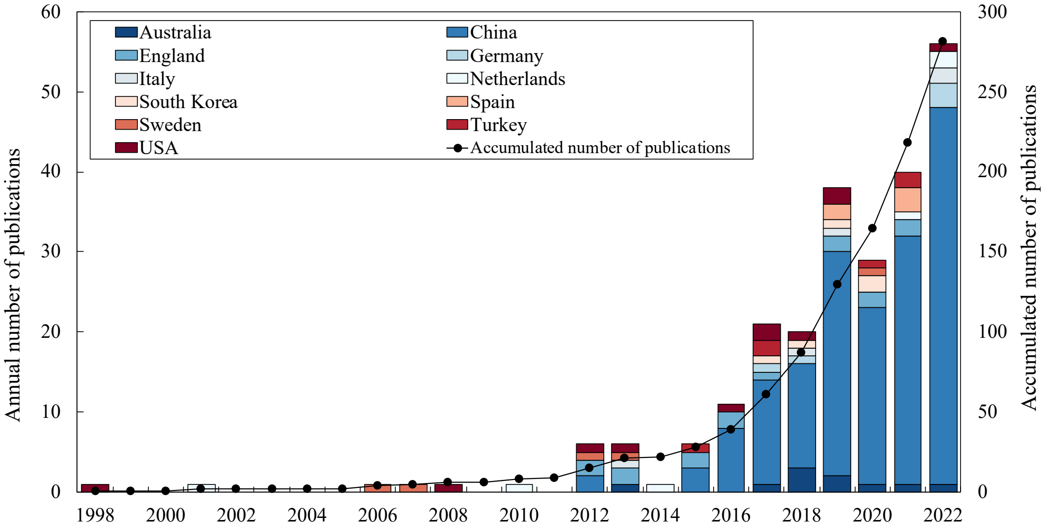


Fig.2-2 Annual trend of CECI research papers published

2.3.2 Contribution and collaboration

The analysis of the author’s contribution and collaboration in the field of carbon emission in the construction industry can show the author’s influence, which is conducive to the development of cooperation between scholars in the field and scholars outside the field to quickly understand the research situation of carbon emission in the construction industry.

There are 884 authors who contributed to the study of carbon emissions from the construction industry. 13 authors have more than five papers, Table 2-2 lists these authors who made major contributions. Cai Weiguang, a professor at Chongqing University in China, has published 22 articles with a total of 1,239 citations. Prof. Cai has not only conducted in-depth research on the carbon emissions of the construction industry but also has a great influence in this field. Prof. Ma Minda, from Lawrence Berkeley National Laboratory, has high average citations, indicating that his research is widely recognized. Prof.Du Qiang from Chang’an University has published 10 articles and made great contributions to the research and development of CECI.

Table 2-2 The top 13 authors with the most published articles in the field of CECI

Rank	Author	Organization	Article	Citations	TLS
1	Cai Weiguang	Chongqing University	22	1239	75
2	Ma Minda	Lawrence Berkeley National Lab	12	890	30
3	Du Qiang	Chang'an University	10	184	44
4	Chen Jindao	Guangzhou Maritime University	8	387	27
5	Hong Jingke	Chongqing University	8	268	33
6	Ren Hong	Chongqing University	8	284	33
7	Shen Liyin	Chongqing University	8	603	30
8	Huo Tengfei	Hebei University of Technology	7	291	33
9	Shi Qian	Tongji University	6	354	19
10	Bai Libiao	Chang'an University	5	53	22
11	Feng Wei	Lawrence Berkeley National Lab	5	216	20
12	Lu Yujie	National University of Singapore	5	237	12
13	Wu Min	Chang'an University	5	114	21

Note: TLS means Total link Strength.

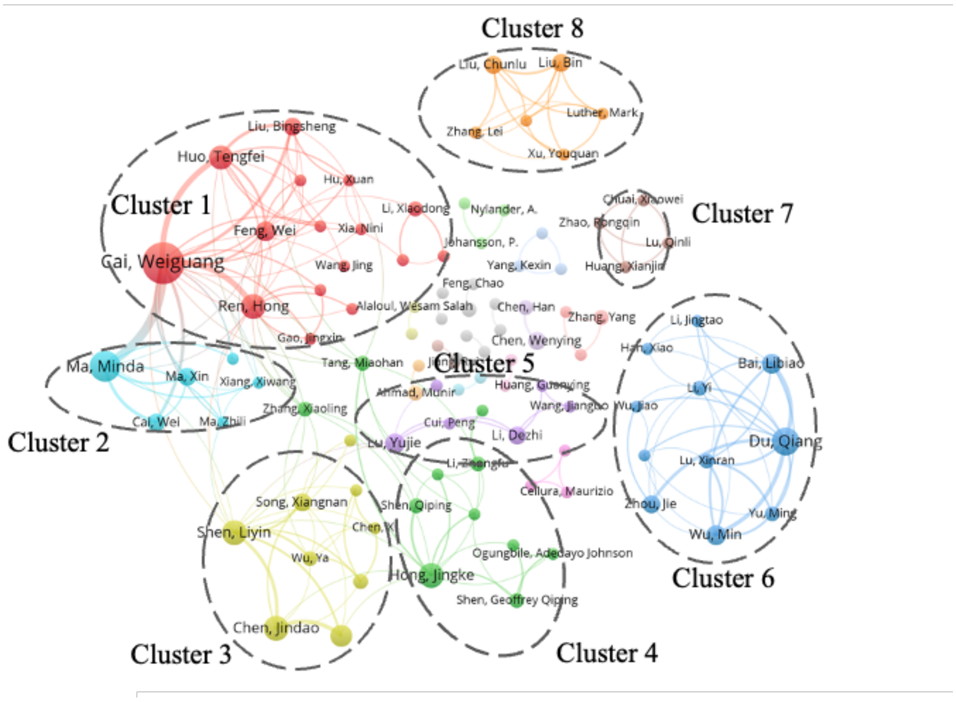


Fig.2-3 Collaboration between authors

Total link Strength (TLK) reveals the frequency of collaboration between authors. Figure 2-3 visualize TLK. Nodes in the figure represent authors, and the larger the node, the more the number of papers published by the author. The lines between nodes indicate cooperation, and the thicker the lines, the closer the cooperation. A cluster consists of nodes, and authors within the cluster collaborate more closely than those outside the cluster.

The 110 authors who published more than 2 articles were imported into VOSviewer for analysis. Eight large clusters are shown in Figure 2-3. The connection among Cluster 1 to Cluster 5 indicates that extensive collaboration already exists in the CECI research area. The largest cluster is led by Prof. Cai Weiguang, and influential scholars such as Huo Tengfei, Ren Hong, and Feng Wei are members of the cluster. Ma Minda, another well-published professor, works closely with Prof. Cai and is core of Cluster 2. Cluster 6, Cluster 7, and Cluster 8 exist independently, with less collaboration with scholars outside the cluster, this means that their research may have some uniqueness.

Eighteen research institutions published more than five research papers related to CECI, as shown in Tables 2-3. Chongqing University ranked first in both total publications and total citations, participating in the publication of 43 articles, accounting for 15.2% of the total. Combined with Figure 2-4, Chongqing University is not only the core of the largest cluster, but also closely related to other clusters, the total link strength is 86. This shows that Chongqing University has developed close cooperation with other institutions in the field of CECI and has made outstanding contributions to the field. Hong Kong Polytech University, Tsinghua University, Lawrence Berkeley National Laboratory ranked 2-4 in the number of related articles published. They all belong to Cluster 1 and come from different countries or regions, indicating that cooperation in the field of CECI has been widely carried out in different regions. The four institutions ranked 5-8 in the number of articles published are the cores of the other four clusters. The four clusters are not closely connected, and the inter-agency cooperation is mainly carried out within the clusters, which has a certain degree of independence. It is worth noting that Southwest University published 5 articles, with a total citation of 527 times and an average citation of more than 100, indicating that the research of this institution is recognized, and the research is significance, can be the focus of manual review.

Table 2-3 The top 18 organizations with the most published articles in the field of CECI

Rank	Organization	Country	Article	Citations	TLS
1	Chongqing University	China	43	2041	86
2	Hong Kong Polytech University	Hong Kong, China	17	684	35
3	Tsinghua University	China	16	484	23
4	Lawrence Berkeley National Laboratory	USA	14	789	27
5	Tongji University	China	14	598	22
6	Chang'an University	China	12	195	9
7	Southeast University	China	8	253	15
8	Dalian University of Technology	China	7	77	10
9	China Association of Building Energy Efficiency	China	6	553	14
10	Chinese Academy of Sciences	China	6	159	12
11	Hebei University of Technology	China	6	152	10
12	North China Electric Power University	China	6	192	3
13	Tianjin University	China	6	134	7
14	Beijing Institute of Technology	China	5	80	17
15	City University of Hong Kong	Hong Kong, China	5	385	12
16	Deakin University	Australia	5	68	10
17	National University of Singapore	Singapore	5	210	10
18	Southwest University	China	5	527	18

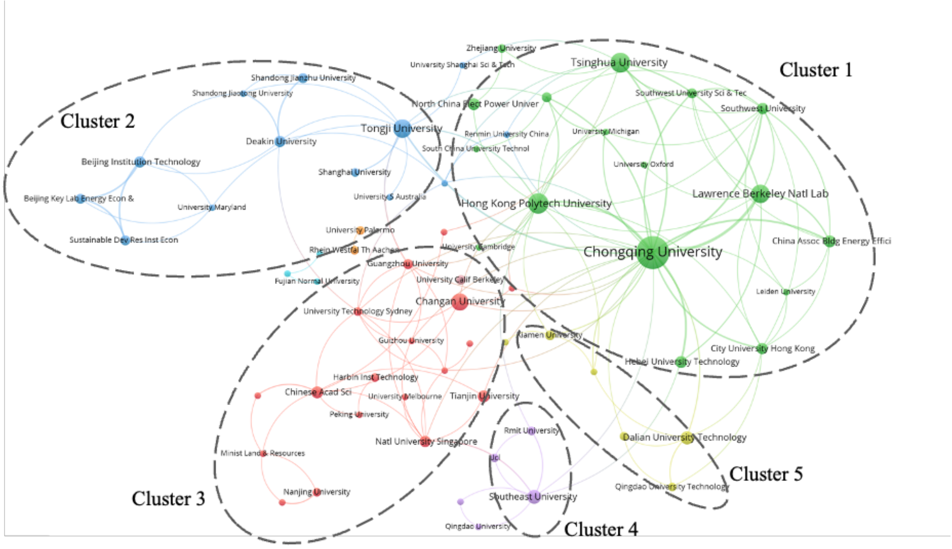


Fig.2-4 Collaboration between organizations

2.3.3 Research trend and frontier

The use of keywords to understand research key points and frontiers is considered feasible and credible(Luo et al., 2019). Co-occurrence analysis was performed using CiteSpace, with keywords proposed by the authors and "Keyword plus" provided by the journals as sources of keywords. Using one year as a slice, the top 10% of keywords appearing in each slice were selected for analysis. A total of 150 keywords were analyzed. As shown in Fig. 2-5, these keywords were divided into 10 clusters. The larger the keyword node, the higher its burst intensity. Topics such as “performance”, “decomposition analysis”, “life cycle assessment”, “CO_2 emission”, “energy savings”, “emissions mitigation”, “scenario analysis” have been extensively studied.

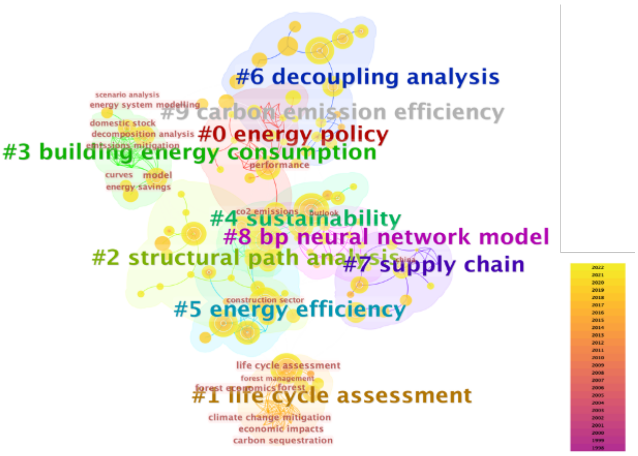


Fig.2-5 Cluster map of the co-occurrence of keywords

The time of emergence and burst of keywords can reflect the change of research key points. The keyword outbreak timeline for cluster #0 is shown in Fig. 2-6. The position of the keywords on the timeline can reflect changes in the study topic. Cluster #0 is tagged with "energy policy". This cluster started with the nodes "Performance" and "Technological innovation" and has continued until now. Several key nodes emerged during this period, such as “material flow analysis”, “sustainability” and “strategy”. The research in this cluster extends from the impact of energy policy on energy efficiency in building operations(Noailly & Batrakova, 2010) to the impact of energy policy on carbon emissions in the construction sector and its upstream sectors(Moynihan & Allwood, 2012). Exploring sustainability possibilities and strategies(Iqbal et al., n.d.; Zhu, Li, et al., 2022) for the building sector is the latest focus of the cluster.

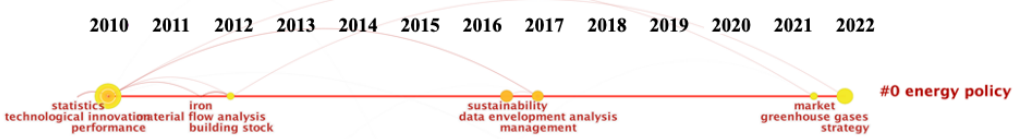


Fig.2-6 Co-occurrence timeline view of cluster #0

As shown in Fig.2-7, cluster #1 is labeled "life cycle assessment", which is also the largest node in the cluster. Life Cycle Assessment is a common method for accounting carbon emissions in the construction sector. The node "forest management" indicates that the research of this cluster started from the link between wood material requirements and environmental management(Eriksson et al., 2012), and the research object is mainly "residential buildings"(Hong, Shen, & Xue, 2016; J.-J. Ma et al., 2015). In recent years, the research focus has shifted to enhancing the environmental performance of buildings to address climate challenges(Balasubramanian et al., n.d.; Dong et al., 2021a).

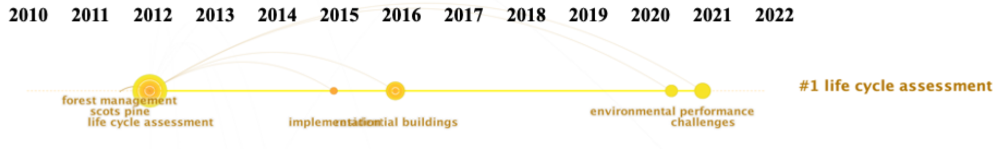


Fig.2-7 Co-occurrence timeline view of cluster #1

As shown in Fig.2-8, Cluster #2 was started in 2016. It is labeled "structural path analysis", which is a method to track and evaluate carbon emissions upstream of the supply chain. This method is commonly used to decompose carbon emissions in the construction industry to find the key structural pathways for carbon reduction(J. Chen et al., n.d.; Hong et al., 2022; Pomponi & Stephan, 2021). The related keywords "impact", "supply chain", "trade" and "demand" are the big nodes of this cluster. As the research progresses, researchers in this cluster are no longer satisfied with the structural path analysis based on the economic model of input-output relationship but keep introducing new methods such as Social Network Analysis(Z. Wang et al., 2022) and Geographically Weighted Regression model(T. Li et al., 2022). Exploring the spatial differences of carbon emissions in the carbon construction industry has become a new hot topic.

Fig.2-8 Co-occurrence timeline view of cluster #2

Cluster #3 is labeled "building energy consumption". As shown in Fig.2-9, the study focuses on the carbon emissions associated with the energy consumption of construction industry(Y. Zhang et al., 2019). This cluster started with a "scenario analysis" to predict the CECI by creating different development scenarios(D. Li et al., 2021). Node "input output" and “decomposition analysis” indicates that input-output method is an important carbon accounting method for this cluster, decomposition analysis is widely used in the cluster to explore the drivers of carbon emissions. There are many methods of decomposition analysis, and the LMDI method is one of them(Zhao et al., 2023), which emerged as an independent node in 2020, indicating that the LMDI method has become the most mainstream decomposition analysis method. As the factors influencing carbon emissions continue to be explored, how to achieve circular economy in the construction industry(Bertin et al., 2022; Roy et al., 2022) becomes the focus of the Cluster #3.

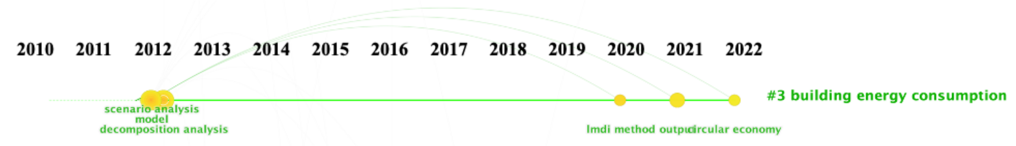


Fig.2-9 Co-occurrence timeline view of cluster #3

As shown in Fig.2-10, cluster #4 focuses on "sustainability". The impact of energy consumption and carbon emissions on the sustainability of the building sector is the focus of this cluster(Huo et al., 2018; M. Ma, Ma, et al., 2019). The nodes for the keywords "CO_2 emissions", "energy consumption" and "construction" are large for the period 2010-2015. The emergence of the "efficiency" node indicates that the focus of this cluster has shifted from carbon accounting to energy efficiency and carbon emission efficiency research and continues to this day(D. Ma et al., 2022). Also, the impact of economic growth, urbanization or policies on carbon emissions is a concern of the cluster(T. Yang et al., 2017; S. Zhang et al., 2021).

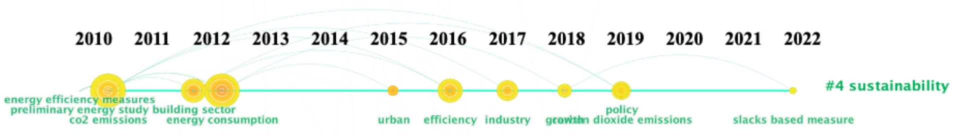


Fig.2-10 Co-occurrence timeline view of cluster #4

Cluster #5 is labeled "energy efficiency". As shown in Fig.2-11, the early studies of this cluster focused on the carbon emissions of the building operation energy(Kesicki, 2012a). In 2015, "embodied carbon" became a key point, indicating that the embodied carbon from construction materials became a hot topic of research(Akan et al., 2017; Giesekam et al., 2016). Then, research has focused on the carbon intensity of building materials(Y. Zhou et al., 2019) and the energy efficiency of building materials manufacturing to find ways to reduce carbon emissions(Hou et al., 2021; Karlsson et al., 2020). In recent years, as the carbon reduction potential of building demolition waste has gained attention(Bertin et al., 2022), the "demolition" node appears in 2022.

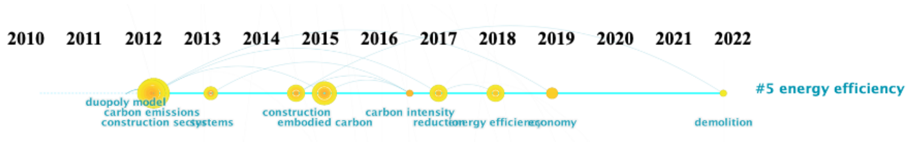


Fig.2-11 Co-occurrence timeline view of cluster #5

As shown in Fig.2-12, cluster #6 is a new cluster that starts in 2016 and ends in 2021 and explodes with a large number of keywords in a short period of time. The cluster is labeled "decoupling analysis", which is a method to reveal whether there is a synchronous relationship between influencing factors and carbon emissions. At the beginning the method was used to analyze the relationship between carbon emissions in the construction industry and the overall economic development of the society(Jiang & Li, 2017), the relationship between building energy consumption and the output value of the construction industry(Du et al., 2019). As the research progresses, decoupling analysis is applied to a smaller view. The relationship between carbon emission intensity of residential buildings and residents' income(Liang et al., 2019), and the relationship between carbon emission of commercial buildings and the development of tertiary industry(M. Ma, Cai, et al., 2019; M. Ma & Cai, 2019) are discussed.

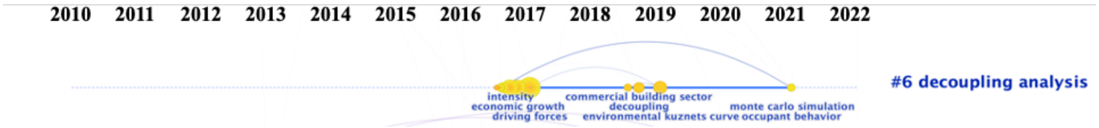


Fig.2-12 Co-occurrence timeline view of cluster #6

Cluster #7 is labeled "supply chain", indicating that the core of this cluster is carbon emissions from upstream industries in the construction industry, such as Fig.2-13. The explosion of the "China" node indicates that the Chinese construction industry is an important focus of the cluster(Shi et al., 2017). In 2017, the carbon footprint became a research hotspot for the cluster, with international and interregional carbon flows being well studied(Guo et al., 2019; Zhao et al., 2023). With China's proposed double carbon target, finding a path to carbon neutrality has become a hot topic, and introducing sustainable energy are considered an important strategy to reach carbon neutrality(Arias et al., 2021).

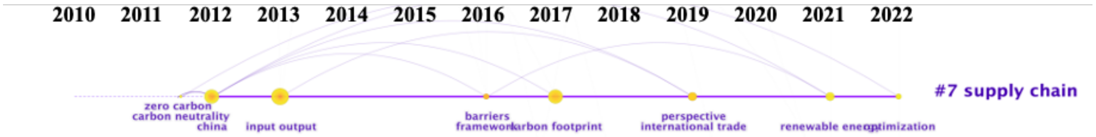


Fig.2-13 Co-occurrence timeline view of cluster #7

As shown in Fig.2-14, cluster #8 and cluster #9 are small clusters. bp neural network model is an algorithm for deep learning. Cluster #8 is labeled with this term, indicating that AI technology has been applied in the field of carbon emissions in the construction industry(Pu et al., 2022). This cluster focuses on the prediction and outlook of carbon emission and its environmental impact in the construction industry (Dai et al., 2022; Gan et al., 2022). Cluster #9 focuses on mitigating the greenhouse effect(H. Chen & Chen, 2019b) from the perspective of carbon emission efficiency and improving production efficiency to achieve sustainable development in the construction industry(Huo et al., 2020; Y.-K. Wang et al., 2022).

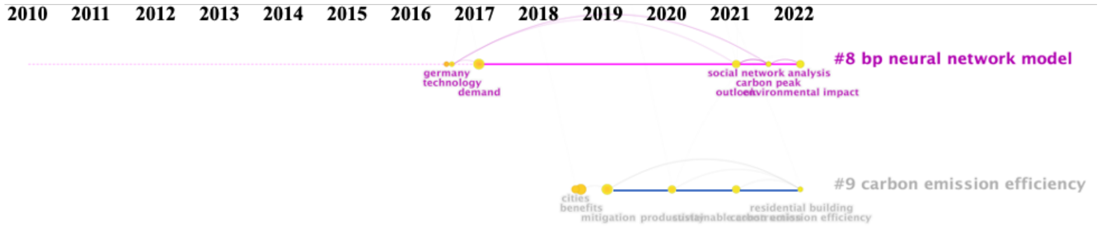


Fig.2-14 Co-occurrence timeline view of cluster #8 and #9

The burst of keywords appeared from 2010 and has continued. These keywords can be summarized into 3 categories. The first category is about carbon accounting methods and accounting boundary, such as “input-output”, “supply chain” and “life cycle assessment”. The second category is about the research scale and object or, such as “China”, “construction sector”. The third category is about the research purpose and carbon analysis methods, such as “climate change mitigation”, “economic impact”, “decoupling analysis”, and “decomposition analysis”. The complex keyword network shows that the carbon emission research of construction industry is widely concerned.

As time goes by, new keywords are emerging and being used frequently, which indicates that carbon emissions in the construction industry is in an explosive period of research, and more studies will be conducted to explore carbon emissions in the construction industry from different perspectives.

2.3.4 Research hotspot

A literature that is heavily cited by other studies in a short period of time is called a citation bursts, representing that the research content of the literature is a hot topic at that stage. And citation bursts have thus become a common method for tracking research hotspots(C. Chen & Song, 2019). When an article or journal is frequently co-cited, it indicates the existence of some underlying relationships, and co-citation analysis is often used to analyze the underlying knowledge structure of a knowledge domain(C. Chen et al., 2010).

(1) Publication co-citation

Table 2-4 lists the 15 publications with the strongest citation bursts. The red line in the table represents the burst of citations. Most of the publications’ citation explosion has occurred in recent years since carbon emissions in the construction industry is an emerging topic. Research literature related to carbon emissions in the construction industry was published after 2016. “Energy” is the first journal to experience a citation burst and is the longest lasting citation burst, lasting 10 years from 2008 to 2018. This demonstrates the earliest and continuing interest of the journal "Energy" in the area of carbon emissions from the construction industry. "China Statistical Yearbook on Construction" is the publication with the strongest citation burst, which burst from 2016 to 2017 and lasted one year. This is somewhat related to the fact that publications examining carbon emissions from China’s construction sector began to proliferate in 2016 and suggests that the yearbook’s data is reliable and widely accepted. "Journal of Engineering Science and Technology Review" is the journal with the strongest citation burst, which received a large number of citations in 2017-2019 as a literature review journal. Among the journals that publish mainly research papers, "Renewable Energy", "Solar Energy" and other journals that focus on energy topics also have a high citation burst.

In addition, journals focusing on construction management, ecology and environment, transportation, etc. have also received more attention. Such as "Nature Environment and Pollution Technology", "Journal of Construction Engineering and Management ", "Transportation Research Part D: Transport and Environment". These journals focus on topics related to the construction industry and can often provide data to calculate carbon emissions from the construction industry or support the assessment of the impact of carbon emissions from the construction industry.

Table 2-4 Top 20 Cited Publications with the Strongest Citation Bursts

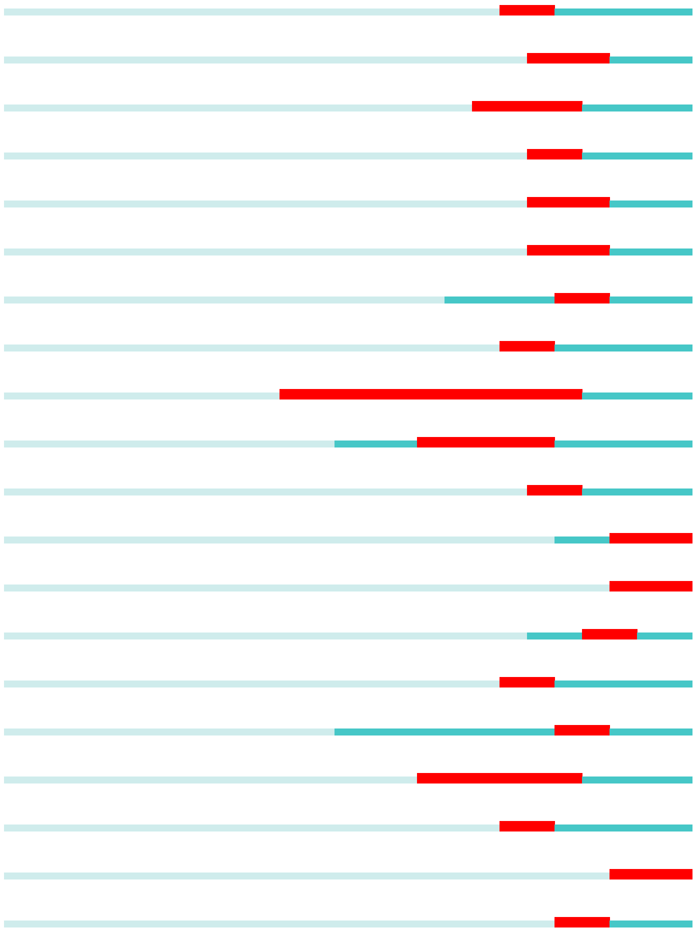
No.	Cited Journals	Strength	Begin	End	1998 - 2022
1	China Statistical Yearbook on Construction	3.53	2016	2017	
2	Journal of Engineering Science and Technology Review	3.5	2017	2019	
3	Renewable Energy	3.3	2015	2018	
4	China Population, Resources and Environment	3.17	2017	2018	
5	Solar Energy	3.11	2017	2019	
6	Nature Environment and Pollution Technology	3.11	2017	2019	
7	Climate Change	2.96	2018	2019	
8	Journal of Construction Engineering and Management	2.94	2016	2017	
9	Energy	2.77	2008	2018	
10	Ecological Economics	2.75	2013	2017	
11	Journal of Tsinghua University (Science and Technology)	2.71	2017	2018	
12	Transportation Research Part D: Transport and Environment	2.7	2020	2022	
13	Management Science	2.63	2020	2022	
14	Transport Policy	2.58	2019	2020	
15	Communications in Nonlinear Sci. and Num. Simulation	2.52	2016	2017	
16	Environmental and Resource Economics	2.5	2018	2019	
17	International Journal of Energy Research	2.36	2013	2018	
18	Construction and Building Materials	2.35	2016	2017	
19	Journal of Civil Engineering and Management	2.3	2020	2022	
20	Impact Carbon Dioxide	2.29	2018	2019	

Table 2-5 Top 20 most co-cited articles

No.	Cited References Author, Year, Source, Vol, Page, DOI	Year	Co-Citation Times	Burst Strength, Begin, End	Citation times
1	Lu YJ, 2016, BUILD ENVIRON, V95, P94 10.1016/j.buildenv.2015.09.011	2016	33	2.12, 2018-2022	131
2	Shi Q, 2017, J CLEAN PROD, V166, P615 10.1016/j.jclepro.2017.08.056	2017	30	-	122
3	Huang LZ, 2018, RENEW SUST ENERG REV, V81, P1906 10.1016/j.rser.2017.06.001	2018	30	3.09, 2019--2022	263
4	Tan XC, 2018, ENERG POLICY, V118, P429 10.1016/j.enpol.2018.03.072	2018	27	-	106
5	Zhou N, 2018, NAT ENERGY, V3, P978 10.1038/s41560-018-0253-6	2018	26	2.73, 2020-2022	169
6	Lin BQ, 2015, BUILD ENVIRON, V94, P239 10.1016/j.buildenv.2015.08.013	2015	25	6.00, 2017-2020	91
7	Chen JD, 2017, J CLEAN PROD, V168, P645 10.1016/j.jclepro.2017.09.072	2017	24	-	96
8	Hong JK, 2016, RENEW SUST ENERG REV, V53, P1303 10.1016/j.rser.2015.09.068	2016	24	1.64, 2016-2017	129
9	Wu Y, 2018, ENVIRON IMPACT ASSES, V71, P60 10.1016/j.eiar.2018.04.001	2018	22	-	134
10	Wu P, 2019, J CLEAN PROD, V221, P552 10.1016/j.jclepro.2019.02.200	2019	21	3.91, 2020-2022	66

No.	Cited References Author, Year, Source, Vol, Page, DOI	Year	Co-Citation Times	Burst Strength, Begin, End	Citation times
11	Wang M, 2018, J CLEAN PROD, V202, P710 10.1016/j.jclepro.2018.08.152	2018	20	2.73, 2020-2022	58
12	Huo TF, 2018, J CLEAN PROD, V185, P665 10.1016/j.jclepro.2018.02.283	2018	19	-	163
13	Du Q, 2019, J CLEAN PROD, V220, P99 10.1016/j.jclepro.2019.02.123	2019	17	3.15, 2020-2022	85
14	Zhang Y, 2019, ENERG POLICY, V134, P0 10.1016/j.enpol.2019.110949	2019	17	3.15, 2020-2022	95
15	Chuai XW, 2015, ENVIRON SCI TECHNOL, V49, P13021 10.1021/acs.est.5b01732	2015	15	3.58, 2017-2020	85
16	Yang T, 2017, ENERGY, V128, P208 10.1016/j.energy.2017.03.098	2017	15	1.80, 2018-2019	63
17	Chen JD, 2019, SUSTAIN CITIES SOC, V44, P604 10.1016/j.scs.2018.10.017	2019	14	-	48
18	Ma MD, 2017, J CLEAN PROD, V143, P784 10.1016/j.jclepro.2016.12.046	2017	14	5.21, 2017-2019	126
19	Hong JK, 2017, RENEW SUST ENERG REV, V73, P85 10.1016/j.rser.2017.01.021	2017	14	-	44
20	McNeil MA, 2016, ENERG POLICY, V97, P532 10.1016/j.enpol.2016.07.033	2016	13	2.04, 2017-2018	84

(2) Literature co-citation

The citation reflects the relationship between the cited literature and citing literatures. The co-citation reflects the relationship between the citing literatures. The number of co-citations in a paper not only reflects the authority of the study but also indicates the emergence of a hot topic. As shown in Table 2-5, the 20 most co-cited literatures and the time of the co-citation outbreak by the research on carbon emissions in the construction industry are listed. The total citations for these papers were also obtained from the WOS database. All of these 20 papers were published after 2015.

Yujie Lu's research started a co-citation burst in 2018 with 33 co-citations and a total of 131 citations. Lu used the carbon emission factor method to calculate the carbon emissions of China's construction industry from 1994 to 2012 and analyzed the main factors influencing the change of carbon emissions. Lu concluded that construction materials are the largest contributor to the increase of carbon emissions, and energy intensity reduces carbon emissions(Lu et al., 2016). This study applies the LMDI method to the study of carbon emissions in the construction industry, which provides a reference for other studies.

Lu's research has been widely recognized since its publication. In terms of highly cited papers that reference Lu's research, Wu summarized Lu's carbon emission calculation method and in introducing the concept of whole life cycle, found that building material manufacturing and building operations contribute 58% and 40% of carbon emissions respectively. Wu identified high development density and better energy efficiency as ways to reduce operational carbon emissions(P. Wu et al., 2019). Zhang further develops the application of LCA in the calculation of carbon emissions from the construction industry with the aim of accounting for carbon emissions from non-combustion processes as well. By developing a new model, Zhang argues that reducing carbon emissions in China's construction industry can be achieved by controlling unnecessary construction activities and improving material production efficiency(Y. Zhang et al., 2019). Wu's and Zhang's studies ranked 9th and 14th in Table 2-5. In terms of recent papers s that reference Lu's research, Zhao uses a modified LMDI method to analyze the impact of demand structure on carbon emissions and concludes that the change in demand structure in the construction industry is one of the main drivers of carbon emissions growth(Zhao et al., 2023). Li decomposes the drivers of carbon emissions from the construction industry in different types of provinces by the LMDI method. li specifies the driving contributions of population, per capita floor area, energy consumption per unit of floor area, and carbon emissions per unit of energy consumption, and points out the strategies for peaking carbon emissions from the construction industry in China.(R. Li et al., 2023)

Qian Shi's study, with the second highest number of co-citations, was also devoted to Carbon emission driving force analysis, receiving 122 citations and 30 co-citations. Shi argues that the SDA method is useful for addressing carbon emissions at the industry and sectoral levels. The SDA method relies on the input-output model. Therefore, Shi first used the input-output method to account for indirect carbon emissions from 1995 to 2009, and then used the SDA method to analyze the drivers of carbon emission changes in the construction industry. Shi believes that final demand is the largest contributor to emissions growth, and that the Chinese economy's high reliance on the construction sector is driving the growth of carbon emissions(Shi et al., 2017). Based on Shi's study and the same methodology, Chen first accounts for the carbon footprint of China's construction industry and argues that the energy sector and the construction materials sector are the main contributors to the carbon emissions of the construction industry(J. Chen et al., 2017). Thereafter, Chen analyzed the differences in carbon emissions from the construction sector between China and the United States and concluded that the final demand effect and the production structure effect are the main drivers that widen the gap between the two countries(J. Chen, Shi, et al., 2019). Chen's study was also recognized and ranked 7th and 17th in Tables 2-5.

Huang's research ranks third in co-citations. Huang used world environmental input-output table 2009 to calculate global carbon emissions from the construction industry and found that China is the largest contributor to carbon emissions. Huang suggests reducing carbon emissions in three ways: developing low-carbon materials, improving energy efficiency of construction machinery, and using renewable energy(Huang, Krigsvoll, et al., 2018). This method of using regional input-output method to analyze carbon footprint has become a hot topic. Hong focuses on energy use in the construction industry in China and uses multi-regional input-output analysis to explore inter-provincial differences. Hong finds that provinces such as Shanxi and Liaoning consume more energy due to pan-construction activities and inefficient construction processes. The cross-regional importation of materials has led to energy flows from resource-rich regions in the central China to resource-poor regions on the east coast(Hong, Shen, Guo, et al., 2016). Hong also conducted an analysis of the drivers of energy demand in the building sector, arguing that the trajectory of energy consumption in China's construction sector is the result of competition between the effects of increased final demand and energy efficiency improvements(Hong, Li, et al., 2017).

Setting up different development scenarios to predict the trend of carbon emission changes in the construction industry is also hot. Both Tan and Zhou's studies account for the carbon emissions generated by building operation energy in China's construction industry by building prediction models. The predictive model developed by Tan's group accounts for carbon emissions through a bottom-up approach. with parameters such as population, urbanization rate, and building size being important variables, and Tan believes that cross-sectoral synergies are better than single-sectoral reductions, and that energy efficiency policies have a significant impact on building emissions reductions. Parameters such as population, urbanization rate, and building size are important parameters of the model. Tan believes that the synergistic effect of cross-sectoral emission reduction will be better than that of a single sector, and that energy efficiency policies have a great impact on building emission reduction(Tan et al., 2018a). Zhou used Berkeley Lab's China 2050 Demand Resource Energy Analysis Model (DREAM), assuming Chinese building growth rates, building envelope efficiency, and other data. Zhou believes that while technologies, systems or practices can greatly reduce building energy consumption and carbon emission, strict policies are still needed to overcome multiple barriers to implementation(N. Zhou et al., 2018).

The 16th and 20th ranked studies also examine carbon emissions from building operations by modeling. Climate, building type, urban-rural configuration, and energy end use are variables in the model in Yang's study. Yang believes that simultaneous control of floor area, energy consumption and energy structure is essential to limit the growth of carbon emissions(T. Yang et al., 2017). McNeil improved the Zhou model by adding the impact of building construction and building obsolescence on the building stock, and found that the greatest opportunities for energy savings would be provided through the implementation of new building codes(McNeil et al., 2016).

In addition, the decoupling analysis of carbon emissions in construction industry from economic development(Du et al., 2019; Y. Wu et al., 2018), the relationship between construction land expansion and spatial and temporal variation of carbon emissions(Chuai et al., 2015), and the evaluation of energy conservation methods(M. Ma, Yan, Du, et al., 2017) are also hot topics.

2.4. Manual review

According to the bibliometric analysis, the research on carbon emissions from the construction industry is a very big topic, and many side studies have been derived. Based on the different research purposes of these studies, the research scales and objects, the accounting boundaries and methods and analysis methods are different, so it is necessary to adopt the manual review method to further explore to determine the research status, research gaps and future research hotspots of the carbon emission in the construction industry.

2.4.1 Gaps in research scales and objects

Carbon emission studies rely on the calculation of energy and emission-related data, and the lack of basic data is an important factor limiting the development of comprehensive and accurate carbon emission accounting. The changes in the scale and object of research on carbon emissions in the construction industry can well reflect the development of research in this field. As shown in Figure 2-15, the collected literature is categorized separately by research scale and research object. The research scales include national scale, regional scale, city scale, building scale & undefined. The research objects cover the whole construction industry (WHI), multiple types of civil buildings (MTCB), single type of civil buildings (STCB) and materials & others (M&O). If different types of civil buildings are included in the study objectives, they will be classified as MTCB. The study of only one type of civil building is classified as a STCB. As shown in Figure 2-16, residential buildings, public buildings, commercial buildings, educational buildings, and office buildings are widely studied civil buildings.

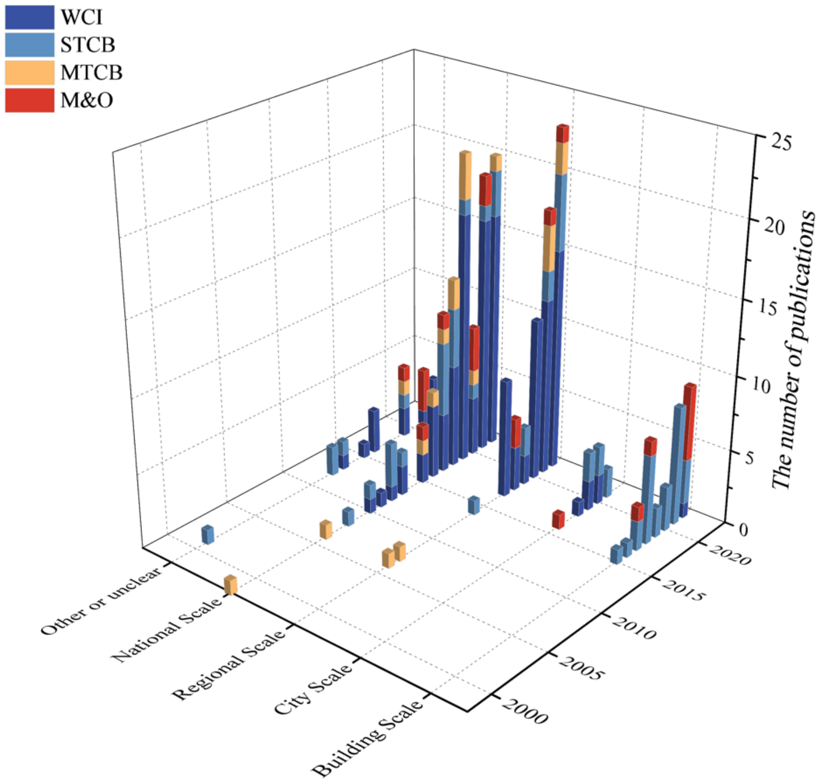


Fig.2-15 Research scale and object of publication

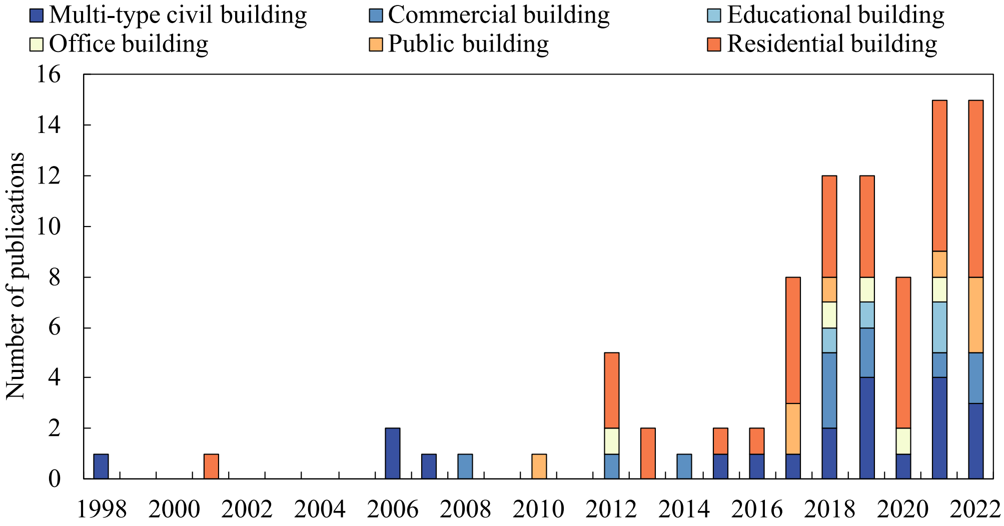


Fig.2-16 Publication of research on civil buildings

(1) National scale

Exploring the carbon emissions of residential buildings from a national scale is the earliest study. In 1998 Koomey et al. conducted an operational carbon emissions projection for U.S. residential buildings based on U.S. Department of Energy report data for commercial and residential buildings throughout the United States(Koomey et al., 1998). Eight years later, a similar study was conducted in Greece where, based on official building census data, Georgopoulou et al. predicted and evaluated the impact of economic support policies on carbon emissions from the operation of residential and tertiary buildings in Greece(Georgopoulou et al., 2006). Based on the same data sources as Koomey, Newell et al. narrowed the study to account for the cost of carbon reduction in the U.S. commercial building sector(Newell & Pizer, 2008).

In 2010, civil buildings are still the mainstream research object, and residential buildings become the hot spot(Lu et al., 2012). Kesicki and Oberheitmann accounted for the carbon emissions of residential buildings in the UK and China respectively, with the aim of exploring the costs and options for carbon reduction in the residential sector(Kesicki, 2012b; Oberheitmann, 2012). Jeong studied the carbon reduction potential of residential buildings in Korea based on long-term energy alternative planning (LEAP) system(Jeong, 2017). Ma mapped out a low carbon roadmap for China’s residential sector through carbon emissions accounting(M. Ma et al., 2020).

As climate issues gained attention, other types of civil buildings were also studied. Pavkovic study on energy efficiency and improvement measures for public buildings in Croatia(Pavkovic et al., 2010). Ma’s team. studied the drivers of carbon emissions from the operation of public buildings(M. Ma, Shen, et al., 2017; M. Ma, Yan, & Cai, 2017; M. Ma, Yan, et al., 2018), commercial buildings(M. Ma, Cai, et al., 2018; M. Ma & Cai, 2018) in China based on the CMBECSS 2.0 database, and compared the differences between China and the United States(Xiang et al., 2022).

In 2010, the WHI became an important object of national scale research. At this time, researchers were focused on the impact of patents, policies, behaviors, standards, and materials on the construction industry(Eriksson et al., 2012; Fink, 2011; Noailly & Batrakova, 2010), without accounting for the energy consumption or carbon emissions of the WHI. In 2013, Kucukvar introduced input-output models to assess the sustainability of the U.S. construction industry (Kucukvar & Tatari, 2013). Since then, WHI carbon emissions studies have been conducted extensively. Cellura and Lin accounts for greenhouse gas emissions from the building sector in Italy(Cellura et al., 2013) and China(Lin & Liu, 2015). Chuai studied the spatial and temporal variation of carbon emissions of the WHI in China(Chuai et al., 2015). Chen conducted an empirical study on the CO_2 emissions of the WHI in China(J. Chen et al., 2017). To date, the exploration of emission reduction pathways at the national scale(Alcantara

& Padilla, 2021) and carbon transfer between countries(L. Zhang et al., 2020) remains a hot topic.

(2) Regional scale

Research at the regional scale began in 2006, and its development history is similar to that of the national scale. Initially focusing on MTCB, Johansson conducted a study of carbon emissions from electricity(Johansson et al., 2006) and primary energy demand(Johansson et al., 2007) for heating residential and office buildings in southern Sweden. As research progressed and data became publicly available, STCB studies were conducted. Kahn examined commercial building electricity carbon emissions in the western United States(Kahn et al., 2014), and Ma studied the carbon intensity(M. Ma, Cai, et al., 2019) and operational carbon transition(M. Ma et al., 2022) of commercial buildings in the top five city clusters in China.

The regional scale WHI carbon emissions study started since 2017. Hu compared the carbon emissions performance of the construction sector by states in Australia(X. Hu et al., 2017). Hong, D. Li and R. Li accounted for carbon emissions from the construction industry in Guangdong Province(Hong, Zhang, et al., 2017) and Jiangsu Province(D. Li et al., 2020; R. Li & Jiang, 2017), and predicted carbon peaking(D. Li et al., 2021). Accounting for and comparing carbon emissions and influencing factors across Chinese provinces has also been widely explored(J. Wang et al., 2022; Wen et al., 2020).

Compared with the national scale, the study of civil buildings at the regional scale is carried out later. The reason for this is the non-disclosure and lack of data. Kahn's research was made possible by a partnership with the power company(Kahn et al., 2014). Ma's research relies on the China Building Energy Consumption Study Report, which was first published in 2016 and proposed a series of data processing methods to remedy the problems of changing caliber , missing indicators, incomplete data, etc.of provincial statistical yearbooks(Cai, 2016). In 2018, the report added carbon emissions-related data for the first time(Cai, 2018). Wang's study comparing the difference in carbon emissions between urban and rural dwellings(J. Wang et al., 2022) is based on the hina building energy consumption calculation method (CBECM) developed by Huo, which addresses the lack of clear delineation of residential energy consumption in the statistics(Huo et al., 2018).

(3) City scale

Only a few studies have examined carbon emissions from construction at the city scale. Hung quantifies WHI carbon emissions in Hong Kong, China（Hung et al., 2019）. Kamei assesses and predicts city transformations in Tokyo, Japan, where carbon emissions from buildings are an important indicator(Kamei et al., 2019). Balali assesses passive measures to reduce energy consumption in buildings using Shiraz, Iran as an example(Balali et al., 2020). Residential buildings and commercial buildings are popular research objects. Ma et al. evaluated the carbon emissions of commercial buildings in four Chinese municipalities, Beijing, Shanghai, Chongqing, and Tianjin(M. Ma, Cai, et al., 2019). Esch-sur-alzette is the second most populous city in Luxembourg and Mastrucci assessed the potential environmental impact of the renovation of residential buildings in this city(Mastrucci et al., 2020).

These studies have been conducted for large cities or cities with special status, and few studies have investigated ordinary cities. City-scale carbon emissions from the construction sector have not yet been in-depth. This is caused by the difficulty of obtaining municipal-level data, for which Shan proposed a method to estimate municipal level through provincial-level data(Shan et al., 2017). Zhao applied this method to accounting for carbon emissions from the construction industry in Hangzhou, China(Zhao et al., 2023). Chen attempted to address the problem using a downscaling approach, estimating city-scale carbon emissions from provincial energy data and gridded socioeconomic parameters, and the study projected carbon reduction pathways for the construction sector in 17 cities in Hubei Province, China(H. Chen & Chen, 2019a). The method has also been applied to various cities in China(H. Chen & Chen, 2019b).

(4) Building scale

The study of building scale has been a hot topic of research(Cellura et al., 2018), but in the past these studies have usually focused on the building itself, without extending the results to the construction sector and without using “construction sector” as a keyword. In the literature retrieved in this paper, such studies are conducted from the perspective of a STCB, using a bottom-up approach to carbon accounting by analyzing the energy, material demand, and C&D waste output of a specific building. Atmaca conducted a carbon emission assessment of two residential buildings in Turkey based on construction drawings, energy consumption data, etc. provided by the construction company(Atmaca, 2017). Huang used a life-cycle assessment of Fuzhou University’s dormitory buildings based on tender information, utility bills and maintenance reports provided by the university, with carbon emissions as one of the indicators(Huang, Liu, et al., 2018). Marey et al. explore the contribution of green concrete to carbon emission reduction in the Egyptian construction industry based on the list of works provided by the general contractor, using actual residential projects as an example(Marey et al., 2022). Compared to other scales, building scale research has been widely studied due to the single object and the fact that complete data can often be obtained directly from the builder, user, etc.

It is now the mainstream to conduct studies on the carbon emissions of the WHI at a large scale like national or regional. Micro-scale carbon emission accounting with case buildings as the research object has also received extensive attention. In contrast, city scale studies at the meso level are fewer and limited to a few cities, leaving a lack of basis for assessing the development of the urban construction industry and formulating policies. As an important implementation unit for carbon peaking and carbon neutrality, it has become imperative for cities to strengthen the accounting of carbon emissions at the city scale.

2.4.2 Unclear accounting boundaries and methods

The determination of accounting boundary is the most important part of carbon emission research. Different accounting boundaries for the same research objectives will produce different accounting results. The accounting boundaries of previous studies are reviewed, and the accounting methods are discussed based on them. The whole life cycle of a building is usually simply divided into four phases: production of building materials, construction, operation, and demolition. The accounting boundary can be divided into two categories accordingly. Bounded by a single phase: Construction (C), Materials (M), Operation (O), Waste (W). The other category is bounded by multiple phases: Construction & Materials(C&M), Materials & Waste(M&W), Construction, Materials & Operation (C, M&O), and Whole life cycle. Classify infrequent and unspecified accounting boundaries as other or not mentioned, as shown in Figure 2-17.

In terms of single-phase boundaries, building operation was the most used accounting boundary in previous studies. and construction and materials also gained some attention, with these three accounting for 29.6%, 9.1%, and 9.5% of the total publications, respectively. Only four studies focus on the demolition phase of buildings, and there is a research gap for carbon emissions from building demolition and waste reuse. Some studies account for carbon emissions in multiple phases, with C&M and whole life cycle carbon accounting being the hot spots, accounting for 28.9% and 6.3% of the total publications.

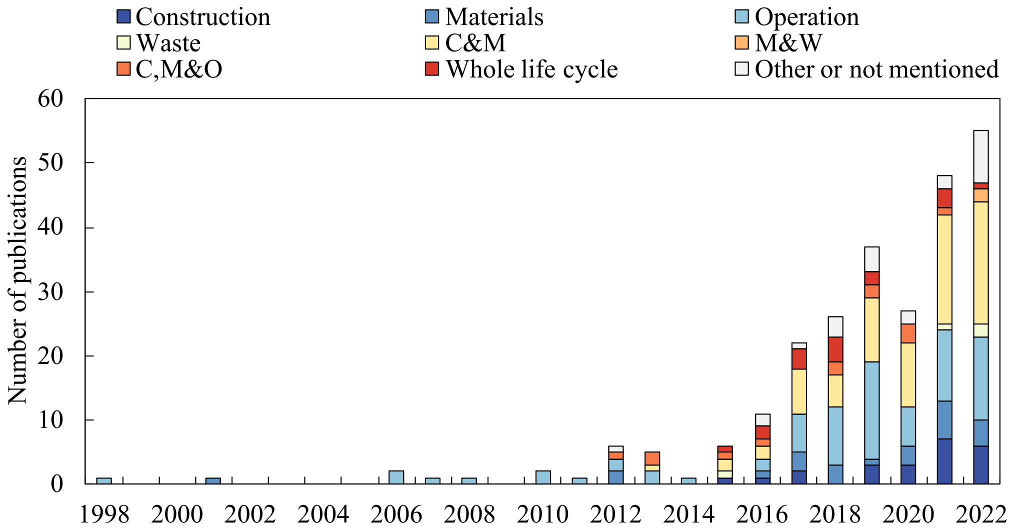


Fig.2-17 Carbon emission accounting boundaries for publications

(1) Research and accounting methods with a single-phase boundary

The carbon emission factor method is the most used method. This method, proposed by the IPCC, is widely applicable and is the basis for carbon accounting, and has been widely used for carbon accounting in the construction industry across all boundaries.

In the study with construction as the boundary, the Carbon emissions from fossil energy and electricity consumed by construction equipment are accounted for. This boundary accounting process is simple, the data source is clear, and the carbon emission factor method is the most suitable method. The accounting of construction carbon emissions in China's construction industry in Chen and Lai's study is achieved through the carbon emission factor method(J. Chen, Xu, et al., 2019; Lai et al., 2019).

In studies that use operation as the accounting boundary, the main accounting is for the carbon emissions of electricity and fossil energy that keep the building running and provide a comfortable environment for the occupants. The carbon intensity method is the commonly used method. This method uses floor area and carbon intensity factors to estimate the carbon emissions of building operations. Tan used the heating energy consumption data in the statistical yearbook to measure carbon emission intensity, and to account for carbon emissions and reduction potential(Tan et al., 2018b). Ma uses the Kaya equation and LMDI method to measure the carbon intensity of buildings to account for the operational carbon emissions of commercial buildings in China(M. Ma, Cai, et al., 2018). Ha estimates the reduction potential of Korean building operation by energy intensity per unit area and makes recommendations(Ha et al., 2019).

Some studies use software or models to predict operational carbon emissions. Cellura uses TRNSYS to model buildings and simulate the impact of climate change on building operating energy(Cellura et al., 2018). Satre-Meloy uses Scout, an open-source software program developed by the U.S. Department of Energy, to estimate carbon emissions from U.S. buildings. The program provides hourly data and is widely used (Satre-Meloy & Langevin, 2019). In addition, C^3IAM/NET-Building mode(Tang et al., 2021), AIM/Enduse model(Xing et al., 2021), LEAP model(S.-H. Kim et al., 2020), etc. are also applied to operational carbon accounting.

The life cycle assessment (LCA) method, which splits the carbon emission process of materials into production, transportation, and installation processes, is a common method in studies that use materials as the accounting boundary. Heravi used this method to evaluate the carbon emissions of building assembled steel frames (Heravi et al., 2020). and Li split the total carbon emissions of wood into five segments: harvesting, raw material transportation, manufacturing, inland transportation of products, and maritime transportation of products to assess the environmental impact(S. Li et al., 2018).

Some studies have measured the carbon emissions of construction materials through material demand models combined with material carbon intensity(Eriksson et al., 2012), material carbon emission intensity data are often obtained from manufacturers or previous studies(Hildebrandt et al., 2017). There are also studies that use carbon emission assessment tools, which are basically demand models and carbon intensity methods(Roy et al., 2022). By entering information about the case building, the building material demand and the amount of carbon emissions can be obtained(Fregonara et al., 2022).

Research using construction waste as the accounting boundary is still in the emerging stage, and life cycle assessment is the main carbon accounting method for this type of research. Backes explores the carbon footprint of the concrete recycling process(Backes et al., 2022). Bertin focuses on the whole life-cycle carbon emissions of reinforced concrete portal frames from design to reuse(Bertin et al., 2022).

In the carbon emission study with single-phase boundary, the accounting process and method are simple. Carbon emission factor method, carbon emission intensity method and life cycle assessment method are commonly used accounting methods. However, some problems have been revealed that these studies are highly dependent on carbon emission factors or carbon intensity factors. These data are often obtained from suppliers or from previous studies based on individual building or project measurements. Using data from different sources will likely lead to biased accounting results, making it difficult to compare data between different regions, organizations, and projects. The measurement results may deviate from the actual and cannot accurately express the current situation of carbon emissions in the construction industry, and cannot reflect the differences between different regions, different organizations and different projects.

(2) Research and accounting methods with a multiple phase boundary

Studies that use the whole life cycle of a building as the accounting boundary are the most typical. These studies usually use life cycle assessment combined with carbon emission factor method to divide the whole life cycle of a building from "cradle to death" into several stages and obtain the whole life cycle carbon emissions of a building by accounting for carbon emissions in each stage and summing them up. This approach is often referred to as Process-based method. Evangelista et al. divided the whole building life cycle into three phases, Pre-operational phase, Operational phase and Post-operational phase, to account for the carbon performance of a typical residential building in Brazil(Evangelista et al., 2018). Huang evaluated the environmental costs of campus buildings in China by accounting for five phases: pre-construction, construction, maintenance, operation and end of life(Huang, Liu, et al., 2018). Based on process-based methods, some studies have developed or used carbon accounting tools(Dong et al., 2021b). Solis-Guzman et al. developed the OERCO2 Project and demonstrated its reliability(Solis-Guzman et al., 2018). Arias accounts for whole-life cycle carbon emissions of campus buildings in Spain with NEST tool(Arias et al., 2021).

Some studies adopted a hybrid method to accounting, with Zhang using the input-output method to account for carbon emissions in the construction and demolition phases and the carbon emission factor method to account for carbon emissions in the operation phase(X. Zhang & Wang, 2016). This method is also called input-output LCA. The same approach was used in the study by Hong et al(Hong, Zhang, et al., 2017).

Thanks to the application of input-output models in the field of carbon emissions, many studies have accounted for carbon emissions using C&M as the boundary. This method uses inter-industry linkages to account for carbon emissions from upstream sectors due to construction industry demand, which are referred to as indirect carbon emissions from the construction industry (indirect CECI). Du et al. used the method to account for indirect CECI in 9 upstream sectors and used the carbon emission factor method to account for direct carbon emissions from construction industry (direct CECI). Accounting for the C&M boundary is accomplished by summing the direct CECI and indirect CECI(Du et al., 2019). Chen, Hong, Wang et al. Accounting for indirect carbon emissions in the construction industry for all upstream sectors of the construction industry(J. Chen, Shen, et al., 2019; Hong et al., 2019; J. Wang et al., 2020).

As in Equation (2-1), some studies account for the M&C boundary with the help of the carbon emission intensity of the material(R. Li & Jiang, 2017), construction materials such as cement, steel, glass and aluminum are usually selected for accounting(Ahmad et al., 2019; Zhu, Chang, et al., 2022). Based on this approach, some studies have considered the material recovery rate, as in Equation 2, known as the simplified LCA method. It is worth noting that this method, although called a simplification of the life cycle assessment method, does not account for carbon emissions from building demolition and operation, etc.(Dai et al., 2022; Y. Wang & Wu, 2022). So, the accounting boundary of such studies is classified as C&M by this paper. At the same time, this method does not account for materials that can be recycled, leaving out the carbon emissions of the waste disposal and the material recycling process.

$$C = C_{dir} + C_{ind} = \sum_i E_i \times F_i + \sum_j M_j \times \beta_j \tag{2-1}$$

$$C = C_{dir} + C_{ind} = \sum_i E_i \times F_i + \sum_j M_j \times \beta_j \times (1 - \varepsilon_j) \tag{2-2}$$

Where, C represents the CO_2 emissions of the construction industry; C_{dir} represents the direct CECI; C_{ind} represents the indirect CECI; E_i represents the consumption of the energy i; F_i represents the CO_2 emission factor of the energy i; M_j represents the consumption of the material j; β_j represents the CO_2 emission intensity of the material j, ε_j denotes the recovery rate of material j.

Studies that use C, M&O as the accounting boundary usually use the carbon intensity method or input-output method to account for material carbon emissions, and then use the carbon emission factor method to account for construction and operation carbon emissions(D. Li et al., 2021; P. Wu et al., 2019). The study of M&W boundary is still in its initial stage. Based on the concept of whole life cycle and material cycle, carbon emission factor method is the current accounting method to account for the carbon emission of material production, transportation, disposal and recycling process(X. Yang et al., 2022).

The determination of accounting boundary is the basis of carbon emission studies, so the standardization of the boundary is especially important. In the carbon emission studies with multiple phase boundary, the accounting boundary is complicated, and the carbon emission accounting is usually done by mixing multiple methods or summing up after accounting in phases. At present, the study of CECI is in its infancy, and there is a certain ambiguity in the definition of boundaries, such as building demolition, waste disposal and recycling are often left out(Ahmad et al., 2020). Accounting methods are also still uncertain, different methods of accounting for the same boundary are often incompatible(Saynajoki et al., 2017).

2.5 Future research directions

This study reviews the literature on carbon emissions from the construction industry from 1998 to 2022, summarizing it from the perspectives of study subjects, scales, accounting methods, and boundaries. The literature search was conducted through WOS and does not cover all studies completed.

Research on carbon emissions in the construction industry is mainly focused on the macroscopic scale of countries and regions, or the microscopic scale of case buildings, and research on the city scale is still in its initial stage. Cities are the main spaces of population concentration and production activities(UN Department of Economic and Social Affairs, 2017), and they are also areas of concentrated resource consumption and environmental load. Cities consume 78% of the world's energy and produce 60% of the greenhouse gases(United Nations, 2020). Japan has committed to achieve net zero carbon emissions by 2050 on a city basis(Ministry of the Environment, 2023), China has established a provincial-led emission reduction system, and cities have become the basic unit of carbon emissions(L. Li & Yang, 2020). And cities are open systems, with building materials often imported from outside, cross-border emissions of CO_2 are prominent(Zhao et al., 2023). Therefore, it is important to account for city scale CECI, identify the sources and places of emissions, reveal the carbon flows between cities, and find the drivers of carbon emissions.

Residential buildings have been fully explored from the perspective of carbon reduction cost(Kesicki, 2012b), technology application(Nassen & Holmberg, 2013), and regional differences(Liang et al., 2019), and the accounting boundary has covered all stages of the whole life cycle(Dong et al., 2021b). However, these studies do not distinguish between urban and rural areas, or take urban dwellings as the subject of study(Huo et al., 2021). Rural housing and urban housing have differences in structure, materials, thermal performance, etc., and there is a large stock of rural housing(Sun et al., 2022). Research on commercial buildings has also been carried out in depth(Su et al., 2022). Ma has conducted carbon accounting, driving force analysis, carbon emission reduction prediction and economic decoupling analysis for commercial buildings at national, regional and city scales, respectively(M. Ma, Cai, et al., 2018;

M. Ma et al., 2022; M. Ma & Cai, 2018). Fewer studies have been conducted for office buildings and educational buildings. With the development of urbanization, the demand for office buildings will be increasing. While educational buildings are different from other civil buildings in terms of indoor environment demand and usage behavior due to their special characteristics(J. Hu et al., 2022). Therefore, further subdivision of civil buildings by type and research on carbon emissions for rural housing, educational buildings, office buildings will also be a direction that can be explored in the future.

In terms of accounting boundaries for carbon emissions, the material, construction and operational boundaries have been well explored, while studies of the demolition phase are often conducted through assumptions. The energy consumption in the demolition phase was assumed to be 9% of the construction phase in X. Zhang's study(X. Zhang & Wang, 2016), Z. Zhang believes that the energy consumed in the demolition phase is about 90% of that in the construction phase Zhang & Wang, 2016), Atmaca assumes 0.2% of the whole life cycle primary energy consumption of a building for demolition carbon emissions(Atmaca, 2017). This huge difference makes carbon accounting uncertainty much higher. The carbon emissions from waste disposal (Atmaca, 2017) and material recycling (Can et al., 2019; Roh et al., 2018) are often neglected. This exposes a gap in the study of carbon emissions from building demolition and waste disposal processes. And supplementing building demolition and construction waste disposal recycling in the accounting boundary will be a very urgent study in the future.

In addition, the research on carbon emissions in the construction industry also suffers from the deficiency of accounting methods. The standardization of carbon emission research methods in the construction industry is low, and a set of reliable and scientific assessment methods and index systems cannot be formed to comprehensively assess carbon emissions in the construction industry. Current accounting methods rely heavily on the carbon emission factor method, the LCA method, the input-output ,method, and the carbon intensity method are all accounting methods based on the carbon emission factor method. It will be major issues to introduce methods such as monitoring method(Kalogerakis et al., 2022), mass balance method(Bareha et al., 2021; J. Kim et al., 2023), which have been fully applied in other disciplines, into the carbon accounting of construction industry and to establish a standard and reliable carbon accounting system.

Reference

Ahmad, M., Jabeen, G., Hayat, M. K., Khan, R. E. A., & Qamar, S. (2020). Revealing heterogeneous causal links among financial development, construction industry, energy use, and environmental quality across development levels. In ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH (Vol. 27, Issue 5, pp. 4976–4996). SPRINGER HEIDELBERG. https://doi.org/10.1007/s11356-019-07299-w

Ahmad, M., Zhao, Z.-Y., & Li, H. (2019). Revealing stylized empirical interactions among construction sector, urbanization, energy consumption, economic growth and CO2 emissions in China. In SCIENCE OF THE TOTAL ENVIRONMENT (Vol. 657, pp. 1085–1098). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.scitotenv.2018.12.112

Akan, M. O. A., Dhavale, D. G., & Sarkis, J. (2017). Greenhouse gas emissions in the construction industry: An analysis and evaluation of a concrete supply chain. In JOURNAL OF CLEANER PRODUCTION (Vol. 167, pp. 1195–1207). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2017.07.225

Alcantara, V., & Padilla, E. (2021). CO2 emissions of the construction sector in Spain during the real estate boom: Input-output subsystem analysis and decomposition. In JOURNAL OF INDUSTRIAL ECOLOGY (Vol. 25, Issue 5, pp. 1272–1283). WILEY. https://doi.org/10.1111/jiec.13127

Arias, A., Leon, I., Oregi, X., & Marieta, C. (2021). Environmental Assessment of University Campuses: The Case of the University of Navarra in Pamplona (Spain). In SUSTAINABILITY (Vol. 13, Issue 15). MDPI. https://doi.org/10.3390/su13158588

Atmaca, N. (2017). Life-cycle assessment of post-disaster temporary housing. In BUILDING RESEARCH AND INFORMATION (Vol. 45, Issue 5, pp. 524–538). ROUTLEDGE JOURNALS, TAYLOR & FRANCIS LTD. https://doi.org/10.1080/09613218.2015.1127116

Backes, J. G., Del Rosario, P., Petrosa, D., Traverso, M., Hatzfeld, T., & Guenther, E. (2022). Building Sector Issues in about 100 Years: End-Of-Life Scenarios of Carbon-Reinforced Concrete Presented in the Context of a Life Cycle Assessment, Focusing the Carbon Footprint. In PROCESSES (Vol. 10, Issue 9). MDPI. https://doi.org/10.3390/pr10091791

Balali, A., Hakimelahi, A., & Valipour, A. (2020). Identification and prioritization of passive energy consumption optimization measures in the building industry: An Iranian case study. In JOURNAL OF BUILDING ENGINEERING (Vol. 30). ELSEVIER. https://doi.org/10.1016/j.jobe.2020.101239

Balasubramanian, S., Shukla, V., Islam, N., & Manghat, S. (n.d.). Construction Industry 4.0 and Sustainability: An Enabling Framework. In IEEE TRANSACTIONS ON

ENGINEERING MANAGEMENT. IEEE-INST ELECTRICAL ELECTRONICS ENGINEERS INC. https://doi.org/10.1109/TEM.2021.3110427

Bareha, Y., Affes, R., Moinard, V., Buffet, J., & Girault, R. (2021). A simple mass balance tool to predict carbon and nitrogen fluxes in anaerobic digestion systems. Waste Management, 135, 47–59. https://doi.org/10.1016/j.wasman.2021.08.020

Bertin, I., Saade, M., Le Roy, R., Jaeger, J.-M., & Feraille, A. (2022). Environmental impacts of Design for Reuse practices in the building sector. In JOURNAL OF CLEANER PRODUCTION (Vol. 349). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2022.131228

Cai, W. (2018). Chinese building energy consumption report. CABEE (2018).

Cai, W. (ed). (2016). Chinese building energy consumption report. CABEE (2016).

Can, C., Zhen, W., & Guoshu, B. (2019). Life-cycle CO2 Emissions and Their Driving Factors in Construction Sector in China. In CHINESE GEOGRAPHICAL SCIENCE (Vol. 29, Issue 2, pp. 293–305). SPRINGER. https://doi.org/10.1007/s11769-019-1029-z

Cellura, M., Guarino, F., Longo, S., Mistretta, M., & Orioli, A. (2013). The role of the building sector for reducing energy consumption and greenhouse gases: An Italian case study. RENEWABLE ENERGY, 60, 586–597. https://doi.org/10.1016/j.renene.2013.06.019

Cellura, M., Guarino, F., Longo, S., & Tumminia, G. (2018). Climate change and the building sector: Modelling and energy implications to an office building in southern Europe. In ENERGY FOR SUSTAINABLE DEVELOPMENT (Vol. 45, pp. 46–65). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.esd.2018.05.001

Chen, C. (2020). A Glimpse of the First Eight Months of the COVID-19 Literature on Microsoft Academic Graph: Themes, Citation Contexts, and Uncertainties. Frontiers in Research Metrics and Analytics, 5, 607286. https://doi.org/10.3389/frma.2020.607286

Chen, C., Ibekwe-SanJuan, F., & Hou, J. (2010). The structure and dynamics of cocitation clusters: A multiple-perspective cocitation analysis. Journal of the American Society for Information Science and Technology, 61(7), 1386–1409. https://doi.org/10.1002/asi.21309

Chen, C., & Song, M. (2019). Visualizing a field of research: A methodology of systematic scientometric reviews. PLOS ONE, 14(10), e0223994. https://doi.org/10.1371/journal.pone.0223994

Chen, H., & Chen, W. (2019a). Carbon mitigation of China’s building sector on city-level: Pathway and policy implications by a low-carbon province case study. In JOURNAL OF CLEANER PRODUCTION (Vol. 224, pp. 207–217). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2018.12.022

Chen, H., & Chen, W. (2019b). Potential impacts of coal substitution policy on regional air pollutants and carbon emission reductions for China’s building sector during the 13th

Five-Year Plan period. In ENERGY POLICY (Vol. 131, pp. 281–294). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2019.04.047

Chen, J., Shen, L., Shi, Q., Hong, J., & Ochoa, J. J. (2019). The effect of production structure on the total CO2 emissions intensity in the Chinese construction industry. In JOURNAL OF CLEANER PRODUCTION (Vol. 213, pp. 1087–1095). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2018.12.203

Chen, J., Shen, L., Song, X., Shi, Q., & Li, S. (2017). An empirical study on the CO2 emissions in the Chinese construction industry. In JOURNAL OF CLEANER PRODUCTION (Vol. 168, pp. 645–654). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2017.09.072

Chen, J., Shi, Q., Shen, L., Huang, Y., & Wu, Y. (2019). What makes the difference in construction carbon emissions between China and USA? Sustainable Cities and Society, 44, 604–613. https://doi.org/10.1016/j.scs.2018.10.017

Chen, J., Song, X., & You, J. (n.d.). Structural paths of changes in CO2 emissions in the Chinese construction industry. In JOURNAL OF ENVIRONMENTAL PLANNING AND MANAGEMENT. ROUTLEDGE JOURNALS, TAYLOR & FRANCIS LTD. https://doi.org/10.1080/09640568.2021.2016381

Chen, J., Xu, C., Managi, S., & Song, M. (2019). Energy-carbon performance and its changing trend: An example from China’s construction industry. In RESOURCES CONSERVATION AND RECYCLING (Vol. 145, pp. 379–388). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.resconrec.2019.03.014

Chuai, X., Huang, X., Lu, Q., Zhang, M., Zhao, R., & Lu, J. (2015). Spatiotemporal Changes of Built-Up Land Expansion and Carbon Emissions Caused by the Chinese Construction Industry. In ENVIRONMENTAL SCIENCE & TECHNOLOGY (Vol. 49, Issue 21, pp. 13021–13030). AMER CHEMICAL SOC. https://doi.org/10.1021/acs.est.5b01732

Dai, D., Li, K., Zhao, S., & Zhou, B. (2022). Research on prediction and realization path of carbon peak of construction industry based on EGM-BP model. In FRONTIERS IN ENERGY RESEARCH (Vol. 10). FRONTIERS MEDIA SA. https://doi.org/10.3389/fenrg.2022.981097

Ding, yiting. (2021, April 2). Strive to achieve carbon peak by 2030 and carbon neutral by 2060—Winning the battle of low-carbon transition. People’s Daily.

Dong, Y., Liu, P., Hossain, M. U., Fang, Y., He, Y., & Li, H. (2021a). An Index of Completeness (IoC) of life cycle assessment: Implementation in the building sector. Journal of Cleaner Production, 283, 124672. https://doi.org/10.1016/j.jclepro.2020.124672

Dong, Y., Liu, P., Hossain, M. U., Fang, Y., He, Y., & Li, H. (2021b). An Index of Completeness (IoC) of life cycle assessment: Implementation in the building sector. In

JOURNAL OF CLEANER PRODUCTION (Vol. 283). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2020.124672

Du, Q., Zhou, J., Pan, T., Sun, Q., & Wu, M. (2019). Relationship of carbon emissions and economic growth in China's construction industry. Journal of Cleaner Production, 220, 99–109. https://doi.org/10.1016/j.jclepro.2019.02.123

Eriksson, L. O., Gustavsson, L., Hanninen, R., Kallio, M., Lyhykainen, H., Pingoud, K., Pohjola, J., Sathre, R., Solberg, B., Svanaes, J., & Valsta, L. (2012). Climate change mitigation through increased wood use in the European construction sector-towards an integrated modelling framework. In EUROPEAN JOURNAL OF FOREST RESEARCH (Vol. 131, Issues 1, SI, pp. 131–144). SPRINGER. https://doi.org/10.1007/s10342-010-0463-3

Evangelista, P. P. A., Kiperstok, A., Torres, E. A., & Goncalves, J. P. (2018). Environmental performance analysis of residential buildings in Brazil using life cycle assessment (LCA). In CONSTRUCTION AND BUILDING MATERIALS (Vol. 169, pp. 748–761). ELSEVIER SCI LTD. https://doi.org/10.1016/j.conbuildmat.2018.02.045

Fink, H. S. (2011). Promoting behavioral change towards lower energy consumption in the building sector. In INNOVATION-THE EUROPEAN JOURNAL OF SOCIAL SCIENCE RESEARCH (Vol. 24, Issues 1–2, pp. 7–26). ROUTLEDGE JOURNALS, TAYLOR & FRANCIS LTD. https://doi.org/10.1080/13511610.2011.586494

Fregonara, E., Ferrando, D. G., & Tulliani, J.-M. (2022). Sustainable Public Procurement in the Building Construction Sector. In SUSTAINABILITY (Vol. 14, Issue 18). MDPI. https://doi.org/10.3390/su141811616

Gan, L., Ren, H., Cai, W., Wu, K., Liu, Y., & Liu, Y. (2022). Allocation of carbon emission quotas for China's provincial public buildings based on principles of equity and efficiency. In BUILDING AND ENVIRONMENT (Vol. 216). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.buildenv.2022.108994

Georgopoulou, E., Sarafidis, Y., Mirasgedis, S., Balaras, C. A., Gaglia, A., & Lalas, D. P. (2006). Evaluating the need for economic support policies in promoting greenhouse gas emission reduction measures in the building sector: The case of Greece. In ENERGY POLICY (Vol. 34, Issue 15, pp. 2012–2031). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2005.02.002

Giesekam, J., Barrett, J. R., & Taylor, P. (2016). Construction sector views on low carbon building materials. In BUILDING RESEARCH AND INFORMATION (Vol. 44, Issue 4, pp. 423–444). ROUTLEDGE JOURNALS, TAYLOR & FRANCIS LTD. https://doi.org/10.1080/09613218.2016.1086872

Guo, S., Zheng, S., Hu, Y., Hong, J., Wu, X., & Tang, M. (2019). Embodied energy use in the global construction industry. APPLIED ENERGY, 256. https://doi.org/10.1016/j.apenergy.2019.113838

Ha, S., Tae, S., & Kim, R. (2019). A Study on the Limitations of South Korea's National Roadmap for Greenhouse Gas Reduction by 2030 and Suggestions for Improvement. In SUSTAINABILITY (Vol. 11, Issue 14). MDPI. https://doi.org/10.3390/su11143969

Heravi, G., Rostami, M., & Kebria, M. F. (2020). Energy consumption and carbon emissions assessment of integrated production and erection of buildings' pre-fabricated steel frames using lean techniques. In JOURNAL OF CLEANER PRODUCTION (Vol. 253). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2020.120045

Hildebrandt, J., Hagemann, N., & Thraen, D. (2017). The contribution of wood-based construction materials for leveraging a low carbon building sector in europe. In SUSTAINABLE CITIES AND SOCIETY (Vol. 34, pp. 405–418). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.scs.2017.06.013

Hong, J., Gu, J., Liang, X., Liu, G., & Shen, G. Q. (2019). Characterizing embodied energy accounting with a multi-dimensional framework: A study of China's building sector. In JOURNAL OF CLEANER PRODUCTION (Vol. 215, pp. 154–164). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2018.12.300

Hong, J., Li, C. Z., Shen, Q., Xue, F., Sun, B., & Zheng, W. (2017). An Overview of the driving forces behind energy demand in China's construction industry: Evidence from 1990 to 2012. In RENEWABLE & SUSTAINABLE ENERGY REVIEWS (Vol. 73, pp. 85–94). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.rser.2017.01.021

Hong, J., Shen, G. Q., Guo, S., Xue, F., & Zheng, W. (2016). Energy use embodied in China's construction industry: A multi-regional input-output analysis. In RENEWABLE & SUSTAINABLE ENERGY REVIEWS (Vol. 53, pp. 1303–1312). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.rser.2015.09.068

Hong, J., Shen, Q., & Xue, F. (2016). A multi-regional structural path analysis of the energy supply chain in China's construction industry. ENERGY POLICY, 92, 56–68. https://doi.org/10.1016/j.enpol.2016.01.017

Hong, J., Wang, C., Chang-Richards, A., Zhang, J., Qiping, G., & Qiao, B. (2022). A spatiotemporal analysis of energy use pathways in the construction industry: A study of China. ENERGY, 239. https://doi.org/10.1016/j.energy.2021.122084

Hong, J., Zhang, X., Shen, Q., Zhang, W., & Feng, Y. (2017). A multi-regional based hybrid method for assessing life cycle energy use of buildings: A case study. In JOURNAL OF CLEANER PRODUCTION (Vol. 148, pp. 760–772). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2017.02.063

Hou, H., Feng, X., Zhang, Y., Bai, H., Ji, Y., & Xu, H. (2021). Energy-related carbon emissions mitigation potential for the construction sector in China. In ENVIRONMENTAL IMPACT ASSESSMENT REVIEW (Vol. 89). ELSEVIER SCIENCE INC. https://doi.org/10.1016/j.eiar.2021.106599

Hu, J., He, Y., Hao, X., Li, N., Su, Y., & Qu, H. (2022). Optimal temperature ranges considering gender differences in thermal comfort, work performance, and sick building syndrome: A winter field study in university classrooms. Energy and Buildings, 254, 111554. https://doi.org/10.1016/j.enbuild.2021.111554

Hu, X., Si, T., & Liu, C. (2017). Total factor carbon emission performance measurement and development. In JOURNAL OF CLEANER PRODUCTION (Vol. 142, Issue 4, pp. 2804–2815). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2016.10.188

Hu, Y., Zhang, Q., Hu, S., Xiao, G., Chen, X., Wang, J., Qi, Y., Zhang, L., & Han, L. (2022). Research progress and prospects of ecosystem carbon sequestration under climate change (1992–2022). Ecological Indicators, 145, 109656. https://doi.org/10.1016/j.ecolind.2022.109656

Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., & Zhang, X. (2018). Carbon emission of global construction sector. Renewable and Sustainable Energy Reviews, 81, 1906–1916. https://doi.org/10.1016/j.rser.2017.06.001

Huang, L., Liu, Y., Krigsvoll, G., & Johansen, F. (2018). Life cycle assessment and life cycle cost of university dormitories in the southeast China: Case study of the university town of Fuzhou. JOURNAL OF CLEANER PRODUCTION, 173, 151–159. https://doi.org/10.1016/j.jclepro.2017.06.021

Huo, T., Ren, H., Zhang, X., Cai, W., Feng, W., Zhou, N., & Wang, X. (2018). China's energy consumption in the building sector: A Statistical Yearbook-Energy Balance Sheet based splitting method. In JOURNAL OF CLEANER PRODUCTION (Vol. 185, pp. 665–679). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2018.02.283

Huo, T., Tang, M., Cai, W., Ren, H., Liu, B., & Hu, X. (2020). Provincial total-factor energy efficiency considering floor space under construction: An empirical analysis of China's construction industry. Journal of Cleaner Production, 244, 118749. https://doi.org/10.1016/j.jclepro.2019.118749

Huo, T., Xu, L., Feng, W., Cai, W., & Liu, B. (2021). Dynamic scenario simulations of carbon emission peak in China's city-scale urban residential building sector through 2050. In ENERGY POLICY (Vol. 159). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2021.112612

Iqbal, M., Ma, J., Ahmad, N., Hussain, K., Waqas, M., & Liang, Y. (n.d.). Sustainable construction through energy management practices: An integrated hierarchal framework of drivers in the construction sector. In ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH. SPRINGER HEIDELBERG. https://doi.org/10.1007/s11356-022-21928-x

Jeong, Y.-S. (2017). Assessment of Alternative Scenarios for CO2 Reduction Potential in the Residential Building Sector. In SUSTAINABILITY (Vol. 9, Issue 3). MDPI AG. https://doi.org/10.3390/su9030394

Jiang, R., & Li, R. (2017). Decomposition and Decoupling Analysis of Life-Cycle Carbon Emission in China's Building Sector. Sustainability, 9(5), 793. https://doi.org/10.3390/su9050793

Johansson, P., Nylander, A., & Johnsson, F. (2006). Electricity dependency and CO2 emissions from heating in the Swedish building sector—Current trends in conflict with governmental policy? In ENERGY POLICY (Vol. 34, Issue 17, pp. 3049–3064). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2005.05.012

Johansson, P., Nylander, A., & Johnsson, F. (2007). Primary energy use for heating in the Swedish building sector—Current trends and proposed target. In ENERGY POLICY (Vol. 35, Issue 2, pp. 1386–1404). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2006.03.025

Kahn, M. E., Kok, N., & Quigley, J. M. (2014). Carbon emissions from the commercial building sector: The role of climate, quality, and incentives. In JOURNAL OF PUBLIC ECONOMICS (Vol. 113, pp. 1–12). ELSEVIER SCIENCE SA. https://doi.org/10.1016/j.jpubeco.2014.03.003

Kalogerakis, G. C., Boparai, H. K., & Sleep, B. E. (2022). The journey of toluene to complete mineralization via heat-activated peroxydisulfate in water: Intermediates analyses, CO2 monitoring, and carbon mass balance. Journal of Hazardous Materials, 440, 129739. https://doi.org/10.1016/j.jhazmat.2022.129739

Kamei, M., Kurisu, K., & Hanaki, K. (2019). Evaluation of long-term urban transitions in a megacity's building sector based on alternative socioeconomic pathways. In SUSTAINABLE CITIES AND SOCIETY (Vol. 47). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.scs.2018.11.041

Karlsson, I., Rootzen, J., Toktarova, A., Odenberger, M., Johnsson, F., & Goransson, L. (2020). Roadmap for Decarbonization of the Building and Construction Industry-A Supply Chain Analysis Including Primary Production of Steel and Cement. In ENERGIES (Vol. 13, Issue 16). MDPI. https://doi.org/10.3390/en13164136

Kesicki, F. (2012a). Costs and potentials of reducing CO2 emissions in the UK domestic stock from a systems perspective. Energy and Buildings, 51, 203–211. https://doi.org/10.1016/j.enbuild.2012.05.013

Kesicki, F. (2012b). Costs and potentials of reducing CO2 emissions in the UK domestic stock from a systems perspective. In ENERGY AND BUILDINGS (Vol. 51, pp. 203–211). ELSEVIER SCIENCE SA. https://doi.org/10.1016/j.enbuild.2012.05.013

Kim, J., Seo, B., Lee, T., Kim, J., Kim, S., Bae, G.-N., & Lee, G. (2023). Airborne estimation of SO2 emissions rates from a coal-fired power plant using two top-down methods: A mass balance model and Gaussian footprint approach. Science of The Total Environment, 855, 158826. https://doi.org/10.1016/j.scitotenv.2022.158826

Kim, S.-H., Lee, S., Han, S.-Y., & Kim, J.-H. (2020). Scenario Analysis for GHG Emission Reduction Potential of the Building Sector for New City in South Korea. In ENERGIES (Vol. 13, Issue 20). MDPI. https://doi.org/10.3390/en13205514

Koomey, J., Martin, N., Brown, M., Price, L., & Levine, M. (1998). Costs of reducing carbon emissions: US building sector scenarios. In ENERGY POLICY (Vol. 26, Issue 5, pp. 433–440). ELSEVIER SCI LTD. https://doi.org/10.1016/S0301-4215(97)00154-7

Kucukvar, M., & Tatari, O. (2013). Towards a triple bottom-line sustainability assessment of the U.S. construction industry. In INTERNATIONAL JOURNAL OF LIFE CYCLE ASSESSMENT (Vol. 18, Issue 5, pp. 958–972). SPRINGER HEIDELBERG. https://doi.org/10.1007/s11367-013-0545-9

Lai, X., Lu, C., & Liu, J. (2019). A synthesized factor analysis on energy consumption, economy growth, and carbon emission of construction industry in China. In ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH (Vol. 26, Issue 14, pp. 13896–13905). SPRINGER HEIDELBERG. https://doi.org/10.1007/s11356-019-04335-7

Li, D., Huang, G., Zhang, G., & Wang, J. (2020). Driving factors of total carbon emissions from the construction industry in Jiangsu Province, China. Journal of Cleaner Production, 276, 123179. https://doi.org/10.1016/j.jclepro.2020.123179

Li, D., Huang, G., Zhu, S., Chen, L., & Wang, J. (2021). How to peak carbon emissions of provincial construction industry? Scenario analysis of Jiangsu Province. Renewable and Sustainable Energy Reviews, 144, 110953. https://doi.org/10.1016/j.rser.2021.110953

Li, L., & Yang, J. (2020). A new method of energy-related carbon dioxide emissions estimation at the provincial-level: A case study of Shandong Province, China. Science of The Total Environment, 700, 134384. https://doi.org/10.1016/j.scitotenv.2019.134384

Li, R., & Jiang, R. (2017). Moving Low-Carbon Construction Industry in Jiangsu Province: Evidence from Decomposition and Decoupling Models. In SUSTAINABILITY (Vol. 9, Issue 6). MDPI. https://doi.org/10.3390/su9061013

Li, R., Yu, Y., Cai, W., Liu, Q., Liu, Y., & Zhou, H. (2023). Interprovincial differences in the historical peak situation of building carbon emissions in China: Causes and enlightenments. Journal of Environmental Management, 332, 117347. https://doi.org/10.1016/j.jenvman.2023.117347

Li, S., Wu, H., & Ding, Z. (2018). Identifying Sustainable Wood Sources for the Construction Industry: A Case Study. In SUSTAINABILITY (Vol. 10, Issue 1). MDPI. https://doi.org/10.3390/su10010139

Li, T., Gao, H., & Yu, J. (2022). Analysis of the spatial and temporal heterogeneity of factors influencing CO2 emissions in China’s construction industry based on the geographically and temporally weighted regression model: Evidence from 30 provinces in China. In

FRONTIERS IN ENVIRONMENTAL SCIENCE (Vol. 10). FRONTIERS MEDIA SA. https://doi.org/10.3389/fenvs.2022.1057387

Liang, Y., Cai, W., & Ma, M. (2019). Carbon dioxide intensity and income level in the Chinese megacities' residential building sector: Decomposition and decoupling analyses. In SCIENCE OF THE TOTAL ENVIRONMENT (Vol. 677, pp. 315–327). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.scitotenv.2019.04.289

Lin, B., & Liu, H. (2015). CO2 mitigation potential in China's building construction industry: A comparison of energy performance. In BUILDING AND ENVIRONMENT (Vol. 94, Issue 1, pp. 239–251). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.buildenv.2015.08.013

Lu, Y., Cui, P., & Li, D. (2016). Carbon emissions and policies in China's building and construction industry: Evidence from 1994 to 2012. Building and Environment, 95, 94–103. https://doi.org/10.1016/j.buildenv.2015.09.011

Lu, Y., Zhu, X., & Cui, Q. (2012). Effectiveness and equity implications of carbon policies in the United States construction industry. In BUILDING AND ENVIRONMENT (Vol. 49, pp. 259–269). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.buildenv.2011.10.002

Luo, T., Tan, Y., Langston, C., & Xue, X. (2019). Mapping the knowledge roadmap of low carbon building: A scientometric analysis. Energy and Buildings, 194, 163–176. https://doi.org/10.1016/j.enbuild.2019.03.050

Ma, D., Zhao, N., Zhang, F., Xiao, Y., Guo, Z., & Liu, C. (2022). Green Total-Factor Energy Efficiency of Construction Industry and Its Driving Factors: Spatial-Temporal Heterogeneity of Yangtze River Economic Belt in China. In INTERNATIONAL JOURNAL OF ENVIRONMENTAL RESEARCH AND PUBLIC HEALTH (Vol. 19, Issue 16). MDPI. https://doi.org/10.3390/ijerph19169972

Ma, J.-J., Liu, L.-Q., Su, B., & Xie, B.-C. (2015). Exploring the critical factors and appropriate polices for reducing energy consumption of China's urban civil building sector. In JOURNAL OF CLEANER PRODUCTION (Vol. 103, pp. 446–454). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2014.11.001

Ma, M., & Cai, W. (2018). What drives the carbon mitigation in Chinese commercial building sector? Evidence from decomposing an extended Kaya identity. In SCIENCE OF THE TOTAL ENVIRONMENT (Vol. 634, pp. 884–899). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.scitotenv.2018.04.043

Ma, M., & Cai, W. (2019). Do commercial building sector-derived carbon emissions decouple from the economic growth in Tertiary Industry? A case study of four municipalities in China. Science of The Total Environment, 650, 822–834. https://doi.org/10.1016/j.scitotenv.2018.08.078

Ma, M., Cai, W., & Cai, W. (2018). Carbon abatement in China’s commercial building sector: A bottom-up measurement model based on Kaya-LMDI methods. In ENERGY (Vol. 165, Issue A, pp. 350–368). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.energy.2018.09.070

Ma, M., Cai, W., Cai, W., & Dong, L. (2019). Whether carbon intensity in the commercial building sector decouples from economic development in the service industry? Empirical evidence from the top five urban agglomerations in China. In JOURNAL OF CLEANER PRODUCTION (Vol. 222, pp. 193–205). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2019.01.314

Ma, M., Feng, W., Huo, J., & Xiang, X. (2022). Operational carbon transition in the megalopolises’ commercial buildings. In BUILDING AND ENVIRONMENT (Vol. 226). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.buildenv.2022.109705

Ma, M., Ma, X., Cai, W., & Cai, W. (2019). Carbon-dioxide mitigation in the residential building sector: A household scale-based assessment. In ENERGY CONVERSION AND MANAGEMENT (Vol. 198). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.enconman.2019.111915

Ma, M., Ma, X., Cai, W., & Cai, W. (2020). Low carbon roadmap of residential building sector in China: Historical mitigation and prospective peak. In APPLIED ENERGY (Vol. 273). ELSEVIER SCI LTD. https://doi.org/10.1016/j.apenergy.2020.115247

Ma, M., Shen, L., Ren, H., Cai, W., & Ma, Z. (2017). How to Measure Carbon Emission Reduction in China’s Public Building Sector: Retrospective Decomposition Analysis Based on STIRPAT Model in 2000-2015. In SUSTAINABILITY (Vol. 9, Issue 10). MDPI. https://doi.org/10.3390/su9101744

Ma, M., Yan, R., & Cai, W. (2017). An extended STIRPAT model-based methodology for evaluating the driving forces affecting carbon emissions in existing public building sector: Evidence from China in 2000-2015. In NATURAL HAZARDS (Vol. 89, Issue 2, pp. 741–756). SPRINGER. https://doi.org/10.1007/s11069-017-2990-4

Ma, M., Yan, R., & Cai, W. (2018). Energy savings evaluation in public building sector during the 10th-12th FYP periods of China: An extended LMDI model approach. In NATURAL HAZARDS (Vol. 92, Issue 1, pp. 429–441). SPRINGER. https://doi.org/10.1007/s11069-018-3210-6

Ma, M., Yan, R., Du, Y., Ma, X., Cai, W., & Xu, P. (2017). A methodology to assess China’s building energy savings at the national level: An IPAT–LMDI model approach. Journal of Cleaner Production, 143, 784–793. https://doi.org/10.1016/j.jclepro.2016.12.046

Marey, H., Kozma, G., & Szabo, G. (2022). Effects of Using Green Concrete Materials on the CO2 Emissions of the Residential Building Sector in Egypt. In SUSTAINABILITY (Vol. 14, Issue 6). MDPI. https://doi.org/10.3390/su14063592

Mastrucci, A., Marvuglia, A., Benetto, E., & Leopold, U. (2020). A spatio-temporal life cycle assessment framework for building renovation scenarios at the urban scale. In RENEWABLE & SUSTAINABLE ENERGY REVIEWS (Vol. 126). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.rser.2020.109834

McNeil, M. A., Feng, W., de la Rue du Can, S., Khanna, N. Z., Ke, J., & Zhou, N. (2016). Energy efficiency outlook in China's urban buildings sector through 2030. Energy Policy, 97, 532–539. https://doi.org/10.1016/j.enpol.2016.07.033

Ministry of the Environment. (2023). Status of Local Governments' Declaration of Virtually Zero Carbon Dioxide Emissions by 2050. https://www.env.go.jp/policy/zerocarbon.html

Moynihan, M. C., & Allwood, J. M. (2012). The flow of steel into the construction sector. In RESOURCES CONSERVATION AND RECYCLING (Vol. 68, pp. 88–95). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.resconrec.2012.08.009

Nassen, J., & Holmberg, J. (2013). On the potential trade-offs between energy supply and end-use technologies for residential heating. In ENERGY POLICY (Vol. 59, pp. 470–480). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2013.03.059

Newell, R. G., & Pizer, W. A. (2008). Carbon mitigation costs for the commercial building sector: Discrete-continuous choice analysis of multifuel energy demand. In RESOURCE AND ENERGY ECONOMICS (Vol. 30, Issue 4, pp. 527–539). ELSEVIER SCIENCE BV. https://doi.org/10.1016/j.reseneeco.2008.09.004

Noailly, J., & Batrakova, S. (2010). Stimulating energy-efficient innovations in the Dutch building sector: Empirical evidence from patent counts and policy lessons. In ENERGY POLICY (Vol. 38, Issue 12, pp. 7803–7817). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2010.08.040

Oberheitmann, A. (2012). CO2-emission reduction in China's residential building sector and contribution to the national climate change mitigation targets in 2020. In MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE (Vol. 17, Issue 7, pp. 769–791). SPRINGER. https://doi.org/10.1007/s11027-011-9343-5

Pavkovic, B., Zanki, V., & Cacic, G. (2010). Energy Efficiency in Building Sector in Croatia—Preliminary Energy Studies. In STROJARSTVO (Vol. 52, Issue 6, pp. 681–694). UREDNISTVO CASOPISA STROJARTVO.

Pomponi, F., & Stephan, A. (2021). Water, energy, and carbon dioxide footprints of the construction sector: A case study on developed and developing economies. In WATER RESEARCH (Vol. 194). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.watres.2021.116935

Pu, X., Yao, J., & Zheng, R. (2022). Forecast of Energy Consumption and Carbon Emissions in China's Building Sector to 2060. In ENERGIES (Vol. 15, Issue 14). MDPI. https://doi.org/10.3390/en15144950

Roh, S., Tae, S., & Kim, R. (2018). Developing a Green Building Index (GBI) Certification System to Effectively Reduce Carbon Emissions in South Korea's Building Industry. In SUSTAINABILITY (Vol. 10, Issue 6). MDPI. https://doi.org/10.3390/su10061872

Roy, K., Su, R., Dani, A. A., Fang, Z., Liang, H., & Lim, J. B. P. (2022). Spatiotemporal Model to Quantify Stocks of Metal Cladding Products for a Prospective Circular Economy. In APPLIED SCIENCES-BASEL (Vol. 12, Issue 9). MDPI. https://doi.org/10.3390/app12094597

Satre-Meloy, A., & Langevin, J. (2019). Assessing the time-sensitive impacts of energy efficiency and flexibility in the US building sector. In ENVIRONMENTAL RESEARCH LETTERS (Vol. 14, Issue 12). IOP PUBLISHING LTD. https://doi.org/10.1088/1748-9326/ab512e

Saynajoki, A., Heinonen, J., Junnila, S., & Horvath, A. (2017). Can life-cycle assessment produce reliable policy guidelines in the building sector? In ENVIRONMENTAL RESEARCH LETTERS (Vol. 12, Issue 1). IOP PUBLISHING LTD. https://doi.org/10.1088/1748-9326/aa54ee

Shan, Y., Guan, D., Liu, J., Mi, Z., Liu, Z., Liu, J., Schroeder, H., Cai, B., Chen, Y., Shao, S., & Zhang, Q. (2017). Methodology and applications of city level CO2 emission accounts in China. Journal of Cleaner Production, 161, 1215–1225. https://doi.org/10.1016/j.jclepro.2017.06.075

Shi, Q., Chen, J., & Shen, L. (2017). Driving factors of the changes in the carbon emissions in the Chinese construction industry. Journal of Cleaner Production, 166, 615–627. https://doi.org/10.1016/j.jclepro.2017.08.056

Solis-Guzman, J., Rivero-Camacho, C., Alba-Rodriguez, D., & Martinez-Rocamora, A. (2018). Carbon Footprint Estimation Tool for Residential Buildings for Non-Specialized Users: OERCO2 Project. In SUSTAINABILITY (Vol. 10, Issue 5). MDPI. https://doi.org/10.3390/su10051359

Su, Y., Miao, Z., Wang, L., & Wang, L. (2022). Energy consumption and indoor environment evaluation of large irregular commercial green building in Dalian, China. Energy and Buildings, 276, 112506. https://doi.org/10.1016/j.enbuild.2022.112506

Sun, Z., Ma, Z., Ma, M., Cai, W., Xiang, X., Zhang, S., Chen, M., & Chen, L. (2022). Carbon Peak and Carbon Neutrality in the Building Sector: A Bibliometric Review. In BUILDINGS (Vol. 12, Issue 2). MDPI. https://doi.org/10.3390/buildings12020128

Tan, X., Lai, H., Gu, B., Zeng, Y., & Li, H. (2018a). Carbon emission and abatement potential outlook in China's building sector through 2050. Energy Policy, 118, 429–439. https://doi.org/10.1016/j.enpol.2018.03.072

Tan, X., Lai, H., Gu, B., Zeng, Y., & Li, H. (2018b). Carbon emission and abatement potential outlook in China's building sector through 2050. In ENERGY POLICY (Vol. 118, pp. 429–439). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2018.03.072

Tang, B., Zou, Y., Yu, B., Guo, Y., & Zhao, G. (2021). Clean heating transition in the building sector: The case of Northern China. In JOURNAL OF CLEANER PRODUCTION (Vol. 307). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2021.127206

UN Department of Economic and Social Affairs. (2017, June 21). World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100 [Interview]. https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html

United Nations. (2020). Cities and Pollution. https://www.un.org/en/climatechange/climate-solutions/cities-pollution

Wang, J., Wang, Z., Peng, S., Li, C., & Wei, L. (2020). Tracing CO2 emissions of China's construction sector. In JOURNAL OF CLEANER PRODUCTION (Vol. 275). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2020.124165

Wang, J., You, K., Qi, L., & Ren, H. (2022). Gravity center change of carbon emissions in Chinese residential building sector: Differences between urban and rural area. In ENERGY REPORTS (Vol. 8, pp. 10644–10656). ELSEVIER. https://doi.org/10.1016/j.egyr.2022.08.208

Wang, Y., & Wu, X. (2022). Research on High-Quality Development Evaluation, Space-Time Characteristics and Driving Factors of China's Construction Industry under Carbon Emission Constraints. In SUSTAINABILITY (Vol. 14, Issue 17). MDPI. https://doi.org/10.3390/su141710729

Wang, Y.-K., Liang, Y., & Shao, L.-S. (2022). Regional differences and influencing factors of the carbon emission efficiency from public buildings in China. In FRONTIERS IN ENVIRONMENTAL SCIENCE (Vol. 10). FRONTIERS MEDIA SA. https://doi.org/10.3389/fenvs.2022.962264

Wang, Z., Zhou, Y., Zhao, N., Wang, T., & Zhang, Z. (2022). Spatial Correlation Network and Driving Effect of Carbon Emission Intensity in China's Construction Industry. In BUILDINGS (Vol. 12, Issue 2). MDPI. https://doi.org/10.3390/buildings12020201

Wen, Q., Chen, Y., Hong, J., Chen, Y., Ni, D., & Shen, Q. (2020). Spillover effect of technological innovation on CO2 emissions in China's construction industry. In BUILDING AND ENVIRONMENT (Vol. 171). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.buildenv.2020.106653

Wu, P., Song, Y., Zhu, J., & Chang, R. (2019). Analyzing the influence factors of the carbon emissions from China's building and construction industry from 2000 to 2015. Journal of Cleaner Production, 221, 552–566. https://doi.org/10.1016/j.jclepro.2019.02.200

Wu, Y., Chau, K. W., Lu, W., Shen, L., Shuai, C., & Chen, J. (2018). Decoupling relationship between economic output and carbon emission in the Chinese construction industry. In

ENVIRONMENTAL IMPACT ASSESSMENT REVIEW (Vol. 71, pp. 60–69). ELSEVIER SCIENCE INC. https://doi.org/10.1016/j.eiar.2018.04.001

Xiang, X., Ma, X., Ma, Z., Ma, M., & Cai, W. (2022). Python-LMDI: A Tool for Index Decomposition Analysis of Building Carbon Emissions. In BUILDINGS (Vol. 12, Issue 1). MDPI. https://doi.org/10.3390/buildings12010083

Xing, R., Hanaoka, T., & Masui, T. (2021). Deep decarbonization pathways in the building sector: China’s NDC and the Paris agreement. In ENVIRONMENTAL RESEARCH LETTERS (Vol. 16, Issue 4). IOP PUBLISHING LTD. https://doi.org/10.1088/1748-9326/abe008

Yang, T., Pan, Y., Yang, Y., Lin, M., Qin, B., Xu, P., & Huang, Z. (2017). CO2 emissions in China’s building sector through 2050: A scenario analysis based on a bottom-up model. In ENERGY (Vol. 128, pp. 208–223). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.energy.2017.03.098

Yang, X., Hu, M., Zhang, C., & Steubing, B. (2022). Urban mining potential to reduce primary material use and carbon emissions in the Dutch residential building sector. Resources, Conservation and Recycling, 180, 106215. https://doi.org/10.1016/j.resconrec.2022.106215

Zhang, L., Liu, B., Du, J., Liu, C., Li, H., & Wang, S. (2020). Internationalization trends of carbon emission linkages: A case study on the construction sector. In JOURNAL OF CLEANER PRODUCTION (Vol. 270). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jclepro.2020.122433

Zhang, S., Li, Z., Ning, X., & Li, L. (2021). Gauging the impacts of urbanization on CO2 emissions from the construction industry: Evidence from China. In JOURNAL OF ENVIRONMENTAL MANAGEMENT (Vol. 288). ACADEMIC PRESS LTD-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.jenvman.2021.112440

Zhang, X., & Wang, F. (2016). Hybrid input-output analysis for life-cycle energy consumption and carbon emissions of China’s building sector. In BUILDING AND ENVIRONMENT (Vol. 104, pp. 188–197). PERGAMON-ELSEVIER SCIENCE LTD. https://doi.org/10.1016/j.buildenv.2016.05.018

Zhang, Y., Yan, D., Hu, S., & Guo, S. (2019). Modelling of energy consumption and carbon emission from the building construction sector in China, a process-based LCA approach. In ENERGY POLICY (Vol. 134). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2019.110949

Zhao, Q., Gao, W., Su, Y., & Wang, T. (2023). Carbon emissions trajectory and driving force from the construction industry with a city-scale: A case study of Hangzhou, China. Sustainable Cities and Society, 88, 104283. https://doi.org/10.1016/j.scs.2022.104283

Zhou, N., Khanna, N., Feng, W., Ke, J., & Levine, M. (2018). Scenarios of energy efficiency and CO2 emissions reduction potential in the buildings sector in China to year 2050. Nature Energy, 3(11), 978–984. https://doi.org/10.1038/s41560-018-0253-6

Zhou, Y., Liu, W., Lv, X., Chen, X., & Shen, M. (2019). Investigating interior driving factors and cross-industrial linkages of carbon emission efficiency in China's construction industry: Based on Super-SBM DEA and GVAR model. JOURNAL OF CLEANER PRODUCTION, 241. https://doi.org/10.1016/j.jclepro.2019.118322

Zhu, C., Chang, Y., Li, X., & Shan, M. (2022). Factors influencing embodied carbon emissions of China's building sector: An analysis based on extended STIRPAT modeling. In ENERGY AND BUILDINGS (Vol. 255). ELSEVIER SCIENCE SA. https://doi.org/10.1016/j.enbuild.2021.111607

Zhu, C., Li, X., Zhu, W., & Gong, W. (2022). Embodied carbon emissions and mitigation potential in China's building sector: An outlook to 2060. In ENERGY POLICY (Vol. 170). ELSEVIER SCI LTD. https://doi.org/10.1016/j.enpol.2022.113222

Chapter 3

RESEARCH OBJECTS AND CARBON ACCOUNTING & ANALYSIS METHODS

CHAPTER 3: Research Objects and Carbon Accounting & Analysis Methods

Contents

3.1 Research Objects

This paper selects Hangzhou, China and Kitakyushu, Japan as research objects to conduct a study on carbon emissions from the city-scale construction industry as shown in figure3-1. Hangzhou is one of the core cities in the Yangtze River Delta region of China, while Kitakyushu is a core city in the Kitakyushu Industrial Area of Japan, which indicates that they share similar city statuses. Moreover, the two cities have similar urbanization rates and population rankings within their respective countries, indicating a certain degree of similarity and comparability.

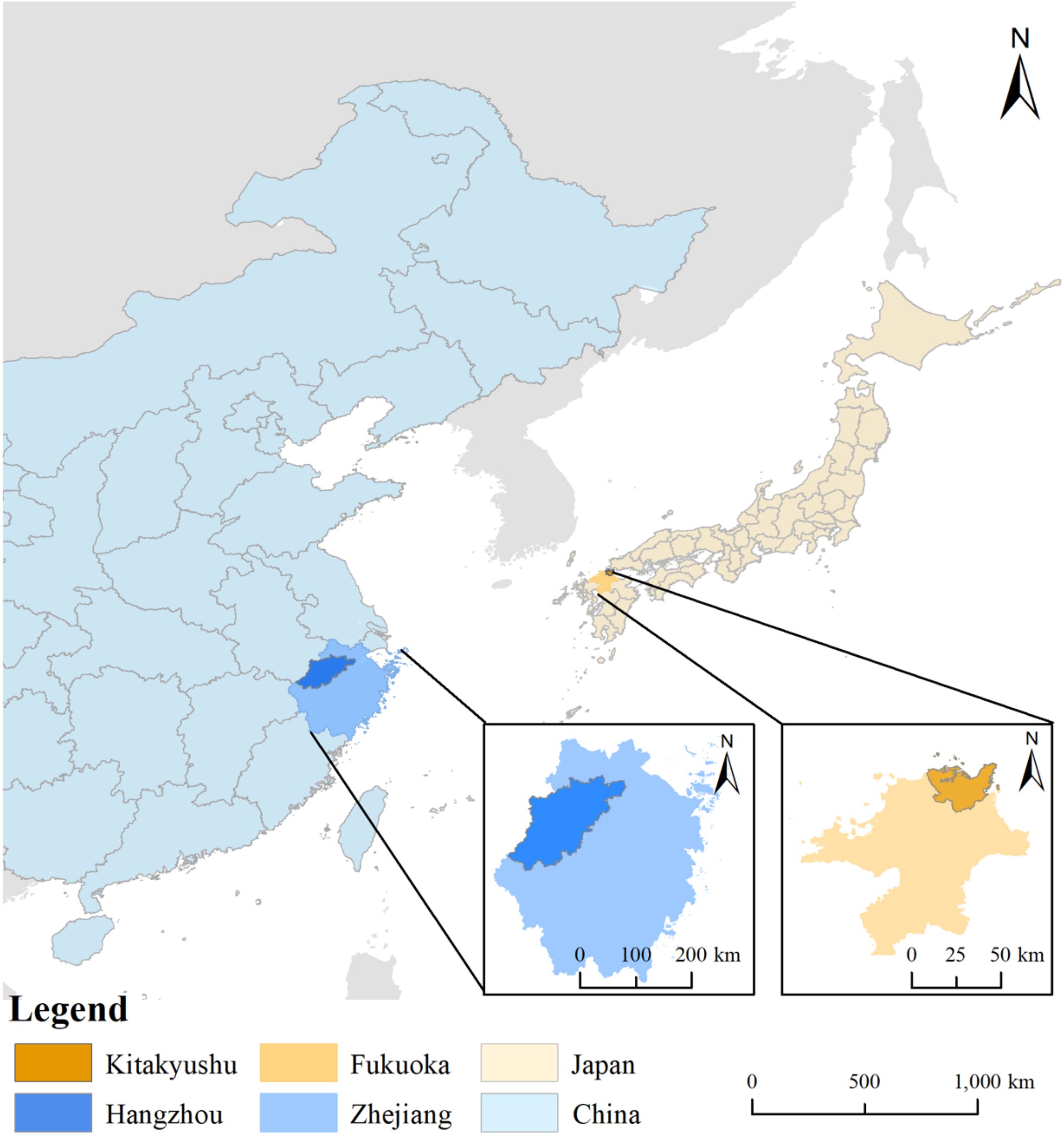


Fig.3-1 Research Objects

However, there are obvious differences in the development stages between Kitakyushu and Hangzhou. Kitakyushu is facing issues such as population decline, aging, and a severe problem of vacant buildings, and is in a stage of urban shrinkage. In contrast, Hangzhou is in a stage of rapid development, with an influx of migrants, a healthy population structure, a thriving construction industry, and constantly increasing building stock. In addition, Hangzhou has also merged with surrounding cities in recent years and is in a stage of rapid urban expansion.

Choosing these two cities as the research objects is helpful to compare and explore the effects of different factors on the carbon emissions of the construction industry, and to predict and investigate the implementation effects of decarbonization strategies for the construction industry in cities at different development stages.

3.1.1 The development of Hangzhou

Hangzhou is located in the eastern region of China and is under the jurisdiction of Zhejiang Province. Hangzhou is composed of 13 districts and counties with a total area of 16,850 km^2. As the provincial capital, Hangzhou has a current permanent population of 12.38 million people, ranking 11th in China in terms of population in 2022 and is one of the mega-cities in China.

(1) Population and urbanization development

Figure 3-2 shows the population and urbanization process of Hangzhou over the past 70 years.

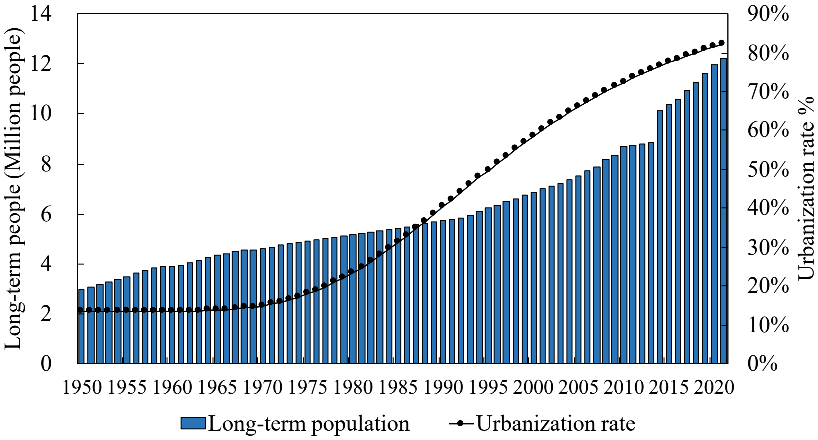


Fig.3-2 Population and urbanization development of Hangzhou

Since 1949, Hangzhou has experienced rapid urbanization and rapid population growth, gradually stabilizing. In 1949, when the People's Republic of China was founded, the population of Hangzhou was about 800,000. With the promotion of urbanization and industrialization, the population of Hangzhou began to grow rapidly. By 1953, the population of Hangzhou had reached 987,000. In 1964, it broke through the 2 million, reaching 2.097 million. Around1978, the population growth rate in Hangzhou slowed down, the population had only increased to 2.147 million. After the reform and opening-up policy, the population growth rate in Hangzhou accelerated again. By 1987, the population of Hangzhou had reached 3.5 million, making it a big city. Since then, the population of Hangzhou has continued to increase. By 2010, the population of Hangzhou had reached 8.1 million, becoming the largest city in Zhejiang Province.

In recent years, with the disappearance of the population dividend, the population growth rate in Hangzhou has slowed down. By 2020, the population of Hangzhou was 10.02 million, an increase of 0.7% over the previous year. The urban population was 6.87 million, accounting for 68.5% of the total population; the rural population was 3.16 million. Hangzhou's urbanization level is quite high, with urban residents becoming the main body of the population. It is expected that in the future, with the aging population and declining fertility rates, the population growth rate in Hangzhou will gradually slow down, and population growth will be mainly driven by in-migration.

(2) Economy development

As shown in figure 3-3, Hangzhou is currently in a critical period of rapid economic development. In the early days of the founding of the People's Republic of China, the economy of Hangzhou was mainly based on agriculture, with a GDP of only 260 million CNY. After the reform and opening-up in 1978, Hangzhou began to develop towards industrialization and modernization, with total GDP and per capita disposable income continuously increasing. By 1986, the GDP exceeded 10 billion CNY, and in 1997, it soared to over 100 billion CNY. In 2015, it broke through the trillion CNY, and in 2020, it reached 1.6 trillion CNY, ranking 8th among all cities in China.

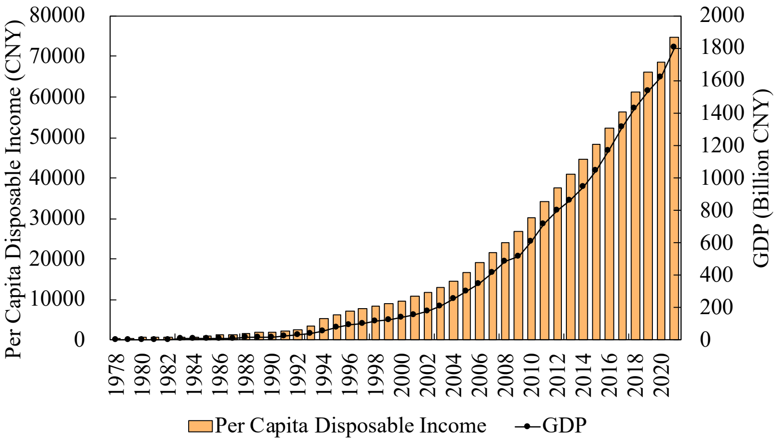


Fig.3-3 Economy development of Hangzhou

In recent years, Hangzhou has promoted major initiatives such as industrial revitalization, construction of two ports and three districts, implementation of a service-oriented priority, development of ten major economies, and the creation of a dual-engine of digital economy and new manufacturing. This has formed a good pattern with the service industry as the main driver and the coordination of the secondary and tertiary industries. Hangzhou has also made significant achievements in the construction of digital economy and smart cities. Currently, Hangzhou has become an important engine and innovation center for China's economic development, with significant improvements in residents' living standards and an annual average growth rate of per capita disposable income of 13.5%.

(3) The development of construction industry

Driven by the rapid urbanization in Hangzhou, the construction industry has received sufficient development. From the 1950s to the early 1970s, which was the initial stage of industrialization and urbanization in Hangzhou, the main task of the construction industry was to restore and rebuild urban infrastructure and housing. In the mid-1970s to the early 1990s, with the acceleration of urbanization, the government launched a series of urban construction plans and policies, including large-scale urban infrastructure construction, and the construction industry gradually played a role in the urbanization process.

Since the 2000s, Hangzhou has entered a new period of urbanization, and the construction industry has expanded rapidly. As shown in Figure 3-4, the gross output value increased from 100 billion CNY to 557 billion CNY from 2005 to 2021, an increase of 4.5 times. Building area increment can also reflect the scale and development speed of Hangzhou's construction industry, which increased from 110 million m^2 to about 331 million m^2.

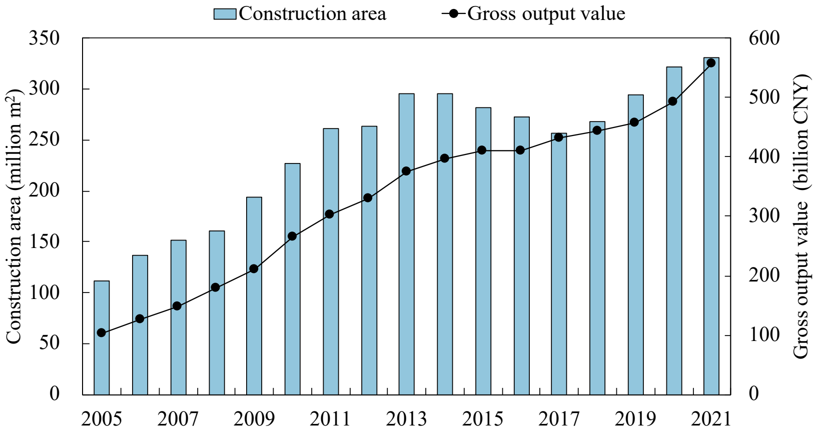


Fig.3-4 The development of construction industry in Hangzhou

In these 17 years, Hangzhou's construction industry development can be divided into 3 phases. From 2005 to 2010 the first phase, the building area increment continued to grow, with an annual growth rate of 17.4%. Correspondingly, the total output of construction has grown rapidly, with an average annual growth rate of 20.8%. It is generally believed that this growth is related to China's accession to WTO in 2001 and the "four trillion" economic stimulus plan proposed by the Chinese government in response to the 2008 world financial crisis (Wang and Feng, 2018).

In 2011, Hangzhou issued a Housing Limited Purchasing Order (HLPO), and the growth of building area increment began to slow down. With the implementation and strengthening of the HLPO, the building area increment began to decrease after 2014, and the period from 2011 to 2017 was regarded as the second stage. The third phase is from 2017 to 2021, Hangzhou won the right to host the Asian Games, and the construction of public buildings related to the Asian Games became the driving force for the building area increment and the growth of the total output value.

3.1.2 The development of Kitakyushu

Kitakyushu City is located at the northern end of Kyushu Island in Japan. It is the second largest city in Kyushu, with a population of 970,000, ranking 13th in Japan in terms of population. It was formed in 1963 by the merger of Moji, Kokura, Tobata, Yahata, and Wakamatsu. The city covers an area of 486.81 km^2. Kitakyushu City is an important industrial and port city in Japan.

(1) Urban development and population

In the early days of its establishment, Kitakyushu implemented a strategy of balanced development guided by the “Multi-Core City Theory” in urban planning. However, due to the high cost of the policy and economic downturn, the strategy of balanced development became difficult to sustain. In 1988, Kitakyushu proposed the concept of “Cultural and Artistic Renaissance,” with Kokura Station as the urban center and Kurosaki Station as the sub-core, shifting from a balanced development route to a centralized city, and significantly changing its policy direction. Currently, Kitakyushu focuses on industries such as technology, environmental protection, and tourism, and was selected as Asia’s first “Green Growth Demonstration City” in 2011.

In 1963, when five cities were merged to form the city of Kitakyushu, its population was 1,032,648, making it the largest city in Fukuoka Prefecture and Kyushu, the seventh largest city in Japan, and the most populous city outside of the three major metropolitan areas. However, due to its heavy industry-based economy, Kitakyushu experienced slow economic growth and a severe outflow of population, resulting in a relatively slow increase in its population. The city’s population peaked in 1979 and has been declining steadily since then, with the population being surpassed by that of Fukuoka City during this period. The decline in Kitakyushu’s population accelerated during the bubble economy period and, although it slowed down in the 1990s, it started to accelerate again in the 2000s. After 2003, the natural growth rate of Kitakyushu’s population turned negative due to aging and low birthrates, and the population fell below one million in 2005. As of 2020, the population of Kitakyushu is only 935,744, as shown in Figure 3-5.

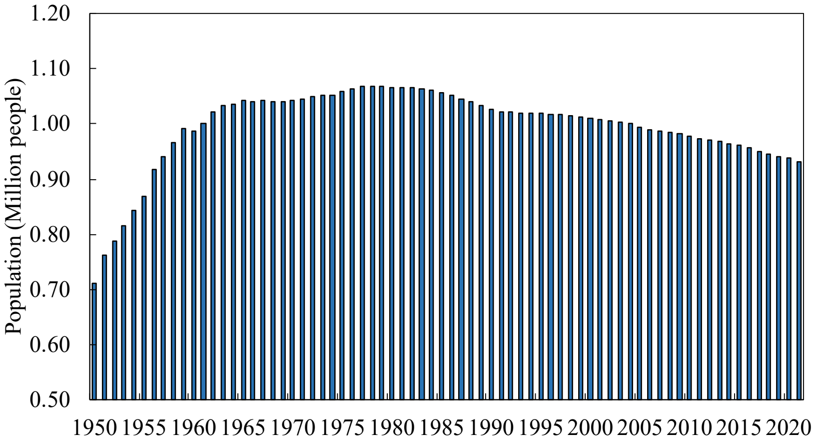


Fig.3-5 Population development of Kitakyushu

Kitakyushu is facing a shortage of young labor resources. With the trend of aging population becoming more serious, young talents are leaving. Kitakyushu City has created a certain gap with neighboring cities and is one of the fastest shrinking cities in Japan in terms of population.

(2) Economy development

Kitakyushu is one of the earliest industrialized cities in Japan. Since the 1950s, Kitakyushu has initiated a series of industrialization and modernization projects, with heavy and chemical industries reaching an advanced level in Japan at that time. During this period, Kitakyushu's economy grew rapidly, with industrial output continuously increasing, becoming an important engine for economic development in the Kyushu region and contributing to Japan's economic growth. In 2014, Kitakyushu's gross domestic product reached 3.5 trillion JPY, of which the secondary industry accounted for about a quarter, with steel and chemical industries having the highest proportion in the industrial sector.

Along with rapid industrialization and high economic growth, Kitakyushu also faced serious environmental pollution problems. With the efforts of the people and the government, Kitakyushu's natural environment has greatly improved. Kitakyushu fully utilized the experience, technology, and skills gained in overcoming pollution problems to carry out international assistance in environmental protection for developing countries, promote the construction of environmental protection cities for waste Reduction, Reuse, and Recycling (3R), and implement environmental policies to build a "Low-carbon Society". Currently, resource recycling and environmental protection industries have become important pillar industries in Kitakyushu.

However, in recent years, Kitakyushu's export market has encountered difficulties due to fluctuations in the world economy and the rise of low-cost countries. Especially for traditional heavy industries such as steel and chemicals, the export market has been continuously suppressed by trade protectionism policies, resulting in a decline in market share and a weakened economic growth momentum. At the same time, the development of emerging industries has been slow. Although Kitakyushu actively promotes the development of emerging industries, its limited innovation capacity and the difficulty in expanding the market have slowed the pace of their development.

(3) The development of construction industry

As an important industrial city, Kitakyushu attracted a large influx of population during the period of rapid economic development in Japan. With the increase in urban population, there was a sharp rise in demand for construction, and the building stock in Kitakyushu showed a rapid growth trend. In addition, stimulated by policies such as the Olympics and government building bonds, the new construction area in Kitakyushu reached a peak of about 2.21 million square meters in 1990, as shown in Figure 3-6.

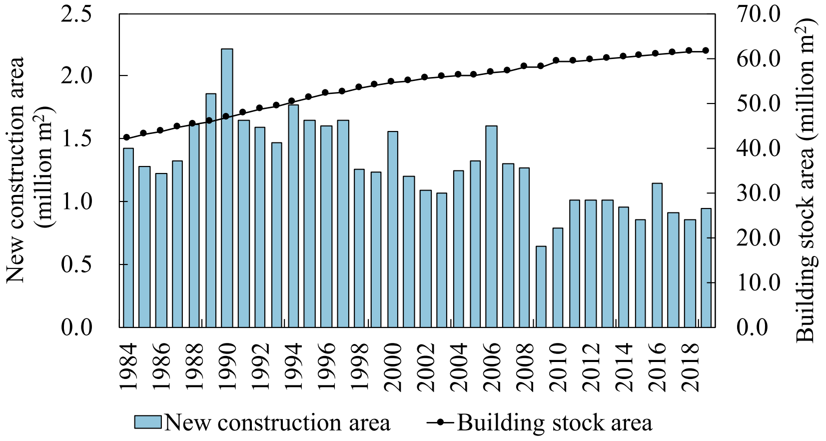


Fig.3-6 The development of construction industry in Kitakyushu

After 1991, Japan experienced the burst of the economic bubble, leading to long-term economic stagnation, and Kitakyushu was severely affected, with its population gradually decreasing. Although policy incentives led to several peaks in new construction area in Kitakyushu, the overall trend of population decline slowed the growth of total building stock. However, the building stock still showed a slow upward trend, with an average annual growth rate of 1.09%. By 2014, the building stock area had surpassed 60 million m^2.

As the population continues to decline, there are many vacant buildings in the city. These vacant buildings not only waste limited resources and become important factors restricting the development of Kitakyushu's construction industry, but also have negative impacts on the urban environment and social stability. Therefore, how to deal with these vacant buildings has become a major problem facing the construction industry in Kitakyushu.

3.2 Carbon emission scopes and boundaries

3.2.1 Standard

The definition of Greenhouse Gas emission boundaries is usually based on the *Greenhouse Gas Protocol* introduced by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) in 1998 (Greenhouse Gas Protocol, 2016). It is composed of a series of standards, guidelines and calculation tools that serve enterprises, organizations, projects, etc. to quantify and report GHG emissions. These standards, guidelines and tools are independent and complementary to each other, and are the basis for enterprises, organizations, projects, etc. to account for and report GHG emissions in order to help the world reach the goal of developing a low-carbon economy. *Greenhouse Gas Protocol* covers the accounting of six greenhouse gases under the *Kyoto Protocol*: Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulfur hexafluoride (SF_6).

The *GHG Protocol* provides standards for the development of GHG emission boundaries. For an accounting enterprise or sector, the GHG accounting system consists of three parts: *Greenhouse Gas Protocol: Technical Guidance for Calculating Scope 3 Emissions (2011)*, *Greenhouse Gas Protocol: Product Life Cycle Accounting and Reporting Standard (2011)* and *Greenhouse Gas Protocol: Corporate Value Chain (Scope 3) Accounting and Reporting Standard (2011)*. These three parts are referred to as *"Enterprise Standard"*, *"Product Standard"*, and *"Scope III Standard"* for short.

There is a certain relationship between these three standards that is linked and complementary， such as Fig.3-7. The "*Scope III Standard"* is based on the *"Enterprise Standard"* to supplement the specification of the GHG situation in Scope 3 of the *"Enterprise Standard",* and the two are in a complementary relationship. The *"Product Standard"* accounts for GHG emissions over the product life cycle for individual products and identifies the best mitigation opportunities over the product's life cycle. It is complementary to the other two standards as a value chain accounting perspective. (Greenhouse Gas Accounting and Reporting, 2022). These three standards provide a comprehensive approach to GHG accounting based on different accounting boundaries. Using the three standards wisely, carbon emissions can be accounted for at various scales, including products, sectors, and enterprises.

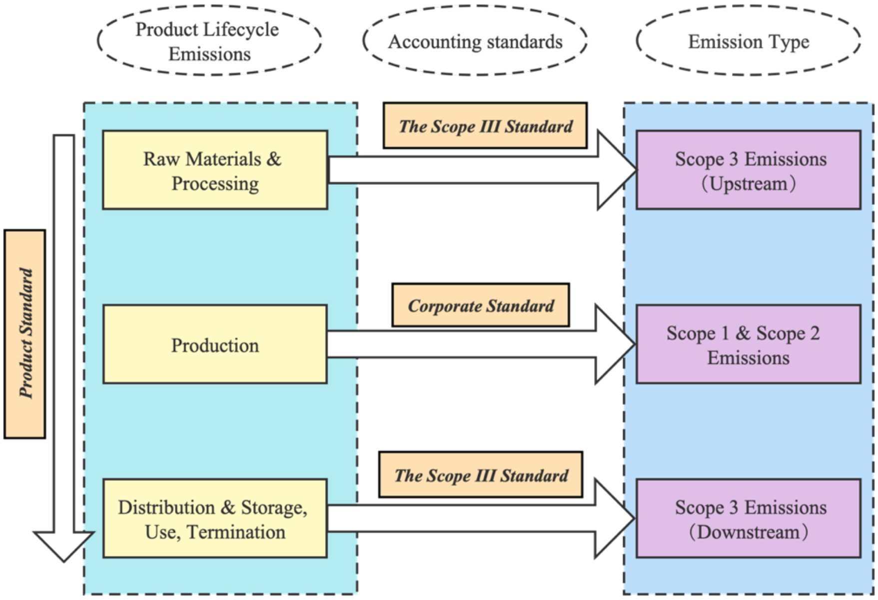


Fig.3-7 Diagram of the relationship between three Standards

3.2.2 Scopes

In order to better distinguish GHG emission boundaries and avoid double counting, the GHG accounting system subdivides GHG emissions into three “Scope” (Greenhouse Gas Accounting and Reporting, 2022), such as Fig.3-8.

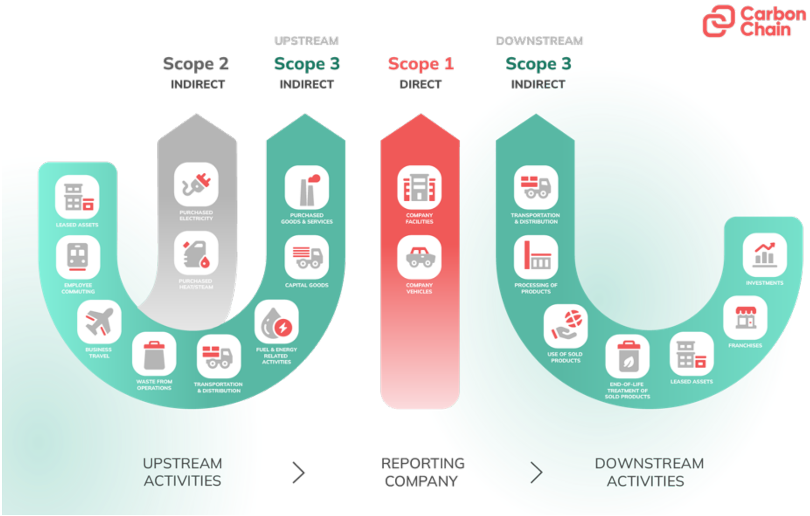


Fig.3-8 Boundary and relationship of Scope 1, 2, 3

Source: Carbon Chain

Scope 1 is emissions that are within the control of the entity and originate from stationary combustion, mobile combustion, fugitive emissions due to unintentional release of gases, and industrial or manufacturing processes and are classified as direct emissions.

Scope 2 is emissions from electricity consumption under the control of the entity, including emissions from the purchase of electricity, steam, heating and cooling, which are classified as indirect emissions. For many companies or sectors accounted for, purchased electricity is one of the largest sources of GHG emissions and the most significant opportunity to reduce GHG emissions. By accounting for Scope 2 emissions, companies can assess the risks and opportunities associated with changes in electricity use and GHG emissions costs(Wiedmann et al., 2021).

Scope 3 involves emissions from the use of manufactured products, employee commuting, travel, etc., and is classified as other indirect emissions. Typically, this includes upstream emissions and downstream emissions. Of these, upstream emissions are from purchased goods and services, capital goods, fuel and energy-related activities, upstream transportation and distribution, and so on. Downstream emissions include downstream transportation and distribution, processing of sold products, use of sold products and so on.(Greenhouse Gas Accounting and Reporting, 2022).

Although most GHG accounting will be detailed based on Scope 1 and Scope 2, Scope 3 value chain emissions are much larger than the sum of Scope 1 and Scope 2, and the scale of emissions should not be underestimated. By accounting for Scope 3 emissions, the entire value chain can be effectively assessed and opportunities for emission reductions can be identified(Alvarez et al., 2019; Harris, 2015; Reavis et al., 2022).

In actual accounting, due to the variability of emission boundaries, GHG emissions are usually categorized into direct and indirect emissions in order to better distinguish emission sources(ISO 14064, 2018). Direct emissions are carbon emissions from the combustion of fossil fuels and industrial processes at facilities or equipment owned or controlled by an organization. This includes fuel emissions from direct heating, electricity, domestic hot water, steam use, etc.(Luo et al., 2019). The direct carbon emissions usually correspond to the GHG emissions with Scope 1. Indirect emissions are carbon emissions from the use or consumption of electricity, heat, cooling and steam from external sources which belong to Scope 2 and greenhouse gas emissions from upstream and downstream production activities which belong to Scope 3. The thermal component includes heat input from cogeneration and district boilers (Daryanto & Setyanto, 2023).

The carbon emission relationship between the construction industry and the upstream and downstream sectors is the focus of this paper. Therefore, this paper defines the carbon emissions from the construction industry in the construction site as direct carbon emissions, and the carbon emissions from the upstream sector due to the demand of the construction industry as indirect carbon emissions. Accordingly, all 3 scopes of carbon emissions are accounted for in this paper.

3.2.3 Boundaries

In terms of the building life cycle, buildings can usually be divided into phases such as design, material production, site construction, building operation, renovation, and demolition (Wang et al., 2020). In this paper, the building life cycle is divided into materialization stage, operational stage, and demolition stage as shown in Figure 3-9. For these 3 stages, the carbon emissions during the building operation stage is not include in this study. In Chapter 4, the carbon emission of materialization stage and demolition stage will be calculated by Top-down way. In Chapter 5, the carbon emissions in materialization stages were calculated by Bottom-up way. Chapter 6 use Bottom-up way calculated the demolition stage carbon emissions.

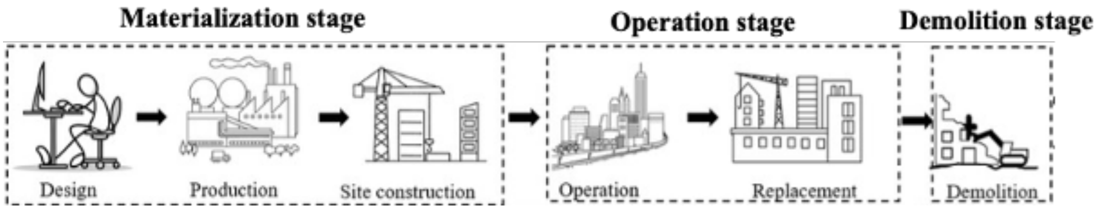


Fig.3-9 Building life cycle

Adapted from Wang He(Wang et al., 2020)

3.3 Carbon accounting methodology

The main forms of carbon accounting can be divided into two categories: measurement-based and calculation-based. Specifically, based on the existing methods for calculating greenhouse gas emissions, there are three main approaches: carbon emission factor method, mass balance method, and measurement-based method. This study employs the emission factor method to conduct research on carbon emissions in the construction industry.

According to the logic of carbon accounting, the accounting can be divided into top-down and bottom-up ways. As shown in the Figure 3-10, it provides an explanation of these two accounting logics. The purpose is the same, which is to calculate the carbon emissions for Sector 1.

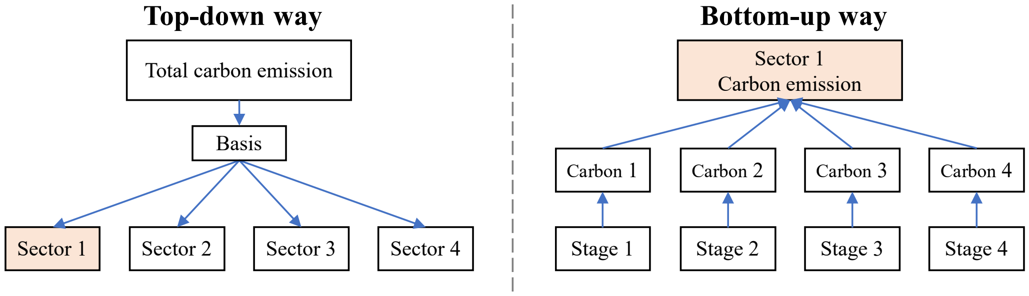


Fig.3-10 Explanation of these two accounting logics

In the top-down way, the total carbon emissions are calculated based on statistical data Then, the total carbon emissions are allocated to various departments based on criteria such as output value. In the bottom-up way, the carbon emissions process of the sector 1 is divided into several stages, and the carbon emissions for each stage are calculated separately. Finally, the carbon emissions for each stage are accumulated.

The input-output method used in chapter 4 is a top-down way to carbon accounting. The process-based life-cycle way is considered to be a bottom-up accounting way.

3.3.1 Carbon emission factor method

(1) IPCC and IPCC Guidelines

Carbon dioxide escapes very quickly and is present in large quantities in the air, making it difficult to capture directly. Therefore, the measurement method is not suitable for carbon emission accounting in the construction industry. Carbon emission factor methods based on fossil energy consumption statistics and fossil energy carbon emission factors are often used. This method is the most widely used carbon emission accounting method and often referred to as the IPCC method because it usually uses the carbon emission factors provided in the *IPCC Guidelines for National Greenhouse Gas Inventories*.

the *IPCC Guidelines for National Greenhouse Gas Inventories* is published by the Intergovernmental Panel on Climate Change (IPCC) in 2006 (IPCC, 2006). The IPCC was created in 1988 jointly by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) with the primary purpose of scientifically assessing climate change, including assessing its magnitude, temporal changes, potential environmental and socio-economic impacts, and proposing response strategies for climate change mitigation.

In 1996, the IPCC prepared and published the first edition of *the Guidelines for National Greenhouse Gas Emission Inventories*, which defined for the first time the categories of greenhouse gases, emission sources and sinks, thus establishing a largely consistent range for national greenhouse gas emission estimates. In the following years, the IPCC prepared the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, *Good Practice Guidance and Uncertainty Management for National Greenhouse Gas Inventories*, and *Good Practice Guidance for Land Use, Land-Use Change and Forestry*, etc. These provisions were finally assembled into *the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.*

The IPCC 2006 Guidelines for National Greenhouse Gas Inventories is by far the most widely accepted and widely used guide to national-level greenhouse gas emissions inventories. The version of the report currently in use was published in 2006, which was updated in 2019 to focus on supplementing GHG emission sources and carbon sinks not covered in IPCC 2006, identifying discrepancies arising from the emergence of new and emerging technologies and production processes, and updates to emission factors.

(2) Introduction of the method

The carbon emission factor is the amount of carbon emissions per unit of energy produced during the combustion or use of each energy source, and it usually refers to the emission factor of carbon dioxide. The carbon emission factor of an energy source can generally be considered to be fixed during use(IPCC, 2006).

The *IPCC 2006 Guidelines for National Greenhouse Gas Inventories* cover gases that contribute to the greenhouse effect, such as CO_2, CH_4, N_2O, HFCs, and PFCs. In the total warming effect of greenhouse gases, CO_2 contributes about 63%, CH_4 about 18%, N_2O about 6%, and other contributions about 13%. To unify the results of measuring the overall greenhouse effect, carbon dioxide equivalent is specified as the basic unit for measuring the greenhouse effect (*AR4 Climate Change 2007*).

According to the basic method of carbon accounting provided by IPCC, according to the carbon emission inventory list, the activity data for each carbon source composition (consumption of each fossil fuel, consumption of limestone raw material, net purchased electricity, net purchased steam, etc.) and the factor corresponding to the activity (carbon content per unit calorific value, carbon content, oxidation rate, etc.), and the product of the two is the emission estimate for that carbon emission item, as in Equation 3-1 and 3-2.

$$CE = AD \times EF \tag{3-1}$$

$$EF = NCV \times CC \times CO \times R \tag{3-2}$$

Where, CE denotes carbon emission (tons CO_2), AD denotes fossil energy consumption (tons or 10^4 m^3), EF denotes carbon emission factor (tons CO_2/tons or tons $CO_2/10^4$ Nm^3), NCV denotes unit fossil fuel calorific value (GJ/tons, GJ/10^4Nm^3), CC denotes carbon content per unit calorific value (tons C/GJ), CO denotes carbon oxidation rate (%), R denotes relative atomic ratio of carbon dioxide to carbon, 44/12.

Table 3-1 Selected energy carbon emission factors in China

Fuel	Unit	NCV (GJ/t, GJ/10^4Nm^3)	CC (t C/GJ)	CO (%)	EF (t CO_2/t, t $CO_2/10^4Nm^3$)
Crude Oil	t	41.8	0.0201	98	3.02
Fuel Oil	t	41.8	0.0211		3.17
Gasoline	t	43.1	0.0189		2.93
Kerosene	t	43.1	0.0196		3.04
Diesel	t	42.7	0.0202		3.10
LPG	t	50.2	0.0172		3.10
LNG	t	51.5	0.0172		3.18
Refinery dry gas	t	46.0	0.0182		3.18
Natural Gas	10^4Nm^3	389.3	0.0153	99	21.62
Coke oven gas	10^4Nm^3	173.5	0.0121		7.62
Blast furnace gas	10^4Nm^3	33.0	0.0708		8.48
Converter gas	10^4Nm^3	84.0	0.0496		15.12
Other gas	10^4Nm^3	52.27	0.0122		2.31

Table 3-2 Selected energy carbon emission factors in Japan

Fuel	Unit	NCV (MJ/kg, MJ/L, MJ/ Nm^3)	CC (kg C/MJ)	EF (kg CO_2/kg, kg CO_2/L, kg CO_2/Nm^3)
Coal	kg	25.7	0.0247	2.33
Kerosene	L	36.7	0.0185	2.49
Gasoline	L	34.6	0.0183	2.32
Crude Oil	L	38.2	0.0187	2.38
Fuel Oil A	L	39.1	0.0189	2.71
Fuel Oil C	L	41.9	0.0195	3.00
Light Oil	L	37.7	0.0187	2.58
Coal Tar	kg	37.3	0.0209	2.86
LPG	kg	50.8	0.0161	3.00
LNG	kg	54.6	0.0135	2.70
City gas	Nm^3	44.8	0.0136	2.23
Coke oven gas	Nm^3	21.1	0.0110	0.851
Blast furnace gas	Nm^3	3.41	0.0263	0.329
Converter gas	Nm^3	8.41	0.0384	1.18

The carbon emission factor method is highly dependent on carbon emission factors. due to differences in technology, fossil energy use, etc., the actual carbon emission often differs from the carbon emissions accounted for through the IPCC carbon emission factor. To enhance the accuracy of accounting results, many countries or industries publish dedicated carbon emission factors. Chapters 5, 6, and 7 of this paper examine the carbon emissions of the construction industry in Japan and China. As shown in Table 3-1, the data related to carbon emission factors in China are obtained from *China Energy Statistical Yearbook*, *Guidelines for the Preparation of Provincial Greenhouse Gas Inventories (Trial)* and *China Greenhouse Gas Inventory Study*. The data related to carbon emission factors in Japan are obtained from *Standard Heat and Carbon Emission Factors by Energy Source (Revised 2013)*, as shown in Table 3-2.

3.3.2 Input-output theory and models

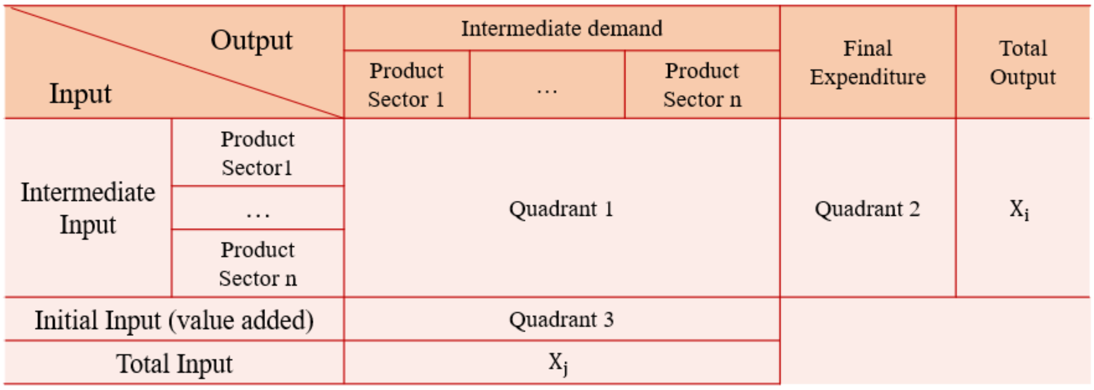
(1) Concepts and development

The Input-Output (IO) model is a quantitative economic model that was originally developed by the American economist Wassily W. Leontief to study economic issues. The IO model has evolved into many variations over time. It can be classified based on different measurement methods as physical and monetary models, as well as dynamic and static models. Furthermore, depending on the scope and scale of the research, it can be applied to national, regional, interregional, sectoral, and enterprise-specific models. With the help of IO models, specialized social issues research can be conducted, such as environmental pollution, population, and world economic structure. This method is known as input-output analysis.

An economy in a region, country, or the world as a whole is an organic whole composed of many economic sectors. The production and distribution of goods and services among these sectors involve complex economic and technical relationships. Each sector has a dual role: on the one hand, it provides products to other sectors as production inputs or to society as consumer goods, investment goods, and exports; on the other hand, its production process also requires inputs from other sectors or from its own production and imports. By preparing input-output tables and models, the inherent connections among various sectors and industrial structures in the national economy can be clearly revealed. It can reflect the direct and indirect relationships between sectors and industries in the production process, as well as the balance relationship between production and distribution, and between production and consumption. Therefore, the Input-Output (IO) model is also known as the interindustry balance method. Furthermore, the IO model can be widely applied to the analysis of similar issues in various regions, sectors of the national economy, and enterprises. When used for regional problems, it reflects the inherent connections among different parts within the region; when used for a particular sector, it reflects the inherent connections among different types of products within that sector; when used for a company or enterprise, it reflects the inherent connections among various processes within it.

(2) Input-output table

The input-output model is represented in the form of tables and is therefore also called an input-output table. There are two types of input-output tables: physical and value-based. An input-output table uses a checkerboard-like table to reflect the product flow between different sectors of the national economy from the perspectives of product output and distribution, usually over a period of one year. The product figures come from statistical data to ensure accuracy. The table can be compiled based on the physical quantity of products or their value. Each method has its practical value. Fig.3-11 shows the format of the input-output table.



Output Input		Intermediate demand			Final Expenditure	Total Output
		Product Sector 1	…	Product Sector n		
Intermediate Input	Product Sector1	Quadrant 1			Quadrant 2	X_i
	…					
	Product Sector n					
Initial Input (value added)		Quadrant 3				
Total Input		X_j				

Fig.3-11 Input-output table

The rows and columns in the input-output table intersect to form three quadrants. The Quadrant 1 represents the value of the products produced by a sector and distributed to other sectors as intermediate products or intermediate use; the column direction represents the value of the products consumed by a sector in the production process from other sectors, also known as input or intermediate consumption. The Quadrant 2 quadrant is formed by the intersection of the rows of each sector and the columns of the final products, reflecting the composition of the final products. The Quadrant 3 is formed by the intersection of the rows of sectors that create new value and the columns of all other sectors, reflecting the initial distribution of income.

(3) Regional input-output table

Regional input-output table is an input-output model prepared for a specific region, which is a component of the overall input-output model. It reflects the comprehensive balance between the production technology linkages and supply and demand among various relevant departments within the region, as well as the generation and distribution of national income in the region. It can be used to predict and analyze various technical and economic issues within the region and between the region and the overall. Depending on the scale of research, the regional-level model is divided into a single-region model, a model between regions, and a balanced regional model.

Compared to a single-region input-output table, the main difference of inter-regional input-output tables, as shown in Figure 3-12, lies in the further breakdown of intermediate usage, intermediate input, and final demand by region, resulting in a greater amount of information included. It allows for the identification of inter-regional connections and other related contents among different regional industries, but also presents a greater challenge in compilation. The inter-regional input-output table is a multi-regional input-output table that not only describes input-output flows but also calculates the impact of demand on regional economies. It comprehensively reflects the production processes and economic relationships among different regions, making it an important method for regional economic research.

In terms of structure, the multi-regional input-output model develops the input-output structure of each sector in each region separately. Thus, in terms of rows, it reflects the distribution of each region’s sectoral products among different sectors in different regions and various final demands. In terms of columns, it reflects the production inputs of each sector in each region from different sectors in different regions and the source structure of each region’s various final demands from different regions and sectors. In terms of content, the multi-regional input-output model endogenizes the exchange of products and services between regions. In the intermediate products section, it records in detail the input and use of each region’s sectoral products within its own region and in other regions.

Output Input			Intermediate demand							Final Expenditure	Total Output
			Region A			…	**Region Z**				
			Sector A-1	…	Sector A-n	…	Sector Z-1	…	Sector Z-n		
Intermediate Input	**Region A**	Sector A-1	Quadrant 1							Quadrant 2	X_i
		Sector A-n									
	…	…									
	Region Z	Sector Z-1									
		Sector Z-n									
Initial Input (value added)			Quadrant 3								
Total Input			X_j								

Fig.3-12 Multi-regional input-output table

Constructing an MRIO table is a time-consuming and labor-intensive task. It requires a clear understanding of the supply and demand situation in each region, based on a large amount of basic data, on top of the regional input-output tables. Secondly, by using regional trade data, the flow of goods between regions is endogenized and connected and adjusted according to the same sector classification, resulting in an input-output model. Therefore, the MRIO model can more comprehensively and systematically reflect the economic situation and connections between countries or regions. In recent years, the MRIO model has been widely used as a tool to track supply chain spillover effects and identify regional heterogeneity, making it an important means of evaluating consumption footprints, sectoral intensities, and conducting trade analysis. Chapter 5 of this paper will use China's Multi-Regional Input-Output (MRIO) model to calculate the carbon footprint of Hangzhou city.

(4) Input-output analysis

Input-output analysis is a quantitative analysis based on the balance relationships in the input-output table. To conduct input-output analysis, it is necessary to first understand the following main coefficients and matrices.

The direct consumption coefficient refers to the value of goods or services consumed directly by a department in the production process per unit of total output, from various other departments. Specifically, the direct consumption coefficient refers to the value of goods or services produced by the i sector, directly consumed by the output of the product sector in the production process. The direct consumption coefficients of each product sector can be represented in matrix form, which is called the direct consumption coefficient matrix and is usually denoted by the A.

$$A_{ij} = \frac{x_{ij}}{x_j}(i,j = 1,2,\dots,n) \tag{3-3}$$

Where, A_{ij} denotes the direct consumption coefficient of sector j for sector i, X_{ij} denotes the value of the product of sector i consumed in the production of sector j, X_j denotes the sector j total inputs.

The direct consumption coefficient reflects the basic characteristics of the production structure in the input-output model, fully revealing the technical and economic connections between various sectors of the national economy, i.e., the strength of interdependence and mutual constraint relationships between sectors. The larger the A_{ij}, the stronger the direct dependency of the sector j on the sector i. If A_{ij}=0, it means that the sector j has no direct dependence on the sector i.

The complete consumption coefficient refers to the value of goods and services from all sectors that need to be fully consumed by a sector per unit. Specifically, the complete consumption coefficient refers to the sum of the direct and indirect consumption of goods or services from the product sector i by the product sector j for every unit of final consumption provided by the sector j. The complete consumption coefficients of each sector can be presented in a table format, called the complete consumption coefficient table or matrix, usually represented by the letter B. The formula for calculating the complete consumption coefficient is:

$$b_{ij} = a_{ij} + \sum_{k=1}^{n} a_{ik} \cdot a_{kj} + \sum_{s=1}^{n}\sum_{k=1}^{n} a_{is} \cdot a_{sk} \cdot a_{kj} + \sum_{t=1}^{n}\sum_{s=1}^{n}\sum_{k=1}^{n} a_{it} \cdot a_{ts} \cdot a_{sk} \cdot a_{kj} + \cdots$$

$$(i, j = 1,2, \dots, n) \qquad (3\text{-}4)$$

Where, $\sum_{k=1}^{n} a_{ik} \cdot a_{kj}$ denotes the first round of indirect consumption of sector j to sector i, $\sum_{s=1}^{n}\sum_{k=1}^{n} a_{is} \cdot a_{sk} \cdot a_{kj}$ denotes the second round of indirect consumption and so on.

The direct consumption coefficient matrix A can also be used to calculate the complete consumption coefficient matrix B, as shown in Formula 3-5.

$$B = (I - A)^{-1} - I \qquad (3\text{-}5)$$

Where, $(I - A)^{-1}$ is called the Leontief inverse matrix and its elements are called the Leontief inverse coefficients, which indicate the full requirement for product sector i when one unit of end use is added to sector j.

The complete consumption coefficient not only reflects the direct technical and economic connections among various sectors of the national economy, but also the indirect technical and economic connections among them, and through linear relationships, links the total output of various sectors of the national economy to final use.

Based on the definitions of the above coefficients and matrices, input-output row and column models can be established. The row model is based on the balance relationship of the input-output table rows. It reveals the use of goods and services produced by various sectors of the national economy and can be used to calculate the output levels that each sector must achieve in order to meet the final demand of certain sectors. The column model is mainly based on the balance relationship of the input-output table columns. It reveals the various inputs that occur during the production process of each sector of the national economy and can be used to study the value formation problem of goods and services produced by each sector.

The row model and column model can be expressed by formulas 3-6 and 3-7. For convenience of calculation, it can be converted into consensus 3-8 and 3-9.

$$AX + Y = X \tag{3-6}$$

$$XH + V = X \tag{3-7}$$

$$X = (I - A)^{-1} \cdot Y \tag{3-8}$$

$$X = V \cdot (I - A)^{-1} \tag{3-9}$$

Where, AX denotes intermediate use, Y denotes final use, X denotes total output or total input, XH denotes intermediate input, H denotes the direct distribution coefficient, V denotes initial input (value added).

Based on the input-output row and column models, combined with other economic theories and assumptions, the input-output table can be used as an important economic analysis tool, applied to many fields such as economic structure analysis, energy and environmental research, regional economic integration and coordinated development, global value chains, etc. It can provide powerful data support for policy formulation and strengthening macroeconomic management.

3.3.3 Life cycle assessment

(1) Definition and content

Life Cycle Assessment (LCA) is a method of evaluating the environmental and resource impacts of a product, process, or service throughout its entire lifecycle. It is a systematic and quantitative approach that assesses the environmental impacts throughout the lifecycle, including the stages of raw material acquisition, production, use, maintenance, recycling, and disposal, to help decision-makers make more comprehensive and sustainable decisions as shown in Figure 3-13. The prominent advantage of LCA is its emphasis on the overall and global nature of the system development process. It divides the evaluation object into several stages from a time perspective, and each stage adopts independent evaluation methods and processes. This reduces the complexity of the evaluation and improves operability.

Fig.3-13 Components of life cycle assessment

Source: National Institute of Standards and Technology (USA)

Among the various definitions of Life Cycle Assessment (LCA), those from the International Organization for Standardization (ISO), the Society of Environmental Toxicology and Chemistry (SETAC), and the European Union are considered authoritative. ISO defines LCA as “a methodology for assessing environmental impacts associated with all the stages of a product’s life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling”. SETAC defines it as “an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental improvements”. The European Union defines it as “A method to assess the environmental impact of products or services over their entire life cycle, from the extraction of raw materials through to final disposal”. These definitions collectively reflect a core feature of LCA, which is the comprehensive analysis and evaluation of all environmental impacts of a product, production, or service throughout its entire life cycle, from cradle to grave.

With the development of industrialization, more and more waste and pollutants have entered the natural ecological environment, exceeding its capacity for digestion and absorption, and causing significant impacts on the environment and human health. At the same time, industrialization also leads to the consumption of natural resources beyond their ability to recover, further disrupting the balance of the global ecological environment. Therefore, people are increasingly hoping to have a thorough, comprehensive, and integrated understanding of the resource consumption and environmental impacts of their various activities, in order to seek opportunities to take measures to mitigate human impacts on the environment. Based on this, the concept of sustainable development has been introduced into LCA.

Figure 3-14 shows the framework of sustainable development-based life cycle assessment. The framework aims to establish a more comprehensive, integrated, systematic, and sustainable LCA method to support decision-makers in considering sustainability in the production and consumption process. The framework also incorporates social, environmental, and economic dimensions into the assessment to evaluate their impact on social, environmental, and economic sustainability, making the evaluation more comprehensive. In addition, the framework also emphasizes the importance of the use phase and end-of-life phase, and provides sustainable development tools and methods, including circular economy, green supply chain management, and sustainable procurement.

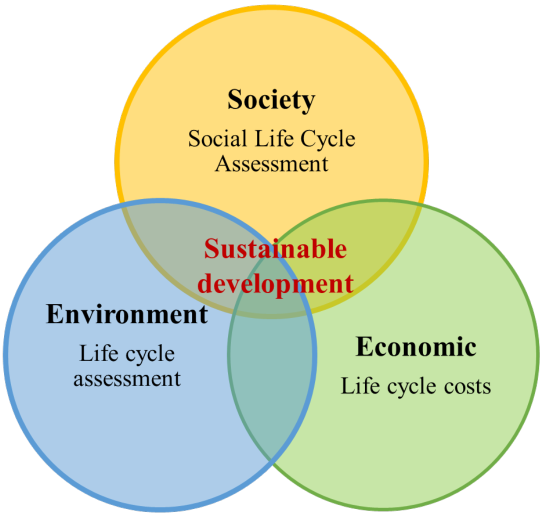


Fig.3-14 The framework of sustainable development-based life cycle assessment

(2) Stages of the LCA

LCA is generally divided into four stages: goal and scope definition, inventory analysis, impact assessment, and result interpretation.

- Goal and scope definition

This stage involves defining the objectives and scope of the LCA study, which is the first and most critical step in LCA research. The goal definition mainly explains the reasons and intended applications for conducting LCA, while the scope defines the functional unit, system boundaries, data allocation procedures, data requirements, and original data quality requirements of the product system being studied. The goal and scope definition directly determine the depth and breadth of the LCA study. Given the repetitiveness of LCA, it may be necessary to continuously adjust and improve the research scope.

- Inventory analysis

The inventory analysis is a fundamental part of the environmental impact assessment in LCA and can directly guide practical applications. It involves the quantitative analysis of resource and energy use and waste emissions to the environment throughout the entire lifecycle stages of a product, process, or activity. The inventory analysis is the core of LCA research and the most mature stage of the research. The main processes involve data collection and verification, correlation of data with unit processes, correlation of data with functional units, data merging, modification of system boundaries, data feedback, and ultimately completing the inventory.

- Impact assessment

Impact assessment is another important step in LCA research after goal and scope definition and inventory analysis. It usually uses certain calculation models to classify and quantify the environmental data obtained from the entire life cycle stages of the product, process, or activity studied in the LCI. Its purpose is to evaluate the environmental impact of the product based on the material and energy consumption data, as well as various emission data provided by the inventory analysis. Essentially, it is a process of qualitatively or quantitatively ranking the results of inventory analysis. It is the core content of LCA and the most difficult part.

The evaluation methods used are generally divided into two categories: “environmental problem method” and “distance-to-target method”. The former focuses on environmental impact factors and mechanisms and converts various environmental disturbance factors into equivalent factors for data standardization and comparative analysis. The latter focuses on the consequences of the impact, characterizing the severity of a certain environmental effect by the distance between the current level and the target level (standard or capacity) of a certain environmental effect. Before establishing the model, impact assessment generally undergoes three processing stages: classification, characterization, and quantification. Classification assigns the input and output data in the LCI to different environmental impact categories, characterization converts different substances in each impact category into a unified unit, and quantification determines the relative contribution or weight of different environmental impact categories, that is, transforms the environmental impact data obtained into non-dimensional environmental indicators in the corresponding environmental impact model, and expects to obtain the overall environmental impact level.

- Result interpretation

The purpose of interpreting the life cycle is to analyze and discuss the results in a transparent manner, address limitations, make recommendations, and report the findings based on the first few stages of LCA or LCI research. Life cycle interpretation is systematic and repeatable, consisting of three elements: identification, assessment, and reporting. The ultimate goal is to provide clear, comprehensive, and consistent explanations of LCA or LCI research results that are easy to understand based on the research purpose and scope.

(3) LCA carbon accounting standards and methods

There are well-established international standards and requirements for LCA greenhouse gas emission accounting. The PAS 2050 specification is the world’s first carbon footprint method standard for LCA, which was released by the British Standards Institution in 2008. It is the world’s first carbon footprint accounting standard and one-third of carbon footprint labeling standards worldwide choose to use the PAS 2050 specification, making it the most widely used carbon footprint standard. The GHG Protocol is one of the earliest greenhouse gas accounting standard projects in the world, and the system is a method system for calculating enterprises, organizations, or products.

In the international standards of ISO, the ISO 14040 series defines the basic framework of LCA, while the ISO 14060 series establishes data management, reporting, and verification models for greenhouse gas emissions. Based on these two system standards, ISO proposed the ISO 14067 standard to address “product carbon footprint.” It absorbs the essence of all existing ISO standards for the first time, confirming LCA as the technical method for quantifying product carbon footprints.

Based on the above standards, the commonly used LCA carbon emission accounting methods can be divided into three categories.

- Process-based Life Cycle Assessment (PLCA)

PLCA is a bottom-up way that uses on-site monitoring, surveys, or other database information to gather all input and output data of a product or service throughout its life cycle. This method is the most traditional and widely used life cycle assessment method (ISO, 199SETAC, 1993, 1998). Its advantage lies in the ability to accurately assess the carbon footprint and environmental impacts of a product or service. The errors are mainly due to the subjective nature of the boundary setting and truncation errors. The method is applied in Chapter 5, 6.

- Input-output Life Cycle Assessment (I-OLCA)

The I-OLCA method adopts the top-down way. When assessing the environmental impact of specific products or services, the method first calculates the energy consumption and carbon emissions at the industry and sector levels and then uses the balance relationship in the input-output table to estimate the carbon footprint between sectors. This method is generally applicable to macro-level calculations of countries and sectors and can fully calculate the carbon footprint and environmental impact of the research object. However, this method’s evaluation is constrained by the input-output table, lacks timeliness, and cannot divide carbon emissions according to the life cycle stages. The method is applied in Chapter 4.

- Hybrid- Life Cycle Assessment (HLCA)

HLCA is a lifecycle assessment method that combines PLCA and I-OLCA. HLCA can be divided into three models: tiered hybrid, input-output hybrid, and integrated hybrid. The advantage of this method is that it not only avoids truncation error but also allows for a targeted evaluation of specific products and their entire lifecycle stages. However, it can result in duplicate calculations.

3.4 Carbon emission analysis methods

3.4.1 Carbon emission decomposition analysis

Decomposition analysis, as an analytical framework for studying the changing characteristics and underlying mechanisms of phenomena, was initially applied in environmental economics research. Due to its ability to decompose factors influencing carbon emissions and quantitatively analyze the impacts of factor changes on emission variations, it has gradually become a popular approach in carbon emission research.

Carbon emission decomposition analysis is typically based on the energy identity, which establishes a quantitative relationship between carbon emissions and their associated influencing factors, and subsequently decomposes the variations in emissions. Currently, the commonly used energy identities include the IPAT identity and the Kaya identity.

The IPAT identity, proposed by Ehrlich and Holdren in 1970, captures the influence of population on environmental pressure. The IPAT identity establishes an identity between environmental impact and population size, per capita wealth, and the level of technology related to the environment. The IPAT identity equation is primarily used to explore the various driving factors behind changes in emissions.

$$I = P \cdot A \cdot T \tag{3-10}$$

Where, I represents emissions and impact, P represents population, A represents wealth, and T represents technological or energy efficiency of economic activities.

The Kaya identity equation, proposed by Kaya, differs from the analytical framework of IPAT. It establishes a connection between economic, policy, and population factors with carbon dioxide emissions resulting from human activities (KAYA, 1989). It can be specifically expressed as follows:

$$CO_2 = \frac{CO_2}{PE} \cdot \frac{PE}{GDP} \cdot \frac{GDP}{P} \cdot P \tag{3-11}$$

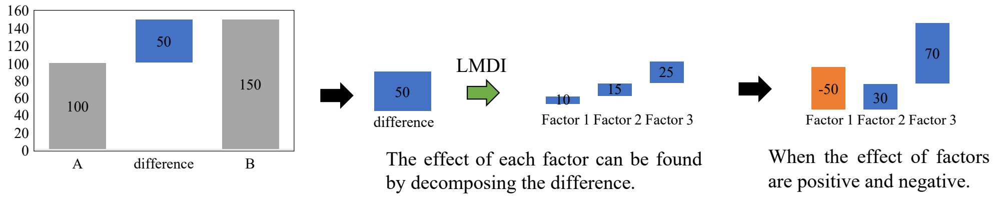
Where, CO_2, PE and GDP represent carbon dioxide emissions, primary energy consumption, and gross domestic product, respectively.

The decomposition model employed in Chapter 4 of this study is an extension of the Kaya identity equation, while the decomposition model utilized in Chapter 5 is an extension of the IPAT identity equation.

3.4.2 The logarithmic mean divisia method

After 40 years of research and development, the methodology of carbon emission decomposition has been broadly categorized into two main approaches: Index Decomposition Analysis (IDA) and Structural Decomposition Analysis (SDA). IDA is a simpler method that originated from the study of industrial energy consumption decomposition in the 1970s and has a wider range of applications. In comparison, SDA is a more complex method that considers the underlying structural changes. The LMDI (Logarithmic Mean Divisia Index) method employed in this study belongs to the IDA approach.

The LMDI method is based on the logarithmic mean Divisia index of energy consumption and emissions. As shown in Figure 3-15, it decomposes the overall carbon emission changes into the contributions of different factors to reveal their respective impacts on emission variations.



The effect of each factor can be found by decomposing the difference.

When the effect of factors are positive and negative.

Fig.3-15 Illustration of carbon emission increment decomposition

The core idea of the LMDI method is to utilize the properties of the logarithmic mean Divisia index to decompose the overall emission changes into the contributions of different factors. Firstly, energy consumption and emission data are transformed into logarithmic form. Then, the growth rates of each factor are calculated for different time periods, and their contributions are obtained through multiplication. Finally, the contributions of each factor are summed up to obtain the overall emission change. In this way, the LMDI method can clearly display the contributions of each factor to the overall emission change, facilitating the identification of key influencing factors and driving forces.

The LMDI method is characterized by its simplicity, ease of calculation, and broad applicability, making it widely used in carbon emission decomposition analysis. It helps researchers gain a deeper understanding of the main driving factors behind carbon emission changes and provides a scientific basis for formulating corresponding policies and measures.

3.5 Carbon emission forecasting methods

3.5.1 System dynamics theory

(1) Definition and development

System Dynamics is a scientific method for studying the dynamic characteristics of complex systems. The main idea of System Dynamics is that the interactions between the various elements within a system can led to the dynamic behavior of the entire system (Jay W & John F, 1969). It views the system as a set of interdependent causal relationships and uses mathematical models to describe the various causal relationships, processes, and feedback loops within the system to predict and control the system's evolution. The significance of System Dynamics lies in its ability to help people better understand and deal with the operational mechanisms of complex systems. Compared to traditional analytical methods, System Dynamics can not only reveal the dynamic changes within a system but can also assist people in developing better policies and decisions through simulation and prediction.

System Dynamics theory was proposed by Professor Jay W. Forrester from Massachusetts Institute of Technology (MIT) in the 1950s. By combining systems theory, control theory, and information theory, he addressed the issue of multiple feedback in complex systems (Jay W, 1958). In 1961, Forrester published his book *Industrial Dynamics*, which systematically introduced the basic theory and methods of System Dynamics. His research results gradually found wide application and recognition in decision analysis, management, and policy-making fields (Jay W, 2017). In 1968, the Urban Dynamics model proposed in *Urban Dynamics* became the first major non-enterprise application of System Dynamics (Jay W & John F, 1969). At this point, System Dynamics was completed theoretically.

In 1971, Prof. Jay W. Forrester extended his research to a global level and used his system dynamics theory to establish the *"World Model II"* simulation model with five important factors, which was published in the book *World Dynamics* (Jantsch, 1971). Forrester's disciple D.H. Meadows completed the future study *The Limits to Growth*, which explores human predicaments and further proposes a more detailed *"World Model III"* (Meadows et al., 1972). These two models caused a great sensation worldwide. After decades of development, system dynamics has become an important tool in modern science and engineering.

(2) Basic concept and flow chart

System dynamics is a way to understand the nonlinear behavior of complex systems over time using information about stocks, flows, internal feedback loops, table functions, and time lags(Rahim et al., 2017). The basic concepts of system dynamics include system, feedback, variable, flow, and stock causality. These basic concepts constitute the foundation and core content of system dynamics analysis, namely mathematical models, and analysis of causal relationships in systems(John D.W, 2015). Understanding and applying these concepts can help people better understand the uncertainty and complexity in systems.

A system is a whole composed of interacting parts. In system dynamics, a system can be any interacting element or organization, such as a single company, a country, an ecosystem, or a person's body. A variable is an attribute that can be measured and tracked in a system. In system dynamics, variables can be physical attributes such as volume and mass, or abstract attributes such as price, demand, and supply. Flow refers to the rate of change of a variable, describing how a variable changes at different time points (Jia & Ding, 2002). For example, a company's sales revenue can be a flow because it describes the company's sales situation over a period of time. Stock refers to the quantity of resources or items stored in a system. Stock can be a variable, usually corresponding to flow. For example, a company's inventory can be a stock because it describes the quantity of items the company has. Feedback is the interaction between variables in a system, which can be positive or negative. Positive feedback means that when one variable increases, it leads to another variable increasing, forming a positive cycle. Negative feedback means that when one variable increases, it leads to another variable decreasing, forming a negative cycle.

Causal loop diagrams are used in the initial stages of model conceptualization to help analysts quickly clarify the causal relationships between multiple variables in a system by abstracting and conceptualizing the actual system into a simplified model representation (Roberts, 1978). Causal relationships between variables can be represented by causal chains, which are lines or arcs with arrows. The direction of the arrow in a causal chain represents the direction of causality between variables, such as Table 3-3, and the "+" or "-" sign next to the arrowhead indicates the polarity of the relationship.

Table 3-3 Causal chains

Chain	Causal
$A \xrightarrow{+} B$	The change in A causes a change in B in the same direction.
$A \xrightarrow{-} B$	The change in A causes a change in the opposite direction of B.

A closed loop formed by connecting causal chains is called a Causal loop diagram (CLD), which is a commonly used graphical tool in system dynamics that helps visualize the causal relationships and feedback loops among various factors in a system. CLDs can help people understand and analyze the complexity of a system, especially in predicting system behavior and designing intervention measures. Drawing a CLD requires a certain understanding and analytical ability of the system and usually requires multiple iterations and adjustments to obtain the most accurate, comprehensive, and easily understandable causal loop diagram (Richardson, 1997). In system dynamics modeling and simulation, CLDs are usually the first step in model building and can provide important references and guidance for subsequent model construction and simulation. CLDs are helpful in visualizing the structure and behavior of a system, and for conducting qualitative analyses. To perform more detailed quantitative analyses, loop diagrams are converted to stock and flow diagrams. Stock and flow diagrams are important tools in system dynamics, used to describe the relationships between various stocks and the flows between them in a system.

(3) System dynamics modeling steps

As shown in figure 3-16, the key steps in building a model using system dynamics mainly include the following five steps:

Define the research object and determine the system boundary. When applying system dynamics theory for analysis, it is necessary to have a deep understanding of the behavioral characteristics of the research object and extract the key issues to be addressed in order to clarify the purpose of modeling. For complex systems involved in the problem, a thorough analysis is required to identify the constituent elements and operating characteristics, and then divide them into subsystems to determine the modeling boundary.

Sort out the relationships between each element and draw a causal loop diagram. Based on the summary of the constituent elements within each subsystem, the causal feedback relationships between each element are clarified, and the variable form of different elements is determined to finally draw the causal loop diagram of each system.

Determine the variable function relationship and establish the system flow chart. Based on the drawn causal loop diagram of elements, economic, statistical, and other theories can be applied to determine the functional relationships between variables. Then, use Vensim software to draw a flow chart model and describe the actual operational status of the system by assigning values to variables. In this process, initial values should be set for different types of variables, and the dimensional consistency between variables should be checked. By establishing a flow chart, complex systems can be abstracted into a set of mathematical relationships and simulated using system dynamics.

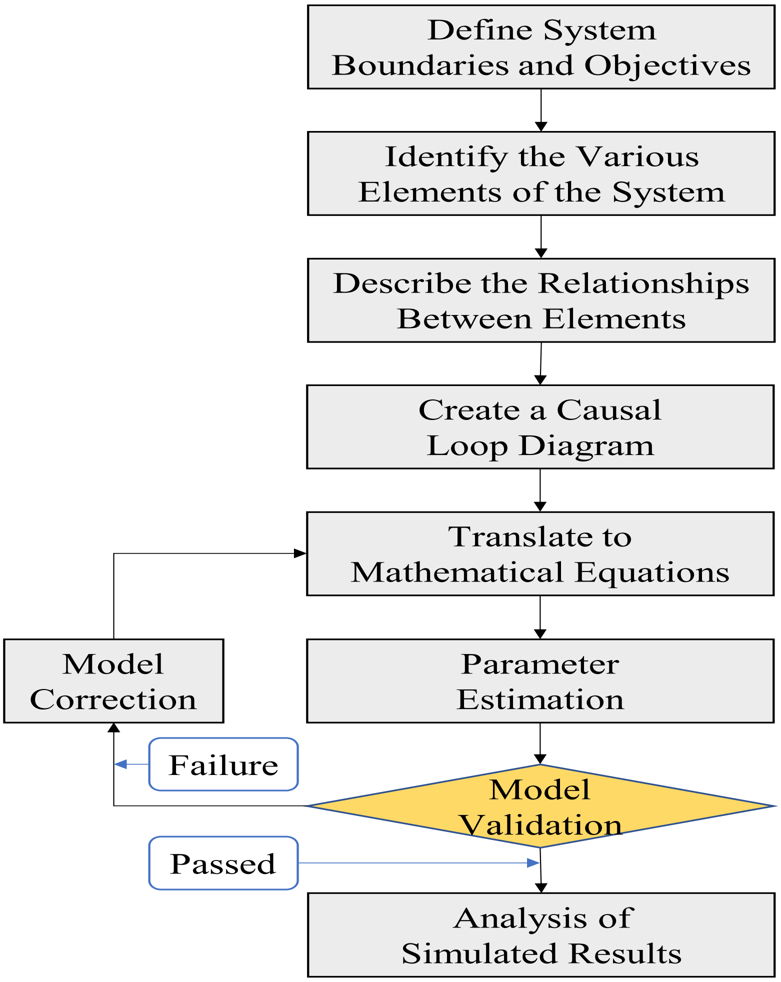


Fig.3-16 System dynamics modeling steps

Conduct system testing to check the effectiveness of the model. Using the established system flow chart model, combined with historical data for effectiveness testing, sensitivity testing of variables should also be performed. Through these tests, system errors can be discovered in a timely manner, inappropriate functional relationships can be corrected, and the accuracy and reliability of the model can be ensured.

Use the system dynamics model for policy design and evaluation. After continuous testing and adjustment, observing the evolution of system behavior and changing the parameter settings for key elements, a reasonable policy design path can be found by simulating development scenarios under different policies. These research results can provide reliable references and decision support for policy makers.

In this paper, system dynamics is used to model urban-scale building stock-flow. The urban population and per capita building area are used as the base data to estimate the future urban new building area and urban building demolition area. The specific use of system dynamics in this paper will be described in Chapters 6 and 7, respectively.

3.5.2 Scenario analysis

(1) Definition and development

Scenario analysis is a method used to analyze complex problems by systematically studying and comparing different scenarios to predict possible outcomes and impacts. This method involves constructing multiple scenarios to explore and analyze different aspects of a problem, which helps in making effective decisions and strategies (Schoemaker, 1991).

Some argue that scenario analysis is not a prediction of future outcomes but rather a continuous process of identifying and judging early signals(Heijden et al., 2009). Through a progressive analysis process, external environmental factors' development trends and main uncertainties are recognized, and the interaction between these uncertainties is analyzed to construct limited "scenarios" (Schoemaker, 1991). Non-mainstream scenarios are continually eliminated while mainstream scenarios are deeply developed with the aim of anticipating environmental changes and reducing uncertainty, ultimately leading to accurate future environmental predictions (S. Gilbert et al., 2005). During this process, decision-makers can gain insights into the environmental factors they may face in the future and make choices and decisions based on the current environmental factors (Schwartz, 2012).

Scenario analysis, initially invented by Herman Kahn in the 1950s, was first applied in strategic planning. In 1967, *The Year 2000: A Framework for Speculation on the Next Thirty-Three Years* provided the first systematic explanation of the term "scenario analysis" (Kahn & Wiener, 1967).. It believed that scenarios described hypothetical development processes of events, which can help take proactive measures to deal with future changes. The future is full of diversity and uncertainty, and multiple potential outcomes could occur. Various possible outcomes and the ways in which they arise constitute a "scenario" (Miller & Waller, 2003) Wack expanded Kahn's ideas by examining in greater detail the theory and processes by which scenario analysis stimulates human thinking and responds to future environmental change (Wack, 1985). Schwartz creatively developed the theory of scenario analysis and proposed a complete scenario analysis process and key points (Schwartz, 2012). The method of scenario analysis has been widely studied(Godet, 2000). With the continuous improvement of information technology and data analysis capabilities, scenario analysis has also continued to develop and improve. Modern scenario analysis typically uses computer simulations and predictive models to analyze potential outcomes under different scenarios. Scenario analysis has been widely applied in business and political fields, as well as in environmental and climate change.

(2) Features and applications

The purpose of scenario analysis is to understand different potential future paths and develop corresponding response measures to reduce or avoid negative impacts. As it can effectively describe the process of change, scenario analysis is often applied in research analyzing long-term uncertain scenarios and situations with a lack of data and non-quantifiable factors. This paper summarizes the application of scenario analysis.

Strategic planning: Scenario analysis has different characteristics from traditional forecasting and planning methods, especially its flexibility and creativity, which makes it more suitable for strategic planning and strategic analysis in the modern complex and changing social environment.

Uncertainty: Scenario analysis is largely based on key uncertainties when describing how the future will unfold, and it has a great advantage when analyzing and modeling those futures with a high degree of uncertainty.

Lack of data: The scenario analysis approach is future history, telling well-organized, multidimensional stories, supported by both quantitative analysis and rich, imaginative, and possibly discontinuous qualitative descriptions.

Enhancing participation and raising awareness: The scenario analysis method requires a multifaceted group of stakeholders and experts to participate in the analysis process, while developing multiple scenario stories based on different assumptions; therefore, the scenario analysis process is not only more widely sourced and universally representative of the participants, but also, has a deeper understanding of the event object.

Due to the uncertainty of future development, scenario analysis is a complex process. Many scholars have summarized the application process of scenario analysis. Schoemaker suggested that scenario analysis can be divided into 10 steps: Define the scope, Identify the major stakeholders, Identify basic trends, Identify key uncertainties, Construct initial scenario themes, Check for consistency plausibility, Develop learning scenarios, Identify research needs, Develop quantitative models, and Evolve toward decision scenarios (Schoemaker, 1995).

Similarly, Gilbert also divides the process into 10 steps: Develop planning premises, Define time horizons and decision space, Historical review, Identify common and conflicting assumptions, Determine indicators for structural variable linked to divergence, Build draft scenarios to fill the decision space, Draft strategies for all competitors, Map strategies against scenarios, Validate alternative strategies, and Select or adapt the most robust strategy (A. L. Gilbert, 2000).

Stanford Research Institute simplifies the process to six steps: Decision making key points, Identify key factors, Identify and analyze extrinsic drivers, Selecting the axes of uncertainty, Developing the logic of the scenario, and Analyze and synthesize the content of the scenario(ISACA., 2009). Fink suggests that scenario analysis can be completed in five steps: Scenario preparation, Scenario field analysis, Scenario prognostics, Scenario development, and Scenario transfer(Alexander & Oliver, 2001).

Although there are differences in the work steps proposed by these scholars, they all share a common characteristic, which is the analysis of scenario key factors. Scholars also unanimously believe that the rigor of this step will have a significant impact on the accuracy of the analysis content. Lena suggests that scenario analysis needs to be based on three fundamental questions about the future: “what will happen?” “What can happen?” “How can a specific goal be achieved?” Multiple paths can be established under each question, and the combination of paths will form different scenarios (Börjeson et al., 2006). Fahey suggests that when building scenarios, four elements should be considered: end states, strategies, drivers, and logic(Fahey, 1999). Dan suggests that scenario analysis can be expressed in three ways: as a work analysis method, as a story description, and as a thinking method(Diaper, 2002).

Based on the various versions of work steps and methods above, this paper summarizes a five-step model of scenario analysis, the main content and process of which are illustrated in figure 3-17.

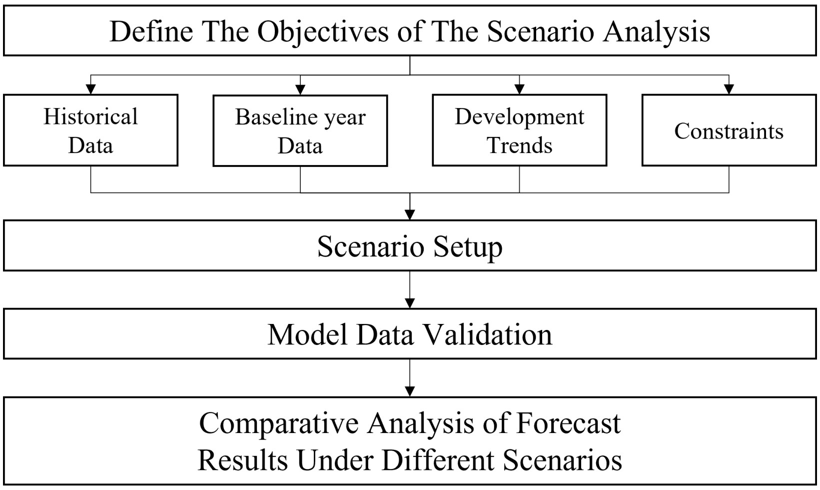


Fig.3-17 The application process of scenario analysis

Scenario analysis is applied by Chapters 6 and 7 of this paper, with the aim of predicting the future development of the construction industry in Hangzhou and Kitakyushu under different technology and policy implementation scenarios, and thus measuring the corresponding carbon emissions, and the specific scenario design will be elaborated later in the paper depending on the research objects.

Reference

Alexander, F., & Oliver, S. (2001, January 3). Scenario management—An approach for strategic foresight—Fink—2000—Competitive Intelligence Review—Wiley Online Library. https://onlinelibrary.wiley.com/doi/abs/10.1002/(SICI)1520-6386(200031)11:1%3C37::AID-CIR6%3E3.0.CO;2-W

Alvarez, S., Tobarra, M., & Zafrilla, J. (2019). Corporate and Product Carbon Footprint under Compound Hybrid Analysis: Application to a Spanish Timber Company. Journal of Industrial Ecology, 23(2), 496–507. https://doi.org/10.1111/jiec.12759

AR4 Climate Change 2007: The Physical Science Basis — IPCC. (2007). https://www.ipcc.ch/report/ar4/wg1/

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. Futures, 38(7), 723–739. https://doi.org/10.1016/j.futures.2005.12.002

Daryanto, Y., & Setyanto, D. (2023). Production Inventory Optimization Considering Direct and Indirect Carbon Emissions under a Cap-and-Trade Regulation. Logistics, 7(1), Article 1. https://doi.org/10.3390/logistics7010016

Diaper, D. (2002). Task scenarios and thought. Interacting with Computers, 14(5), 629–638. https://doi.org/10.1016/S0953-5438(02)00062-0

Fahey, L. (1999). Competitor scenarios: Projecting a rival's marketplace strategy. Competitive Intelligence Review, 10(2), 65–85. https://doi.org/10.1002/(SICI)1520-6386(199932)10:2<65::AID-CIR9>3.0.CO;2-Z

Gilbert, A. L. (2000). Using multiple scenario analysis to map the competitive futurescape: A practice-based perspective. Competitive Intelligence Review, 11(2), 12–19. https://doi.org/10.1002/(SICI)1520-6386(200032)11:2<12::AID-CIR4>3.0.CO;2-E

Gilbert, S., Michele, G.-C., & Jr. (2005, March). Large Group Scenario Planning: Scenario Planning With the Whole System in the Room—Gilbert Steil, Michele Gibbons-Carr, 2005. https://journals.sagepub.com/doi/abs/10.1177/0021886304272888?journalCode=jaba

Godet, M. (2000). The Art of Scenarios and Strategic Planning: Tools and Pitfalls. Technological Forecasting and Social Change, 65(1), 3–22. https://doi.org/10.1016/S0040-1625(99)00120-1

Greenhouse Gas Accounting and Reporting. (2022). Greenhouse Gas Accounting and Reporting FOR THE PRIVATE EQUITY SECTOR. https://www.unpri.org/download?ac=16265

Greenhouse Gas Protocol. (2016). Global Protocol for Community-Scale Greenhouse Gas Emission Inventories An Accounting and Reporting Standard for Cities.

http://www.cbcsd.org.cn/sjk/nengyuan/standard/international/20150213/download/Global-Protocol-for-Community-Scale-Greenhouse-Gas-Emission-Inventories.pdf

Harris, J. (2015). The Emerging Importance of Carbon Emission-Intensities and Scope 3 (Supply Chain) Emissions in Equity Returns. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.2666753

Heijden, K. van der, Bradfield, R., Burt, G., Cairns, G., & Wright, G. (2009). The Sixth Sense: Accelerating Organizational Learning with Scenarios. John Wiley & Sons.

IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/

ISACA. (2009). The Risk IT Framework excerpt.

ISO 14064. (2018). ISO 14064-1:2018(en), Greenhouse gases—Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. https://www.iso.org/obp/ui/#iso:std:iso:14064:-1:ed-2:v1:en

Jantsch, E. (1971). World dynamics. Futures, 3(2), 162–169. https://doi.org/10.1016/0016-3287(71)90038-3

Jay W, F. (1958). Industrial dynamics: A major breakthrough for decision makers. Harvard Business Review, 36(4), 37–66.

Jay W, F. (2017, December 20). Industrial Dynamics: Journal of the Operational Research Society: Vol 48, No 10. https://www.tandfonline.com/doi/abs/10.1057/palgrave.jors.2600946?journalCode=tjor20

Jay W, F., & John F, C. (1969). Urban Dynamics.

Jia, R., & Ding, R. (2002). System Dynamics: Complex Analysis of Feedback Dynamics.

John D.W, M. (2015). Strategic Modelling and Business Dynamics: A Feedback Systems Approach. https://onlinelibrary.wiley.com/doi/book/10.1002/9781119176831

Kahn, H., & Wiener, A. J. (1967). The Next Thirty-Three Years: A Framework for Speculation. Daedalus, 96(3), 705–732.

KAYA, Y. (1989). Impact of carbon dioxide emission control on GNP growth: Interpretation of proposed scenarios. Intergovernmental Panel on Climate Change/Response Strategies Working Group, May. https://ci.nii.ac.jp/naid/10021966297/en/

Luo, W., Sandanayake, M., & Zhang, G. (2019). Direct and indirect carbon emissions in foundation construction – Two case studies of driven precast and cast-in-situ piles. Journal of Cleaner Production, 211, 1517–1526. https://doi.org/10.1016/j.jclepro.2018.11.244

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). Limits To Growth. In Green Planet Blues (5th ed.).

Miller, K. D., & Waller, H. G. (2003). Scenarios, Real Options and Integrated Risk Management. Long Range Planning, 36(1), 93–107. https://doi.org/10.1016/S0024-6301(02)00205-4

Rahim, F. H. A., Hawari, N. N., & Abidin, N. Z. (2017). Supply and Demand of Rice in Malaysia: A System Dynamics Approach. 6(4).

Reavis, M., Ahlen, J., Rudek, J., & Naithani, K. (2022). Evaluating Greenhouse Gas Emissions and Climate Mitigation Goals of the Global Food and Beverage Sector. Frontiers in Sustainable Food Systems, 5. https://www.frontiersin.org/articles/10.3389/fsufs.2021.789499

Richardson, G. P. (1997). Problems in causal loop diagrams revisited. System Dynamics Review, 13(3), 247–252. https://doi.org/10.1002/(SICI)1099-1727(199723)13:3<247::AID-SDR128>3.0.CO;2-9

Roberts, E. B. (1978). Managerial Applications of System Dynamics. MIT Press.

Schoemaker, P. J. H. (1991). When and how to use scenario planning: A heuristic approach with illustration. Journal of Forecasting, 10(6), 549–564. https://doi.org/10.1002/for.3980100602

Schoemaker, P. J. H. (1995). Scenario Planning: A Tool for Strategic Thinking. MIT Sloan Management Review. https://sloanreview.mit.edu/article/scenario-planning-a-tool-for-strategic-thinking/

Schwartz, P. (2012). The Art of the Long View: Planning for the Future in an Uncertain World. Crown.

Wack, P. (1985, September 1). Scenarios: Uncharted Waters Ahead. Harvard Business Review. https://hbr.org/1985/09/scenarios-uncharted-waters-ahead

Wang, H., Zhang, Y., Gao, W., & Kuroki, S. (2020). Life Cycle Environmental and Cost Performance of Prefabricated Buildings. Sustainability, 12(7), Article 7. https://doi.org/10.3390/su12072609

Wiedmann, T., Chen, G., Owen, A., Lenzen, M., Doust, M., Barrett, J., & Steele, K. (2021). Three-scope carbon emission inventories of global cities. Journal of Industrial Ecology, 25(3), 735–750. https://doi.org/10.1111/jiec.13063

Chapter 4

CARBON EMISSION ACCOUNTING AND DRIVING FORCE ANALYSIS OF CONSTRUCTION INDUSTRY WITHIN A CITY SCALE

CHAPTER 4: CARBON EMISSION ACCOUNTING AND DRIVING FORCE ANALYSIS OF CONSTRUCTION INDUSTRY WITHIN A CITY SCALE

Contents

4.1 Contents

Construction is an energy-intensive industry, with the production of building materials, transportation and construction consuming energy and emitting carbon dioxide. Reducing Carbon Emissions from the Construction Industry (CECI) is critical to meeting the “dual carbon” target, as it shared 30% of the total carbon emissions. How to estimate carbon emissions at the city-scale is another issue. This chapter focuses on the city-scale, establishing a framework to explore the carbon emissions trajectory. The driving force was clarified by the Logarithmic Mean Divisia Index method. The results show that in the case of Hangzhou in 2019, carbon emissions caused by fossil energy consumption in the construction site (called direct CECI) account for 3.3% of the total CECI. A large part of emission is from indirect CECI which includes the secondary energy (47.2%) and embodied carbon in material or production (38.9%), which are mainly emitted outside Hangzhou, because of building materials import. By comparing the effects of each factor on the CECI in Hangzhou and Kitakyushu, this chapter also found that construction scale and demand structure were the main driving force of CECI growth, while the decrease in energy consumption will significantly restrain the increase of CECI. This study will contribute to the sustainable development of cities and society.

4.2. Introduction

Ever since humans mastered fire, humans have been on a path to change the planet’s carbon cycle. With the Industrial Revolution and the increasing use of coal and oil, a large amount of carbon dioxide was released prematurely, breaking the original healthy pattern of the carbon cycle. At present, the amount of carbon dioxide in the atmosphere has reached its greatest level in 2 million years, rising from 280ppm before the Industrial Revolution to 415ppm, far exceeding the regulation capacity of nature (Ruddiman, 2014). The global surface temperature has also reached the highest in 100,000 years due to the aggravation of the greenhouse effect (AR6 Climate Change, 2022). Environmental and climate problems such as glacier melting, sea-level rise, drought, and flood have come one after another, and the climate revolution to control carbon dioxide emissions is imminent.

Many countries have committed to reducing carbon emissions and controlling the greenhouse effect (UNEP and UNEP DTU Partnership, 2021). China has set a goal of peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060, referred to as the “dual carbon” goal (Ding, 2021). At present, China is the largest greenhouse gas emitter, emitting 10,243.4 million tons of carbon emissions in 2020, accounting for 31.8% of the global total (Statistical Review of World Energy, 2021). With the proposal of China’s “dual carbon” goal, all provinces have rapidly formulated goals and plans. Anhui and Zhejiang provinces have set specific quantified targets for replacing non-petrochemical energy. Hunan and Hubei provinces will reduce carbon emissions by adjusting and optimizing their industrial and power structures. Hebei, Shanxi, and Inner Mongolia aim at safe and efficient coal mining and clean and efficient utilization. The emission reduction system led by the provincial level has gradually been determined, and cities have become the basic unit of carbon emissions (Li and Yang, 2020). This means that carrying out carbon emission research at the city-scale is of great significance to better achieve emission reduction targets and limit the increase of carbon emissions. As the fifth largest carbon emitter, Japan has passed legislation to become carbon neutral by 2050, and by the end of 2022, 823 local governments in Japan have pledged to achieve zero carbon dioxide emissions by 2050.

The carbon emissions from the construction industry (CECI) account for 28%-34% of China's total emissions (Shi et al., 2017), which brings tremendous pressure on the Chinese government to reduce emissions (He et al., 2020) and is an essential task for realizing the "dual carbon" goal. As a resource-intensive industry, the construction industry consumes many products from the upstream sector as building materials and will bear the responsibility for the carbon emissions of these products (Wang and Zhang, 2008). The production and transportation of building materials and the construction stage of the building are often referred to as the materialization process of building. In this process, a large number of carbon emissions will be generated. About 16% of China's overall energy consumption is used in building materials production such as cement, steel, and others (Chang et al., 2010), and carbon emission accounts for about 40% of China's total. The construction stage of buildings accounts for about 6% of the carbon emissions in the whole life cycle of buildings (Lu et al., 2016).

Cities are open systems, building materials often come from external input, and carbon dioxide emission is prominent across borders. It's critical to identify the source and location of carbon emissions, as well as the carbon trajectory between cities and the variables that drive carbon emissions. Furthermore, as the construction industry will gradually be included in the scope of carbon emission trading, it is of economic significance to carry out city-scale CECI research.

Zhejiang has a developed economy and is one of the fastest-growing provinces in China. In recent years, the newly built area of Zhejiang province has remained among the top two in China. As the capital of Zhejiang province, Hangzhou's total output value of the construction industry in 2020 is 492.5 billion CNY (Wang, 2021; Zhejiang Statistical Yearbook, 2021), ranking first in the province and with the largest CECI. At the same time, Hangzhou has a complete range of industries, with all upstream sectors of the construction industry except the coal washing and mining industry. Research on the CECI of Hangzhou can well reflect the carbon flow between the construction industry and the upstream sector. Kitakyushu is Japan's first metropolitan area outside the three metropolitan areas designated by government decree, heavy industry developed, complete statistics.

Kitakyushu is in a state of contraction, facing an exodus of people as heavy industry declines in the Japanese economy. By comparing the driving forces of carbon emission in the construction industry in Kitakyushu, Japan and Hangzhou, China, the differences in influencing factors of carbon emission in the construction industry under different development trends can be shown.

In addition, the CECI of the city-scale has not been thoroughly studied, and it will be challenging to evaluate and formulate policies for the construction industry in the context of the "dual carbon" goal. Therefore, this chapter selected Hangzhou city, establishing a framework based on a nested multi-regional input-output model (MRIO model) to quantify the CECI from 2005 to 2019. And decomposed the incremental carbon emissions into contributions of different factors by using the LMDI method, in an attempt to find out the factors influencing the change of CECI and the ways of emission reduction in the construction industry. And select Kitakyushu city for comparison to verify the influencing factors. The results will be helpful for the managers of construction enterprises to understand the responsibility and management of carbon emissions and for policymakers to evaluate and make decisions on the development of the construction industry.

4.3. Review

4.3.1 Carbon emissions from the construction industry

Some studies have assessed CECI, focusing on macro or micro-scale carbon emissions (Hong et al., 2015). National carbon emission data are easy to obtain and well-studied. The driving factors and influencing factors of carbon emission growth are the research hotspots, and it is generally believed that building materials and building operations contribute the most to the increase of CECI (Lu et al., 2016; Wu et al., 2019). With the proposal of the "dual carbon" goal, carbon emission efficiency and carbon peak research began to be paid attention to. Zhou found that the carbon emission efficiency of China's construction industry was declining (Zhou et al., 2019), and Li believed that China's construction industry needed to improve the energy saving efficiency to achieve carbon peak in 2030 (B. Li et al., 2020). Research on provincial CECI is also one of the hot topics. Du believed that there was a positive correlation between the provincial economy and CECI (Du et al., 2019). Li selected Jiangsu province, a province with developed construction industry, and believed that reducing indirect and operational carbon emissions is the keyway to emission reduction, based on this, they made carbon emission prediction (Li et al., 2020; Li et al., 2021).

More studies have assessed CECI from a micro perspective, these studies use construction and operation data to calculate building carbon emissions in detail. Ding measured the carbon emissions in the materialization process of building (Ding et al., 2020). Zhang compared the carbon emissions in the whole life cycle of the two buildings (Zhang et al., 2020). Wang estimated the carbon emissions of prefabricated buildings during the whole life cycle and found it was beneficial to reducing the CECI (Wang et al., 2020). Through such detailed calculations from the building perspective, it is possible to analyze and discuss whether the city can achieve zero emissions (Pan and Pan, 2018). In addition, some scholars calculated the embodied carbon of buildings from the building materials and explored the carbon emission responsibility of the construction industry (Chen et al., 2022).

Due to insufficient statistical data, only a few studies have explored the CECI at the city-scale in China, generally focusing on municipalities directly under the central government: Beijing, Shanghai, Chongqing, and Tianjin (Ma and Cai, 2019) or super-large cities like Hong Kong (Hung et al., 2019), while few studies have investigated ordinary cities. At the same time, previous studies focused on the carbon emissions from building operations, while few studies on the other stages of building. The analysis of the responsibility of carbon emissions in the construction industry was not perfect, and the research on cross-border emissions was not clear.

4.3.2 Carbon emissions estimation methods

There is currently no universal and accurate carbon emission measuring standard, and the IPCC method suggested by the Intergovernmental Panel on Climate Change (IPCC) is a commonly recognized estimating approach. This method is characterized by easy data acquisition, simple calculation process, and wide application scope. It has been applied in animal husbandry, industry, transportation, electric power, and technology. Some scholars have introduced the concept of economic input-output into carbon emission estimation and put forward the input-output method. They considered one industry's carbon emission pulling effect on other industries (Li et al., 2021) and calculated the indirect carbon emissions, conducive to the division of carbon emission responsibility sed on the input-output method. Yu divided the supply side and demand side of carbon emissions of the transportation industry (Yu et al., 2021), Li and Shi investigated the driving effect of the construction industry on carbon emissions of other sectors (D. Li et al., 2020; Shi et al., 2017). In addition, some studies used remote sensing to observe atmospheric carbon concentration to calculate carbon flux (Schuh et al., 2021).

The top-down carbon emission estimation method is above, and the bottom-up process corresponds. The bottom-up approach subdivides the carbon emissions of the tested objects by category, calculates the carbon emissions by characteristics, and sums up the total carbon emissions. Life cycle assessment (LCA) is a standard method, Luo divided the building into three stages and established models for carbon emission estimation (Luo and Chen, 2020). Ding developed a BIM-based carbon emission estimation system (Ding et al., 2020). The in-situ measurement method (Popita et al., 2015) and carbon emission mapping method (Wu et al., 2018) based on spatial carbon emission prediction are also bottom-up estimation methods. To estimate the total CECI in Hangzhou and clarify the emission place and sector, this study uses the IPCC method to estimate the direct CECI, and the input-output method to estimate the indirect CECI.

4.3.3 Method of carbon emission increment breakdown

There are several approaches to investigating the elements that influence carbon emissions, each of which has its characteristics and applicability. Structural decomposition analysis (SDA) and index decomposition analysis (IDA) are more commonly used methods. The main difference is that SDA is based on the input-output structure; IDA only needs the data of each sector (Li et al., 2020), which means that the SDA method has higher requirements on the data of the input-output table. Although the SDA method can be used for more detailed analysis, it has disadvantages due to the limitation of a complicated compilation of input-output tables (Yu and Kong, 2017). In comparison, the IDA method is simple and widely applicable. The IDA method can be further subdivided into many forms (Wang and Feng, 2018) such as LMDI and Laspeyres method. The LMDI method has the advantages of complete decomposition, no residual and is easy to use, which has become the usual approach for carbon emission breakdown (Lu et al., 2016). This method has been used in a wide range of fields, such as the manufacturing industry in Japan (Yagi and Kokubu, 2019) and Thailand (Chontanawat et al., 2020), the chemical industry and logistics industry in China (Lin and Long, 2016; Quan et al., 2020), industrial park in South Korea (Jung et al., 2012), power generation industry in Latin America (De Oliveira-De Jesus, 2019), comparison of economic development between China and the USA (Wang et al., 2018), coal consumption in The United Kingdom(Wang and Song, 2021), etc.

The LMDI method has also been widely applied in the construction industry. Li found that area factor and output value intensity were the driving factors for the growth of CECI (Li et al., 2020). He believed that total output and energy emission efficiency were the driving factors for the change of CECI (He et al., 2020). Lu found that building materials contributed the most to CECI (Lu et al., 2016). The LMDI method is an effective method to explore the driving factors of CECI.

4.4. Method and data source

Figure 4-1 shows the framework of quantifying CECI at the city-scale. The IPCC method is used to calculate direct carbon emissions, the nested multi-regional input-output model is used to estimate the indirect carbon emissions and distinguish the cross-border emissions. Finally, direct and indirect carbon emissions are added to obtain the total CECI. In addition, the hybrid LMDI method is used to decompose the direct CECI and the indirect CECI, and the key factors affecting CECI are obtained.

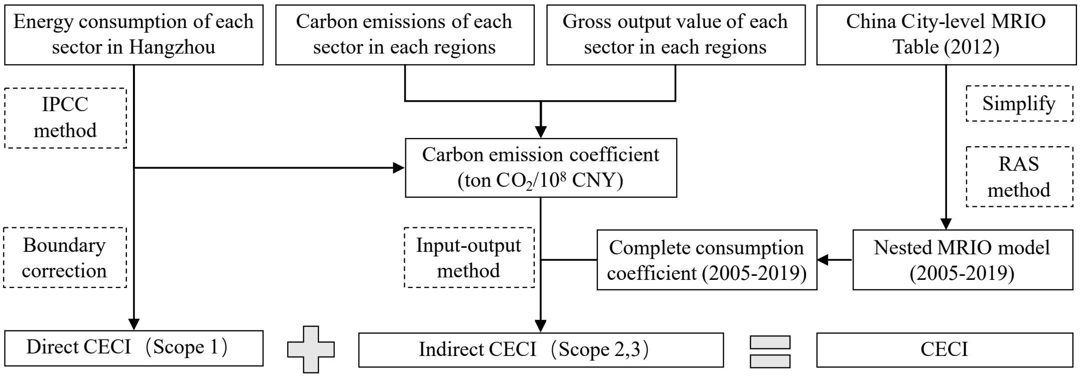


Fig.4-1 The framework of quantify CECI

4.4.1 Research scope and data sources

The CECI studied in this chapter refers to the embodied carbon emission of buildings, including direct carbon emissions and indirect carbon emissions. Direct carbon emission refers to the carbon emission caused by fossil energy consumption on the construction site. In contrast, indirect emissions are carbon dioxide emitted by other sectors as a result of the construction industry. Furthermore, due to the data source for carbon emissions, some emissions related to the cement production process are included in the calculation (Shan et al., 2020). Therefore, the three scopes in the international GHG protocol are all within the estimation range of this study (Development WBCFS and Institute WR, 2012).

Under the IPCC's carbon emission accounting rule (IPCC, 2006), the accounting in this chapter is based on consumption. The carbon emissions in the supply chain and distribution are attributed to the construction industry in Hangzhou. The statistical data and input-output table used in this chapter are mainly from the Hangzhou Statistical Yearbook (Hangzhou Bureau of Statistics, 2006-2020), Zhejiang Statistical Yearbook (Zhejiang Provincial Bureau of Statistics, 2006-2020), China Statistical Yearbook (National Bureau of Statistics of China, 2006a-2020a), and China Energy Statistical Yearbook (National Bureau of Statistics of China, 2006b-2020b). As the energy consumption data of some sectors are not counted in Hangzhou Statistical Yearbook, Shan's method (Shan et al., 2017) is adopted to estimate the energy consumption data of these sectors by using the data of Zhejiang. This method has passed the verification and has good stability.

Carbon Emission Accounts & Datasets (CEADs) provide a free shared download of carbon emission data for academic research. The China City-level MRIO Table 2012(Zheng et al., 2021) and the carbon emission inventory (Shan et al., 2018, 2016) used in this chapter are downloaded from CEADs. Carbon emissions from Tibet, Taiwan, Hong Kong, and Macao were not counted caused of a lack of data. Zhejiang Province does not disclose the energy consumption of sectors. CEADs used the national economic census data from 2008 and the total energy consumption of Zhejiang each year to estimate the carbon emissions of each sector in other years (Shan et al., 2018; Guan et al., 2021). This method assumes that the economy remains structurally stable, and the other years' total carbon emissions will be allocated to various sectors according to the 2008 economic structure. Zhejiang province stopped coal production in 2013 (Xu, 2013), and its economic structure changed. Therefore, this chapter adjusts the carbon emission of the Zhejiang coal industry after 2013 and allocates its carbon emission to other sectors.

4.4.2 Method for direct carbon emission

In this chapter, the IPCC method is adopted to estimate the direct CECI, which is widely used at present. The estimating process is as follows:

$$C_D = \sum_1^n Q_q \cdot EF_q \tag{4-1}$$

Where, C_D denotes direct carbon emission (tCO_2), Q_q denotes the energy q consumed by activities in the construction industry (t), EF_q denotes the emission factor of energy q (tCO_2/t or $tCO_2/10^4\ Nm^3$).

Depending on the method of collection and calculation, the value of EF_q may vary. The calculating approach and parameter in The General Principles for Accounting and Reporting GHG Emissions by Industrial Enterprises (GB/T32150-2015) were used in this research, which is considered to have sound comprehensiveness and reliability (D. Li et al., 2020). The emission factor of raw coal is estimated in proportion to its composition. The calculation process is as follows:

$$EF = V_c \cdot V_u \cdot R_c \cdot 44/12 \tag{4-2}$$

Where, V_c denotes low heating values (GJ/ton or $GJ/10^4\ Nm^3$), V_u denotes carbon content per unit of heating value (GJ), R_c denotes the rate of carbon oxidation (%), 44/12 denotes the transformation coefficient from carbon to CO_2.

The statistical yearbook calculates the energy consumption of construction activities in Hangzhou, which is inconsistent with the accounting boundary of CECI in Hangzhou. In this study, the winning bid quantity of the construction project is used to correct the boundary.

4.4.3 Method for indirect carbon emission

In this study, the indirect CECI is estimated using the input-output approach. This model, proposed by Leontief (Leontief, 1936), was first used to analyze the economic relationship between sectors and was later widely used to estimate energy consumption and carbon emissions. Using the complete consumption coefficient, the carbon emissions of other sectors caused by the construction industry can be quickly estimated. The process of estimating indirect carbon emissions by the input-output method is as follows:

$$C_I = \sum_1^n (C_{i,j}/X_{i,j}) \cdot (X \cdot k_{i,j}) \tag{4-3}$$

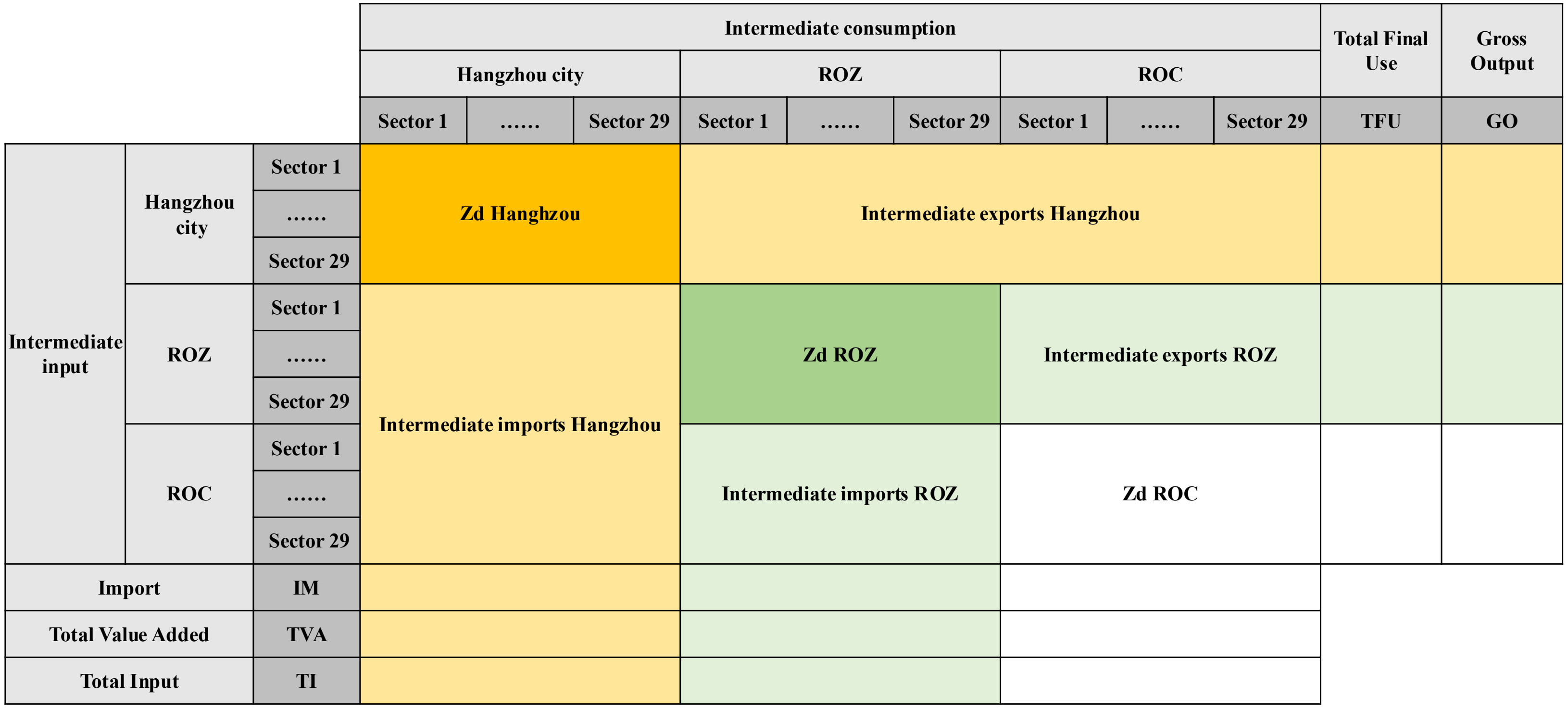
Where, C_I denotes indirect carbon emission (tCO_2), $C_{i,j}$ denotes the direct carbon emissions of sector i in region j (tCO_2), $X_{i,j}$ denotes the total output of sector i in region j (10^8 CNY), $C_{i,j}/X_{i,j}$ represents carbon emission coefficient (ton $CO_2/10^8$ CNY) in Fig.4-1, X denotes the total output of the construction sector in Hangzhou (10^8 CNY), $k_{i,j}$ denotes the construction industry's complete consumption coefficient in Hangzhou to sector i in region j.

China city-level MRIO Table 2012 contains 313 administrative units in China. This chapter mainly studies the CECI of Hangzhou. It considers its carbon flow relationship with the rest of Zhejiang province (ROZ) and the rest of mainland China (ROC), so as shown in Figure 4-2, China city-level MRIO Table (2012) is simplified. A nested MRIO model is established to calculate the driving amount of the construction industry in Hangzhou to other sectors in the three regions (Gilles et al., 2021). At the same time, due to different data sources, sector classification is different. According to the Classification Rules of National Economy Sectors (GB/T4754-2017), variable data is consistently classified into 29 sectors in this study as shown in Table 4-1.

To sum up, the nested MRIO model used in this chapter includes 3 regions and 29 sectors. Compared with other studies, it can analyze the carbon emission relationship between Hangzhou city and the outside, which is beneficial to clarify the carbon flow of the Hangzhou construction industry.

Table 4-1 Division and coding of sectors

Code	Sector	Code	Sector
01	Agriculture, Forestry, Animal Husbandry and Fishery	17	Manufacture of special purpose machinery
02	Mining and washing of coal	18	Manufacture of transport equipment
03	Extraction of petroleum and natural gas	19	Manufacture of electrical machinery and equipment
04	Mining and processing of metal ores	20	Manufacture of communication equipment, computers and other electronic equipment
05	Mining and processing of nonmetal and other ores	21	Manufacture of measuring instruments
06	Food and tobacco processing	22	Other manufacturing and waste resources, repair of metal products, machinery and equipment
07	Textile industry	23	Production and distribution of electric power and heat power
08	Manufacture of leather, fur, feather and related products	24	Production and distribution of gas
09	Processing of timber and furniture	25	Production and distribution of tap water
10	Manufacture of paper, printing and articles for culture, education, and sport activity	26	Construction
11	Processing of petroleum, coking, processing of nuclear fuel	27	Wholesale and retail trades, accommodation and catering
12	Manufacture of chemical products	28	Transport, storage, and postal services
13	Manufacture of non-metallic mineral products	29	Other Service Industries
14	Smelting and processing of metals	OI	Other Industrial sectors, sector 03-26 without 13, 14, 23
15	Manufacture of metal products	OS	Other Service sectors, sector 27 and sector 29
16	Manufacture of general-purpose machinery		



			Intermediate consumption									Total Final Use	Gross Output
			Hangzhou city			ROZ			ROC				
			Sector 1	……	Sector 29	Sector 1	……	Sector 29	Sector 1	……	Sector 29	TFU	GO
Intermediate input	Hangzhou city	Sector 1	Zd Hanghzou			Intermediate exports Hangzhou							
		……											
		Sector 29											
	ROZ	Sector 1	Intermediate imports Hangzhou			Zd ROZ			Intermediate exports ROZ				
		……											
		Sector 29											
	ROC	Sector 1				Intermediate imports ROZ			Zd ROC				
		……											
		Sector 29											
Import		IM											
Total Value Added		TVA											
Total Input		TI											

Fig.4-2 The nested MRIO model

4.4.4 Method for extending input-output models

The estimating of indirect carbon emissions depends on the input-output table, however generating it is time-consuming and labor-intensive. Based on Zheng's research (Zheng et al., 2021), this chapter established a nested MRIO model for 2012. If only this model is used to estimate indirect carbon emissions from 2005 to 2019, the study will lack timeliness. Therefore, it is necessary to extend the input-output model of other years by economic data.

Methods used to extend input-output tables can be classified into a statistical approach, optimization method, and macroeconomic method (Fan and Wan, 2007). This chapter adopts the biproportional scaling method (RAS method) (R, 1962), which belongs to the statistical method. This method is accurate, simple, and easy to operate (Trinh and Phong, 2013).

RAS method is an algorithm to estimate the input flow in the middle of the input-output table of the target year given the following data: intermediate input matrix and a total output of the base year input-output table, the total output of each industry in the target year, total intermediate input of each sector in the target year, total intermediate use of each sector in the target year. This method is usually expressed by formula (4-4).

$$A_n = R_n \dots R_2 R_1 A_0 S_1 S_2 \dots S_n \tag{4-4}$$

Where, A_0 and A_n denote the base year's and target year's direct consumption coefficients, R_i and S_i represent alternative coefficient and manufacturing coefficient, which are the intermediate parameter generated by iterative calculation.

4.4.5 Method for driving force of carbon emissions

The LMDI method used in this chapter is a kind of IDA method, which has become the mainstream carbon emission analysis method. The Kaya identity (KAYA, 1989) proposed by Professor Kaya at the first IPCC conference is one of the most used energy identities. In this equation, carbon emission increments are decomposed into carbon emissions per unit of energy consumption, energy consumption per unit of GDP, GDP per unit of population, and population. With the deepening of research, Kaya identity is constantly expanded.

Based on previous studies, this chapter adds energy consumption (He et al., 2020), building area increment, and output value (D. Li et al., 2020) into identity, and categorizes the factors affecting CECI into the following six elements. Namely, carbon emission intensity (CI), energy consumption structure (ES), energy intensity (EI), demand structure (DS), output value intensity (VI), and construction scale (A).

The hybrid LMDI model can distinguish different stages of construction based on LMDI. Therefore, this model is presented to investigate the factors that drive direct and indirect CECI in Hangzhou. The carbon emissions can be decomposed as Formula (4-5), Formula (4-6), and Formula (4-7).

$$C = C_D + C_I = C_D + C_{I,HZ} + C_{I,ROZ} + C_{I,ROC} \tag{4-5}$$

$$C_D = \sum_q \frac{C_{D,q}}{E_q} \cdot \frac{E_q}{E_{con}} \cdot \frac{E_{con}}{V_{con}} \cdot \frac{V_{con}}{A} \cdot A = \sum_q CI_{D,q} \cdot ES_{D,q} \cdot EI_D \cdot VI_D \cdot A_D \tag{4-6}$$

$$C_{I,HZ} \; or \; C_{I,ROZ} \; or \; C_{I,ROC} =$$

$$\sum_{q,i} \frac{C_{I,q,i}}{E_{q,i}} \cdot \frac{E_{q,i}}{E_i} \cdot \frac{E_i}{DV_i} \cdot \frac{DV_i}{TDV} \cdot \frac{TDV}{A} \cdot A = \sum_{q,i} CI_{I,q,i} \cdot ES_{I,q,i} \cdot EI_{I,i} \cdot DS_I \cdot DVI_I \cdot A_I \tag{4-7}$$

Where, $C_{D,q}$ denotes direct CECI from the use of energy q (tCO_2), E_q and E_{con} denote energy q consumption and total energy consumption in the construction industry (GJ), V_{con} denotes the total output of the construction industry (10^8 CNY), A denotes construction scale (building area increment), $C_{I,q,i}$ denotes indirect CECI from the use of energy q in sector i (tCO_2), $E_{q,i}$ and E_i denote energy q consumption and total energy consumption in the sector i (GJ), DV_i denotes the output of sector i in this area driven by Hangzhou construction industry (10^8 CNY), TDV represents the total output value driven by Hangzhou construction industry (10^8 CNY).

As shown in equations (4-8) and (4-9), the addition form of LMDI decomposition is utilized to explain the difference in carbon emissions increment between the target year (T) and the base year (0). The additional form of the decomposition result demonstrates the essential contribution of influencing variables to carbon emissions increment.

$$\Delta C_D = C_D^T - C_D^0 = \Delta CI_D + \Delta ES_D + \Delta EI_D + \Delta VI_D + \Delta A_D \tag{4-8}$$

$$\Delta C_I = C_I^T - C_I^0 = \Delta CI_I + \Delta ES_I + \Delta EI_I + \Delta DS_I + \Delta DVI + \Delta A_I \tag{4-9}$$

Equation (10) can be used to compute the difference in direct carbon intensity ΔCID between the target and base years (4-10).

$$\Delta CI_D = \sum_q \frac{C_{D,q}^T - C_{D,q}^0}{\ln C_{D,q}^T - \ln C_{D,q}^0} \cdot \ln\left(\frac{CI_{D,q}^T}{CI_{D,q}^0}\right) \tag{4-10}$$

Using a similar method, $\Delta ES_D, \Delta EI_D, \Delta VI_D, \Delta A_D, \Delta CI_I, \Delta ES_I, \Delta EI_I, \Delta DS_I, \Delta DVI, \Delta A_I$ can be calculated.

It should be noted that the EF of fossil energy was set as a constant in the calculation of direct carbon emissions, so $CI = 1$ in Formula (6) and $\Delta CI = 0$ in Formula (8). The indirect carbon emission data comes from CEADs, and EF is unknown, so CI will not be studied in this chapter. In addition, the incremental decomposition of indirect CECI excludes the process emissions from cement production.

4.5. Result

4.5.1 The trajectory of CECI in Hangzhou

(1) Construction industry and CECI accounting

Hangzhou's construction industry is fast expanding. As shown in Figure 4-3, the gross output value increased from 100 billion CNY to 450 billion CNY from 2005 to 2019, an increase of 3.5 times. Building area increment can also reflect the scale and development speed of Hangzhou's construction industry, which increased from 110 million m^2 to about 300 million m^2.

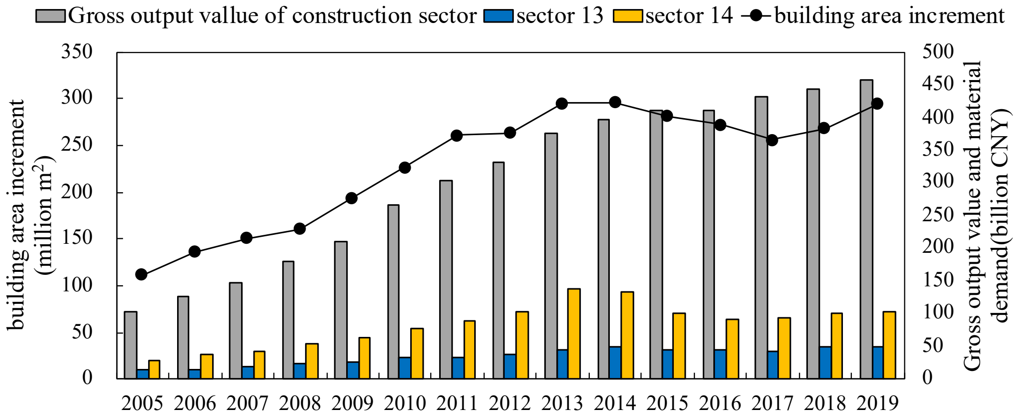


Fig.4-3 The construction industry in Hangzhou

As shown in Figure 4-4, based on the framework of quantify CECI, the CECI in Hangzhou is estimated. The carbon emission from Hangzhou construction industry increased firstly and then decreased and reached its peak in 2014 at 50.2 million tons. Indirect CECI accounts for the majority of total CECI (97%-98%). The carbon emission from Hangzhou construction industry can be described as "low construction emission, high industry driving." Compared with other studies (about 96%), indirect CECI in Hangzhou accounts for a higher proportion, meaning Hangzhou's construction industry should focus on and control indirect CECI to reduce carbon emissions.

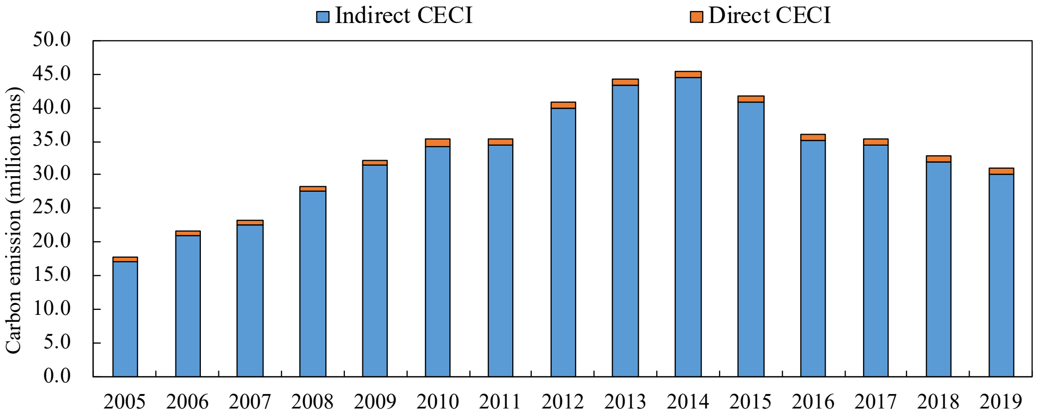


Fig.4-4 The CECI in Hangzhou

(2) The direct CECI in Hangzhou

In general, the direct CECI is increasing. As shown in Figure 4-5, the construction industry in Hangzhou emitted 0.61 million tons of CO_2 by fossil energy in 2005, while it emitted 1.03 million tons 15 years later, an increase of 69%. The changing trend of carbon emission is similar to that of the building area increment, which means that the development of the construction industry in Hangzhou leads to increased direct carbon emission. Before 2011, carbon emissions increased rapidly with the increase of building area increment, peaking at 1.05 million tons of CO_2 in 2011, with an average annual growth rate of 11.47%. From 2011 to 2016, influenced by the HLPO, as the growth rate of the building area increment slowed down until it began to decrease, carbon emissions first fluctuated and then began to decline, with an average annual decline of 2.7%. After 2017, with the increase of building area increment, carbon emissions started to increase after a one-year lag.

The consumption of raw coal, gasoline, diesel oil, and kerosene are the source of direct carbon emissions in Hangzhou construction industry. Construction machinery diesel fuel is the most common source of direct CECI, accounting for 72 % to 85 %, and gasoline is the second most common source of direct CECI. The rest comes from raw coal consumption, which is used to hydrate concrete and heat builders in winter (MHURD, 2011). Notably, carbon emissions from raw coal (4.5% to 2.1%) and diesel (82.0% to 74.0%) are decreasing. In contrast, the share of carbon emissions from gasoline has increased by about 10%.

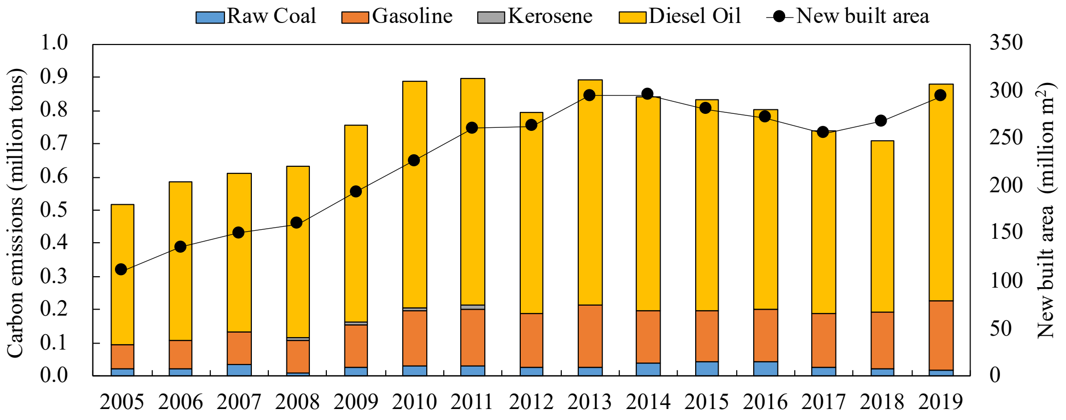


Fig.4-5 The direct CECI in Hangzhou

(3) The indirect CECI in Hangzhou

The indirect CECI change can be divided into two stages. Prior to 2014, indirect CECI was on the rise, peaking at 44.4 million tons in 2014. Then, indirect CECI shows a decreasing trend. In Fig.4-6 to Fig.4-8, indirect carbon emissions are divided by region and sector. The line represents the change of indirect carbon emissions in regions, and the bar chart expresses the proportion of carbon emissions of each sector in regions.

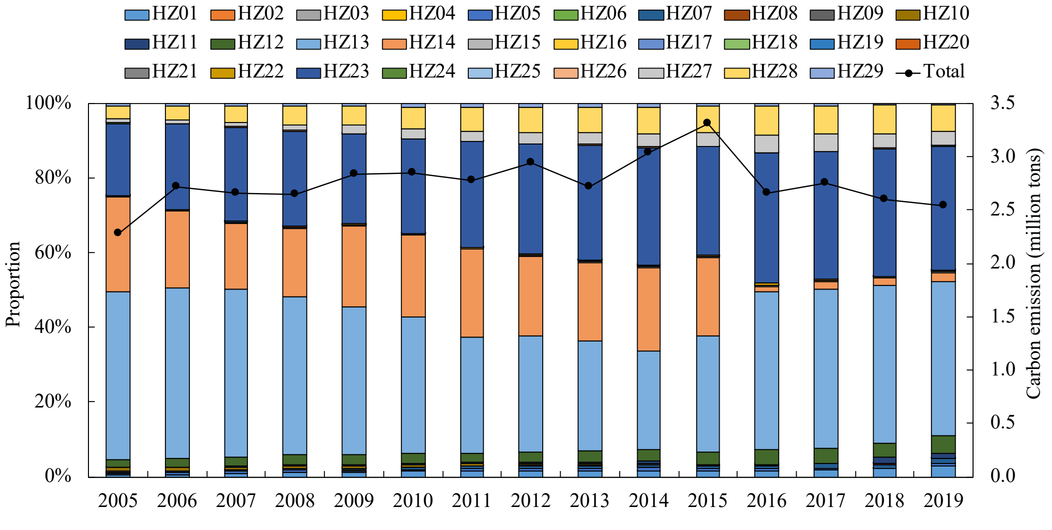


Fig.4-6 Indirect CECI in divided by sector (Hangzhou)

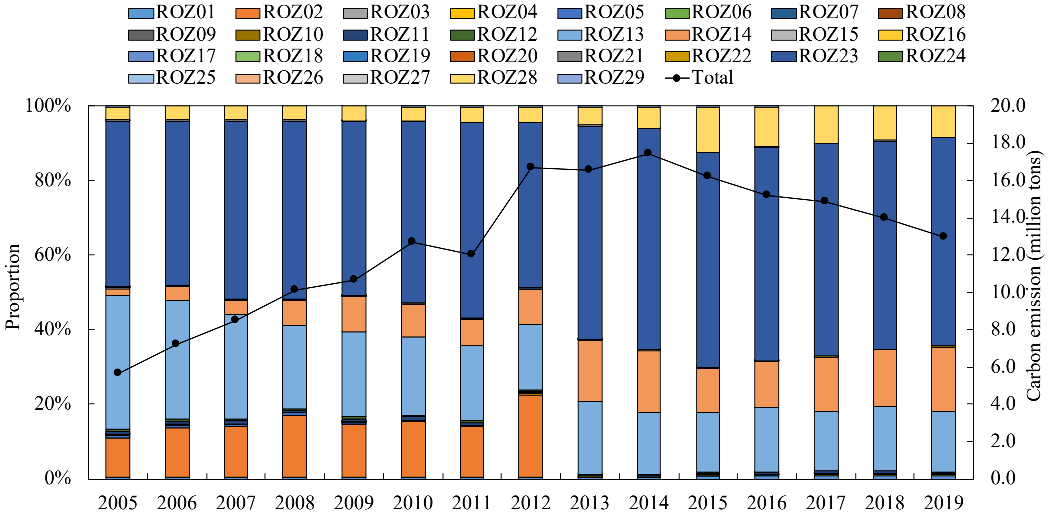


Fig.4-7 Indirect CECI in divided by sector (ROZ)

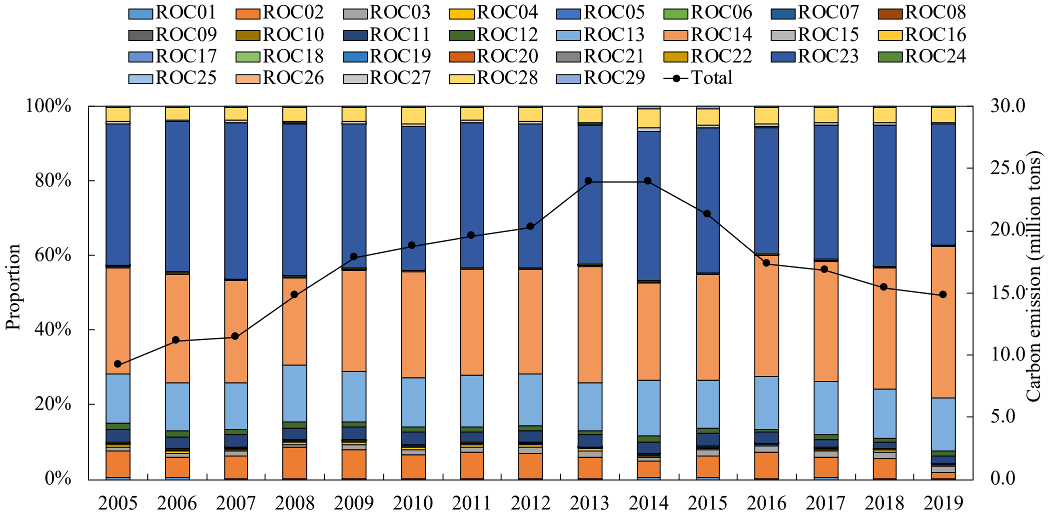


Fig.4-8 Indirect CECI in divided by sector (ROC)

It can be found that the Hangzhou construction industry is highly dependent on resource imports and has a noticeable carbon emission spillover. Only 6.2%-13.3% of indirect CECI are locally emitted, and the emissions are stable at 2.3-3.3 million tons. Hangzhou's construction industry's primary indirect carbon emissions are in the ROC, accounting for 47%-57.0%, reaching the peak of 23.9 million tons in 2014. ROZ is also an important emission region, at its peak, 17.4 million tons of indirect carbon emissions are emitted here. After 2013, the proportion of ROZ gradually increased, and by 2019, it had reached 44.5%, close to ROC.

Carbon emissions from electricity use in the construction industry are the primary source of indirect carbon emissions, accounting for 37.6% to 47.2% of the total. The consumption of fossil energy in the manufacturing of building materials, represented by steel (Sector 14), is the second-largest source of indirect carbon emissions, accounting for 16.8% to 24.8% of the total. Sector 13, which produces cement, another vital building material, is the third-largest source of carbon emissions, accounting for 15.5% to 24.8% of the total. In addition, sector 02 including coal production, and sector 28 including transportation are also important sources of indirect carbon emissions from the construction industry in Hangzhou.

In Hangzhou and ROC, Hangzhou's construction industry mainly emitted CO_2 in sectors 13, 14, and 23. With the closure of large steel mills in 2016(Hangzhou Municipal Government, 2014), the carbon emission of Sector 14 in Hangzhou is significantly reduced. In ROZ, the construction industry in Hangzhou mainly drove carbon emissions in sectors 2, 13, and 23. Since 2013, the carbon emissions of sectors 14 and 28 in ROZ have increased significantly. It may be caused by the transfer of the metal smelting industry in Hangzhou. In 2013, Changguang Coal Yard was closed, and Zhejiang no longer produced coal (Xu, 2013). Therefore, the indirect carbon emissions of sector 02 in ROZ were reduced to 0.

4.5.2 The driving force of CECI in Hangzhou

Formula (5) - (10) is used to decompose the CECI increment in Hangzhou and explore the key driving force. The results are shown in Table 4-2. From 2005 to 2019, the CECI in Hangzhou increased by 13.68 million tons, mainly from indirect CECI (13.26 million tons, 96.9%), while the increment of direct CECI was only 0.42 million tons. The proportion of direct carbon emission increment in total increment (3.1%) is higher than that of total direct CECI in total carbon emission of Hangzhou (2.3%), which indicates that the emission reduction effect of the construction industry in Hangzhou is not as good as that of other sectors.

In general, carbon emission intensity (△CI, 10.33 million tons), demand structure (△DS, 22.84 million tons) and construction scale (△A, 25.64 million tons) were the factors promoting the increase of CECI in Hangzhou. The energy intensity (△EI, -31.27 million tons) is crucial to restrain the growth of carbon emissions. Output value intensity (△VI/△DVI, -9.95 million tons) and energy consumption structure (△ES, -3.91 million tons) contribute little to carbon emission reduction.

Table 4-2 Decomposition results of carbon emission increment in construction industry (Million tons)

Period	△CI		△ES		△EI		△VI/△DVI		△A		△DS	Total
	direct	indirect	direct	indirect	direct	indirect	direct	indirect	direct	indirect	indirect	
2005-2006	0.00	-2.11	0.00	-0.03	-0.05	-1.88	0.00	3.16	0.13	3.24	-1.64	0.82
2006-2007	0.00	4.03	0.00	-0.04	-0.08	-2.83	0.04	-1.46	0.07	1.95	2.83	4.51
2007-2008	0.00	-0.38	-0.03	0.05	-0.09	-1.88	0.10	2.81	0.04	1.43	2.39	4.44
2008-2009	0.00	0.51	-0.01	-0.09	0.02	-0.47	-0.03	-3.99	0.15	5.23	2.40	3.73
2009-2010	0.00	0.91	-0.02	0.02	-0.05	-4.80	0.08	2.20	0.15	4.68	-0.24	2.93
2010-2011	0.00	0.77	-0.04	-0.18	-0.09	-2.21	-0.01	-5.41	0.15	4.54	2.42	-0.06
2011-2012	0.00	0.20	-0.04	-0.08	-0.16	-1.35	0.08	3.80	0.01	0.34	2.91	5.70
2012-2013	0.00	1.23	0.00	0.39	-0.01	-8.85	0.01	4.45	0.11	4.27	1.82	3.43
2013-2014	0.00	-0.28	-0.02	-0.25	-0.10	-0.70	0.06	-11.03	0.00	0.06	13.17	0.91
2014-2015	0.00	-0.26	-0.02	-0.44	-0.02	1.64	0.08	-7.99	-0.05	-2.04	6.11	-2.98
2015-2016	0.00	1.32	0.01	-0.49	-0.04	-0.13	0.03	-4.30	-0.03	-1.17	-0.88	-5.68
2016-2017	0.00	2.94	-0.04	-0.93	-0.08	-3.02	0.10	7.57	-0.06	-2.01	-5.14	-0.66
2017-2018	0.00	1.94	-0.08	-1.45	0.02	-3.24	-0.02	0.71	0.04	1.49	-1.33	-1.91
2018-2019	0.00	-0.48	-0.02	-0.12	0.19	-1.02	-0.06	-0.93	0.09	2.82	-1.97	-1.50
Total	0.00	10.33	-0.30	-3.61	-0.54	-30.73	0.46	-10.41	0.81	24.83	22.84	13.68

4.6. Discussion

4.6.1 Influence on direct CECI in Hangzhou

In the growth of direct CECI, the construction scale is the main driving factor, Hangzhou has built 3,469 million m^2 of new buildings in 15 years. Output value intensity (VI) also has a noticeable driving, and the output value intensity increases by 67.0%. The increase of VI indicates that the investment of real estate enterprises in building per unit area increases. The hot property market in Hangzhou may be the factor behind the growth of carbon emissions. This view is supported by Fan (Fan and Zhou, 2019). The increase in real estate investment will push up land prices and encourage local governments to sell more land for construction, generating a lot of energy consumption and carbon emissions.

EI was the main factor that restrained the growth of direct CECI in Hangzhou. This result is different from the viewpoints of some studies. He believes EI is a factor promoting the growth of CECI in China (He et al., 2020), Wang believes EI has no contribution to the change of CECI in Zhejiang (Wang and Feng, 2018), while Li's research supports the viewpoints of this study (Li et al., 2020). This difference mainly comes from the research scale and construction technology of the research object, indicating the importance of targeted carbon emission analysis from the city-scale. This indicates that over the past 15 years, the technological progress of construction in Hangzhou had a positive impression on emission reduction, and the technological progress is faster than in other regions. EI promoted the growth of carbon emissions in 2009-2011. The construction industry in Hangzhou still has extensive energy use, and stricter control strategies need to be adopted (Zhou et al., 2019).

ES is also an essential factor to restrain the growth of carbon emissions, and its role is stable. The energy consumption structure of the Hangzhou construction industry has changed in the past 15 years. It is mainly manifested by the decrease in the proportion of diesel, and the increase in the proportion of electric energy. It may be related to the mechanization of construction (Intelligent research consulting, 2021). As shown in Figure 4-9, a decrease in the proportion of diesel is the main factor inhibiting the growth of direct carbon emissions.

In the above analysis, only fossil energies are considered, electricity has a significant impact on the energy consumption structure of the construction industry. This chapter also explores the decomposition analysis of carbon emissions after adding electric energy. The electricity carbon emission factor is from the National Center for Climate Strategy.

With the addition of electricity, ES becomes the driving factor for the growth of carbon emissions, driving Hangzhou CECI to increase by 0.62 million tons. Electricity and diesel oil are the crucial factors driving and restraining the increase of CECI in Hangzhou, respectively. The result is inconsistent with Hu's research (Hu and Zhu, 2015). This is due to the different directions of the energy structure change. During the period Hu studied from 1996 to 2012, the primary energy source in the construction industry changed from coal to diesel and electricity. In this study, electricity is gradually replacing diesel. Whether more energy sources with a small carbon emission coefficient are used will affect the drive of ES to carbon emission.

In the short term, the change of construction industry energy consumption structure in Hangzhou is not conducive to reducing carbon emissions because the region where Hangzhou is located is still dominated by thermal power generation, which has a large emission factor. In the long run, with the implementation of clean energy policies such as hydropower and photovoltaic power generation (Zhejiang D&RC, 2021, 2018), the potential of carbon emission reduction is brought about by the change of energy consumption structure in the construction industry is enormous.

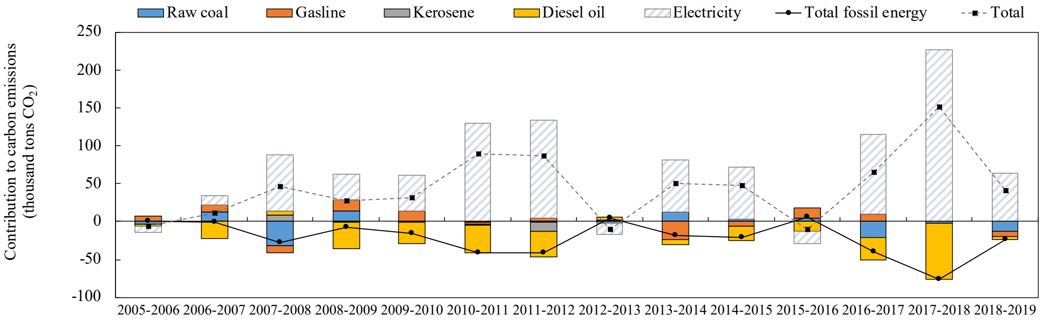


Fig.4-9 Contribution of ES to the growth of direct CECI

4.6.2 Influence on indirect CECI in Hangzhou

Indirect CECI is emitted by the upstream sector of the construction industry. The contribution of all six factors to indirect CECI is divided into three phases of construction industry development in Hangzhou and summarized in Figure 4-10.

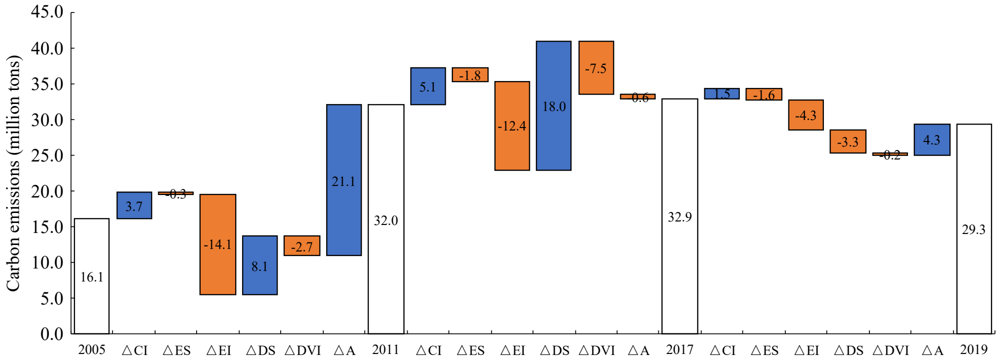


Fig.4-10 Changes in indirect CECI driven by six factors in Hangzhou

(1) Construction scale (A)

The construction scale is the most important factor affecting the change of indirect CECI. This result is supported by Li (D. Li et al., 2020) and Shi (Shi et al., 2017). Shi used the SDA method and obtained the same results. In Shi's study, the final demand effect is used to represent the floor area increment. In 2005-2011, due to the rapid increased in the demand for building materials, construction scale contributed the largest proportion (133%) to the increase in the indirect CECI, this is similar to Wang's research on China's construction industry (Wang et al., 2015).

(2) Demand structure (DS) and demand value intensity (DVI)

Production structure effect (PS) is a driving factor of carbon emission commonly used by SDA method, and it is considered that LMDI method cannot be used to analyze production structure effect (Shi et al., 2017). This chapter fills this gap in the LMDI method and further decomposes PS into demand structure (DS) and demand value intensity (DVI).

The demand structure was the second largest contributor (172%) to the indirect CECI growth and can be explained by the increasing complexity of construction products. In 2005-2019, conventional masonry buildings are gradually being replaced by more complex frame structure buildings (Xu et al., 2006), which consume more upstream carbon intensive products, such as steel. This is consistent with Minx's point (Minx et al., 2011).

The change of demand structure in the construction industry also proves this point of view such as Fig.4-11, the proportion of Hangzhou construction industry's demand for the energy sector increased from 9% to 21% from 2005 to 2015, which is an important reason for the growth of carbon emissions driven by the demand structure. After 2015, as Hangzhou completed the elimination of key industries (Hangzhou Municipal Government, 2015), the energy efficiency of the building materials industry was improved. Although the demand for building materials continues to grow, the demand for energy has decreased, and the demand structure became a factor that restrains the growth of carbon emissions.

The demand value intensity was the second major restraining factor (-79%) to the indirect CECI growth. It means that the material and labor required for the unit area are reduced, indicating that the progress of construction technology is conducive to the reduction of carbon emissions. Shi's study put forward similar opinions on the explanation of the decreased effect of product structure (Shi et al., 2017).

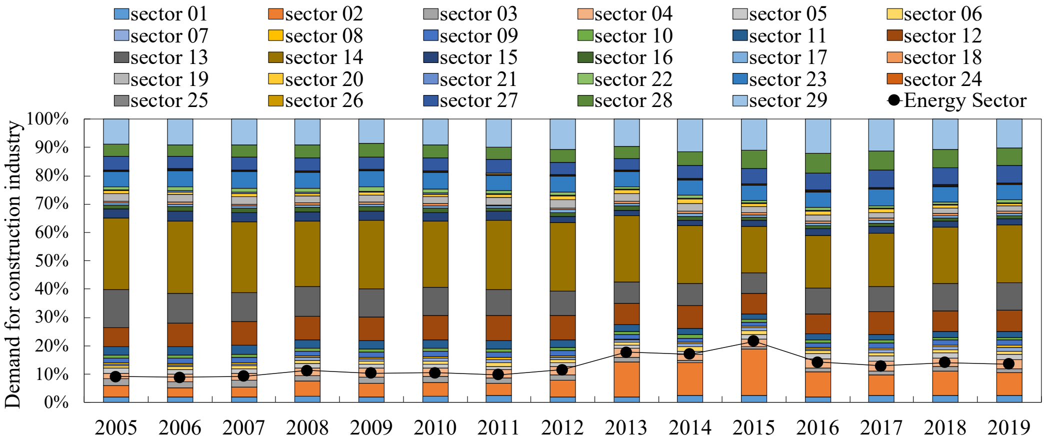


Fig.4-11 Demand structure in construction industry

(3) Energy intensity (EI)

In the past 15 years, the upstream sector's energy intensity has been the essential factor to restrain the growth of indirect carbon emissions such as Figure 4-12, which is similar to the finding of Nie (Nie et al., 2016). From a macro perspective, the increase in China's industry's general energy use efficiency can explain the above results. The emission reduction effect of energy intensity in industries fluctuated, which Zhou attributed to the fact that China's industrial development mode is still extensive and has a negative impact (Zhou et al., 2019).

EI of upstream sectors in Hangzhou reduced indirect carbon emissions by 3.3 million tons for Hangzhou's construction industry, with HZ13 and HZ14 being the most significant contributors. As the sectors with high energy consumption, these two materials sectors are the main objects of industrial structure adjustment. Driven by the Five-Year Plan and Hangzhou municipal policies (Hu and Zhu, 2015), the backward enterprises are constantly eliminated. The energy efficiency of the two sectors is improved, which is beneficial to emission reduction. 2015 is the target year of the 12th Five-Year Plan and the target year for Hangzhou to fully complete the elimination task of iron and steel, cement, and other vital industries (Hangzhou Municipal Government, 2015). Around 2015, there may be expansion and rough production to reach the target (Lu et al., 2016), resulting in reduced energy efficiency and fluctuations in ΔEI.

EI of upstream sectors in ROZ reduced indirect carbon emissions by 15.1 million tons. The orderly closure of coal mines and technologically backward power plants in Zhejiang (Yuan, 2014) can effectively improve energy efficiency (Cherni and Kentish ,2007). In 2013, the withdrawal from coal production greatly enhanced the energy efficiency of sector 02, reducing emissions by 4.5 million tons. The energy efficiency of ROZ23 is steadily improved, and the emission reduction effect is stable, with a total emission reduction of 7.1 million tons. The reason why ROZ14 promotes the growth of carbon emissions may be that ROZ region has undertaken the transfer of the Hangzhou steelmaking industry, making the sector consume more energy.

The improvement in energy efficiency in the upstream sector of ROC reduced Hangzhou's indirect CECI by 12.3 million tons. The most prominent is ROC23, which reduces emissions by 6.85 million tons. These emissions reduction contributions can be explained by policy-driven energy efficiency improvements in China's industrial sector (Liu et al., 2021).

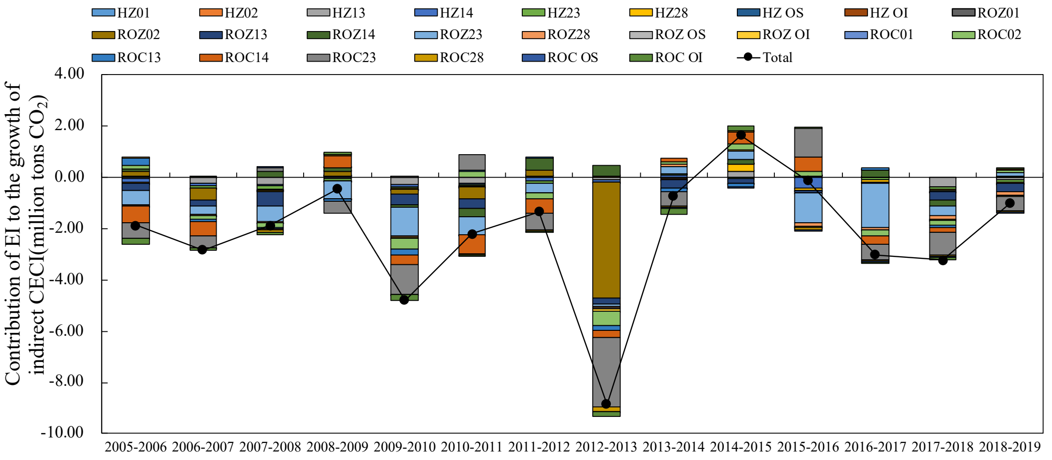


Fig.4-12 Contribution of EI to the growth of indirect CECI

(4) Energy consumption structure (ES)

Similar to Wang's study, ES is modestly curbing the growth of carbon emissions (Wang and Feng, 2018), the energy consumption structure of sectors is shown in Appendix. The power of emission reduction mainly comes from the decrease of dependence on coal. With the reduction of coal use, the energy consumption structure will be conducive to removing indirect CECI (Naughton, 2007). This view is supported by Lu, who believes that reductions coal production and consumption have contributed to emissions reductions (Lu et al., 2016).

As shown in Figure 4-13, Energy structure adjustment has achieved initial results in ROZ and Hangzhou. The most significant contributor to emission reduction is ROZ23. Before 2006, ROZ and Hangzhou power generation enterprises had a single energy consumption structure and only used coal. After introducing natural gas generating units, natural gas accounted for an increased proportion in the energy consumption structure. The other two major emission reduction contributors, HZ14 (2015-2016) and ROZ13 (2013-2018) are also driven by the increase in the proportion of natural gas in the energy consumption structure. The upgrading of the industrial structure causes the change in the energy consumption structure of these two sectors.

A slight decrease in the proportion of coal in the ROC energy consumption structure has no apparent impact on CECI. ROC is advised to accelerate the shift away from coal and promote natural gas and clean energy to reduce carbon emissions in the construction industry.

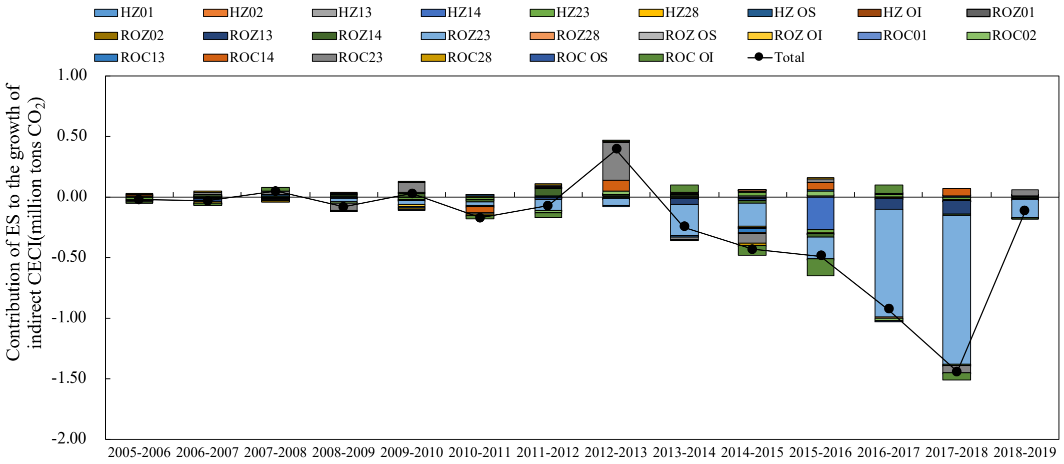


Fig.4-13 Contribution of ES to the growth of indirect CECI

4.7. CECI in Kitakyushu, Japan

Using the same method, the CECI in another research subject, Kitakyushu City, Japan, were calculated, and the main driving factors causing carbon emissions changes were obtained through decomposing the carbon emission differences.

4.7.1 CECI accounting

Compared with the complex accounting method for the CECI of Hangzhou, the accounting for the CECI in Kitakyushu is relatively simple due to the public availability of energy and carbon emission data. The National Institute for Environmental Studies of Japan provides an environmental impact intensity data manual based on input-output tables, which details the environmental impact intensity of the construction industry, and direct and indirect CECI can be calculated using this data.

This paper used the carbon emission intensity for 2005, 2011, and 2015 provided by the institute and interpolated the data for other years. As shown in Figure 4-14, the carbon emissions of Kitakyushu's construction industry from 2005 to 2019 are displayed. Compared with Hangzhou, the total CECI of Kitakyushu are smaller, and there is no obvious trend of change. This may be related to the relatively stable building stock in Kitakyushu.

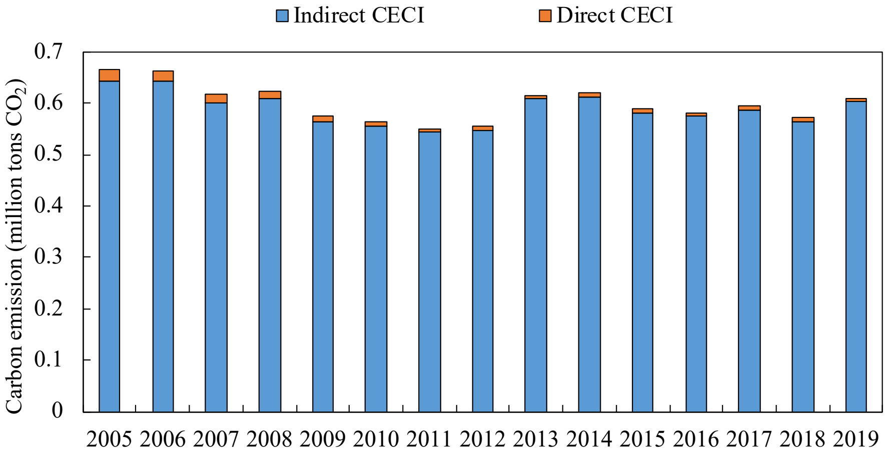


Fig.4-14 Carbon emission from construction industry in Kitakyushu

The direct CECI in Kitakyushu have shown a decreasing trend followed by a stable period. In 2005, the construction sector in Kitakyushu emitted 21,937.4 tons of CO_2 through the use of fossil fuels, which rapidly decreased to only 6,539.4 tons in 2011. From 2012 to 2019, the direct CECI remained relatively stable, fluctuating around 7,000 tons. The changes in direct carbon emissions were influenced by a reduction in construction area and a decrease in carbon emission intensity. From 2005 to 2011, the construction area in Kitakyushu showed a decreasing trend, from 1.3 million m^2 to 1.0 million m^2. Additionally, the carbon emission intensity decreased from 0.096 to 0.039 tons CO_2/million JPY. After 2012, the construction area and carbon emission intensity remained stable at around 1.0 million m^2 and 0.035 tons CO_2/million JPY, respectively. Direct CECI accounted for a relatively small proportion of the total CECI, ranging from 1.1% to 3.1%, which was lower than that of Hangzhou.

As shown in Figure 4-15, the sources of direct carbon emissions in Kitakyushu are relatively complex, and its energy structure has undergone significant changes. In 2005, the main sources of carbon emissions were fuel oil and natural gas, accounting for 33.8% and 24.95%, respectively. At the same time, kerosene and diesel were also important sources of carbon emissions, accounting for 15.5% and 17.6%, respectively. Over time, the use of fuel oil and natural gas gradually decreased, and by 2015, these two fossil fuels accounted for only 10.3% and 1.9%, respectively, of CECI. Meanwhile, the proportion of kerosene, diesel, and gasoline gradually increased, accounting for 27.5%, 32.4%, and 27.9%, respectively.

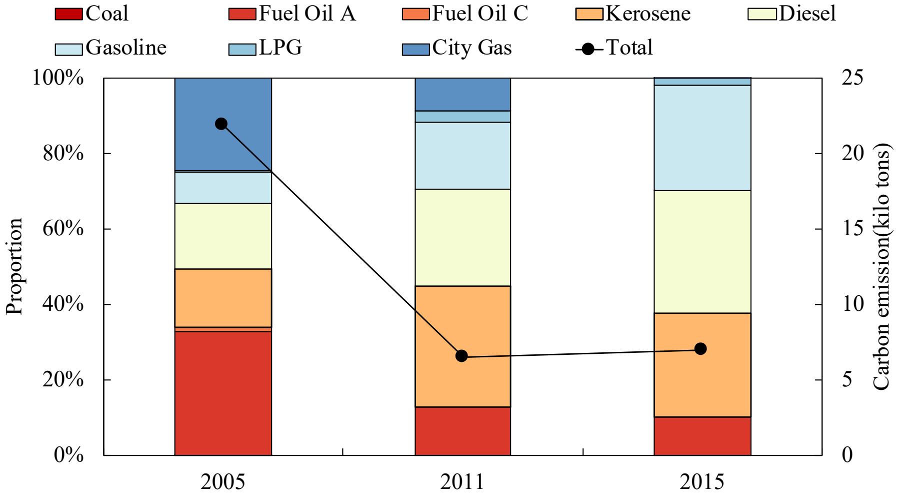


Fig.4-15 The source of direct CECI in Kitakyushu

Indirect CECI is the main factor causing fluctuations in the total CECI in Kitakyushu. Between 2005 and 2019, the indirect CECI fluctuated between 0.54 and 0.65 million tons, with higher emissions in 2005 and 2006, exceeding 0.64 million tons. The indirect carbon emissions in the remaining years were approximately around 0.6 million tons. Figure 4-16 shows the classification of indirect carbon emissions by source sector. Indirect CECI was relatively stable across upstream sectors, with only the S7 sector showing fluctuations.

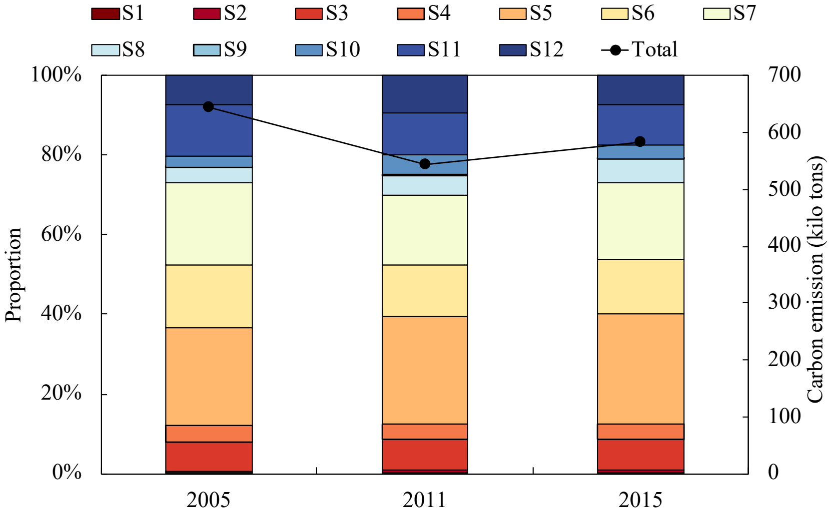


Fig.4-16 The trajectory of indirect CECI in Kitakyushu

Similar to Hangzhou, the material sectors are important contributor to carbon emissions. Among them, the largest contributor is the non-metallic mineral product industry (S5), which contributes more than 25% of the total indirect carbon emissions. This sector provides high-carbon materials such as cement and bricks for the construction industry. The non-ferrous metal product industry (S7) is also a major carbon emitting sector, accounting for approximately 20%

of the total indirect CECI. The contribution of the steel industry (S6) ranges from 12.9% to 15.6%. In addition, the transportation sector (S11) contributes approximately 10% of carbon emissions. The difference from Hangzhou is mainly in the energy-related sector (S10), whose contribution accounts for only 2.6% to 5.1% of the total indirect CECI. This difference may be due to differences in the two countries' carbon emission responsibilities and carbon accounting boundaries.

4.7.2 Direct CECI decomposition

Figure 4-17 shows the decomposition of direct CECI in Kitakyushu. Over the 10-year period from 2005 to 2015, direct CECI decreased by 149,300 tons.

From 2005 to 2011, direct carbon emissions decreased significantly, with the main driving force being the improvement in energy efficiency, contributing 74.9% of the emission reduction, or 115,400 tons. The decrease in newly built area was also an important factor, contributing 31,800 tons to carbon reduction. In addition, energy structure and output intensity were also reasons for the decrease in carbon emissions. The carbon emission intensity has had a negative effect on carbon reduction, and the reason may be that with the advancement of energy technology, the combustion efficiency of fossil fuels has improved, leading to more carbon elements being oxidized into carbon dioxide. Overall, the improvement in energy technology played a significant role in reducing CECI in Kitakyushu during these six years.

From 2011 to 2015, direct CECI showed an increasing trend, driven mainly by output intensity. The increase in output intensity indicates that a larger amount of construction is needed per unit area, possibly due to the loss of economies of scale in the construction industry. Although energy efficiency and energy structure still contributed to carbon reduction, the amount of contribution decreased significantly, possibly due to energy technology entering a bottleneck period after rapid progress.

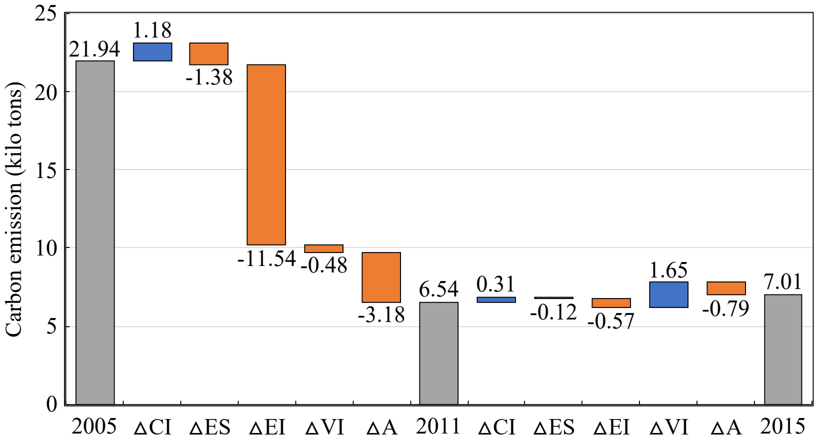


Fig.4-17 Direct CECI decomposition in Kitakyushu

4.7.3 Indirect CECI decomposition

The results of the decomposition of indirect CECI in Kitakyushu are shown in Figure 4-18. Over the 10 years from 2005 to 2015, indirect CECI decreased by 62.1 kilotons. Although the reduction in indirect CECI is greater than that of direct CECI, the reduction effect of indirect CECI is not as good as that of direct CECI in terms of the total amount. This means that the construction industry has a better carbon reduction effect than upstream sectors.

In the six years from 2005 to 2011, the reduction in indirect CECI reached 99.6 kilotons. All influencing factors made a positive contribution to carbon reduction. Among them, the reduction of newly built area was the main contributor to carbon emission reduction, contributing 70.5 kilotons of carbon reduction. Changes in energy structure and improvement in energy efficiency in upstream sectors contributed 12.9 kilotons and 3.9 kilotons of carbon reduction, respectively.

From 2011 to 2015, indirect CECI showed an upward trend, increasing by 37.5 kilotons of carbon emissions. Similar to direct carbon emissions, the intensity of output value is the main factor causing the growth of carbon emissions, indicating that producing the same weight of materials requires more input, which will result in more energy consumption. In addition, demand structure is also a factor causing the growth of carbon emissions, indicating that the construction industry in Kitakyushu used more high-energy-consuming materials in these four years than before. Another driving factor for carbon growth is energy structure, which may be caused by the closure of nuclear power plants in Japan after 2011, resulting in changes in energy structure. The reduction in newly built area contributed 45.5 kilotons of carbon emissions to curb the growth of carbon emissions.

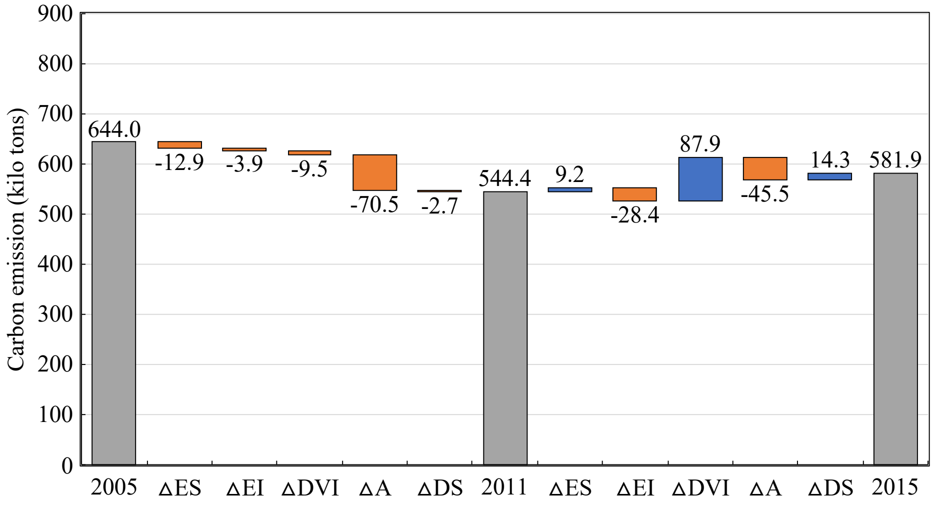


Fig.4-18 Indirect CECI decomposition in Kitakyushu

Overall, the carbon emissions of the construction industry in Kitakyushu showed a downward trend, and the driving force for carbon reduction came from the reduction in newly built area and energy intensity.

4.8. Summary

This chapter aims to estimate the CECI of city-scale, explore the carbon emission trajectory between the Hangzhou construction industry and other sectors in regions, and clarify responsibility of the construction industry. By establishing a framework to quantify the city-scale CECI and using the hybrid LMDI method, this chapter tracks the CECI, studies the driving force of carbon emission change in the Hangzhou and Kitakyushu construction industry from 2005 to 2019.

Although the CECI of Hangzhou reached its peak in 2014 and decreased slowly as the result, the total emissions are still large, and emission reduction contribution of the construction industry mainly comes from the upstream sector. In terms of carbon trajectory, CECI of Hangzhou spillover is serious, with a large amount of carbon dioxide is emitted through the upstream sector emissions in the field. The indirect carbon emissions sources of the construction industry in Hangzhou mainly come from sector13 and sector14 in the building materials industry, sector02 and sector23 in the energy industry, and sector28 in the transportation industry, which needs to be paid great attention. In terms of factors affecting carbon emissions, building area increment had the most significant influence on the increase of CECI in Hangzhou. Energy intensity was the most critical factor to restrain carbon emissions. The upstream sector’s energy consumption structure and energy efficiency contribute to the reduction of carbon emissions, indicating that China’s emission reduction policies and industrial structure transformation policies have achieved specifics in recent years. The demand structure proposed in this study is one of the critical reasons for the growth of Hangzhou CECI, it reveals that construction industry emission reduction needs the support of the upstream industry.

In addition, this chapter analyzed the factors influencing the reduction of carbon emissions in Kitakyushu and found that the carbon emissions from the city’s construction industry are relatively stable. The reduction of newly constructed building area and the decrease in energy intensity are the main driving factors for the reduction of carbon emissions in Kitakyushu City, while the intensity of output value is a factor that inhibits carbon reduction. By comparing the carbon emission change factors of two cities, the main driving factors for carbon emission changes in urban construction industry were revealed, and these driving factors are equally applicable to cities in different stages of development. Therefore, the results of this study have certain guiding significance for urban planning and carbon emission reduction in the construction industry.

Finally, the limitations of this chapter are as follows. Due to data limitations, this study does not consider the impact of inflation on carbon emission estimation. The carbon emission relationship between Hangzhou city and other regions is also limited to two larger scales, Zhejiang Province, and China. Studying carbon flow between cities in more detail will be the focus of future research.

Appendix

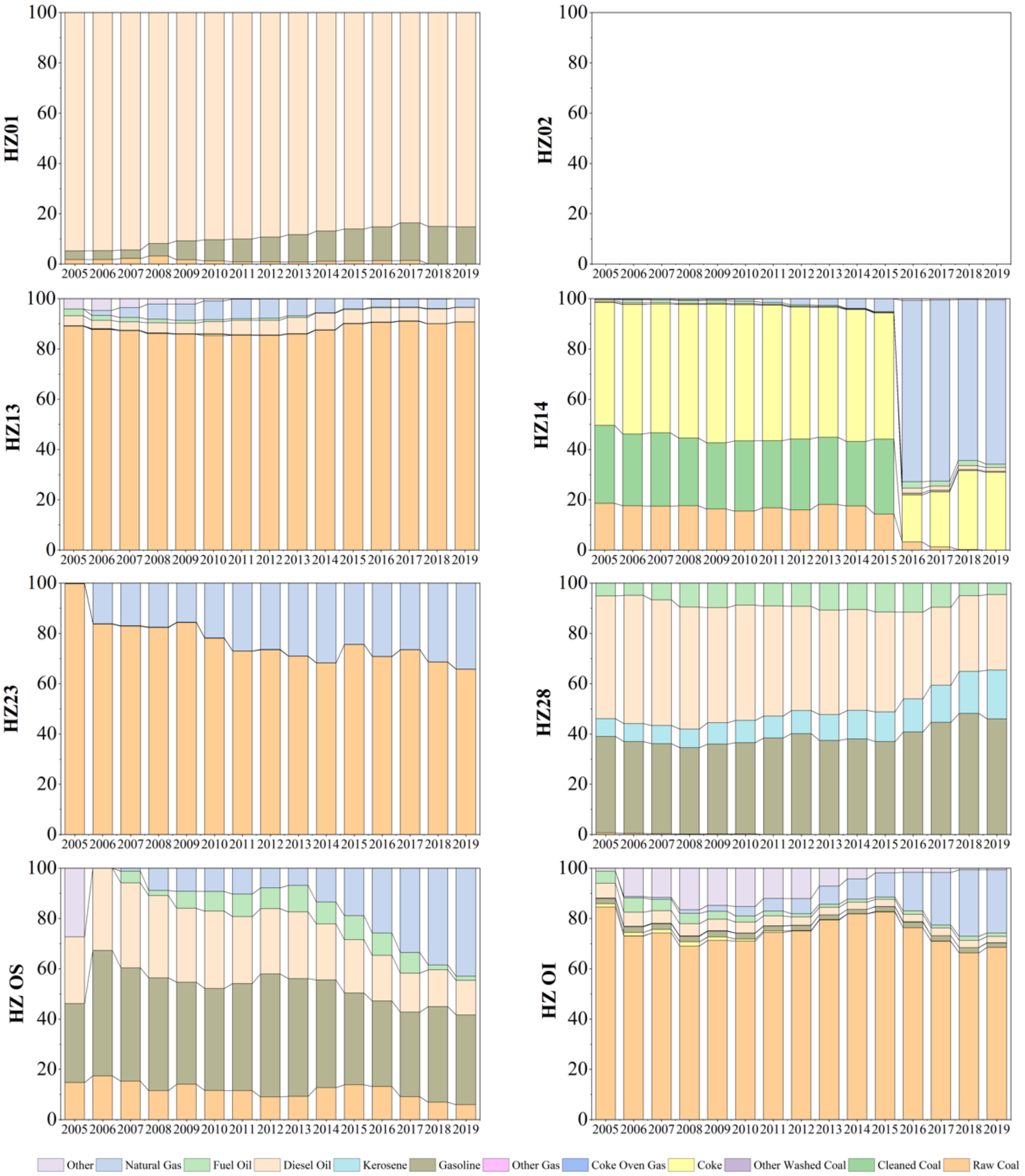


Fig.4-A1 Energy consumption structure of main upstream sectors (Hangzhou)

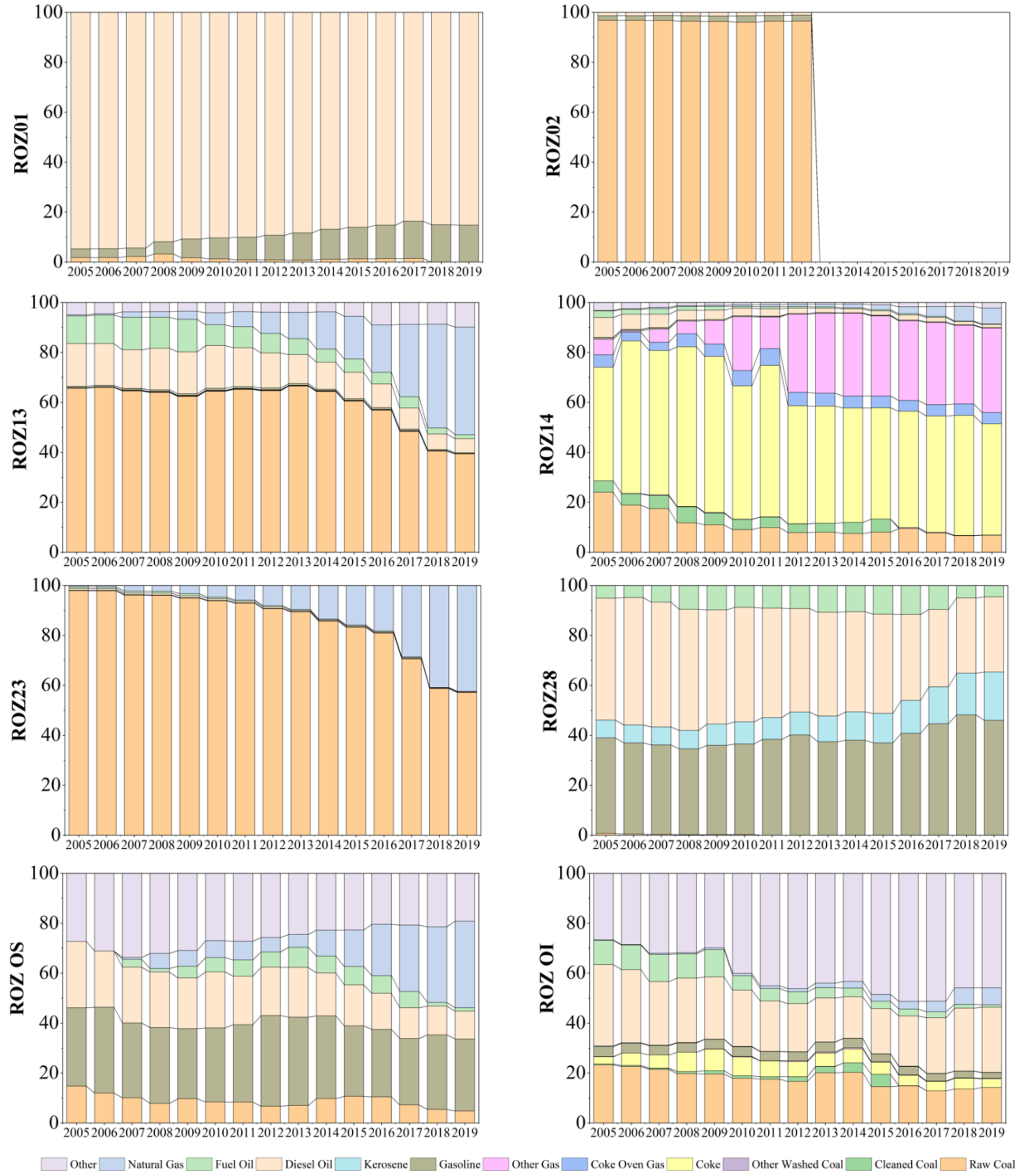


Fig.4-A2 Energy consumption structure of main upstream sectors (ROZ)

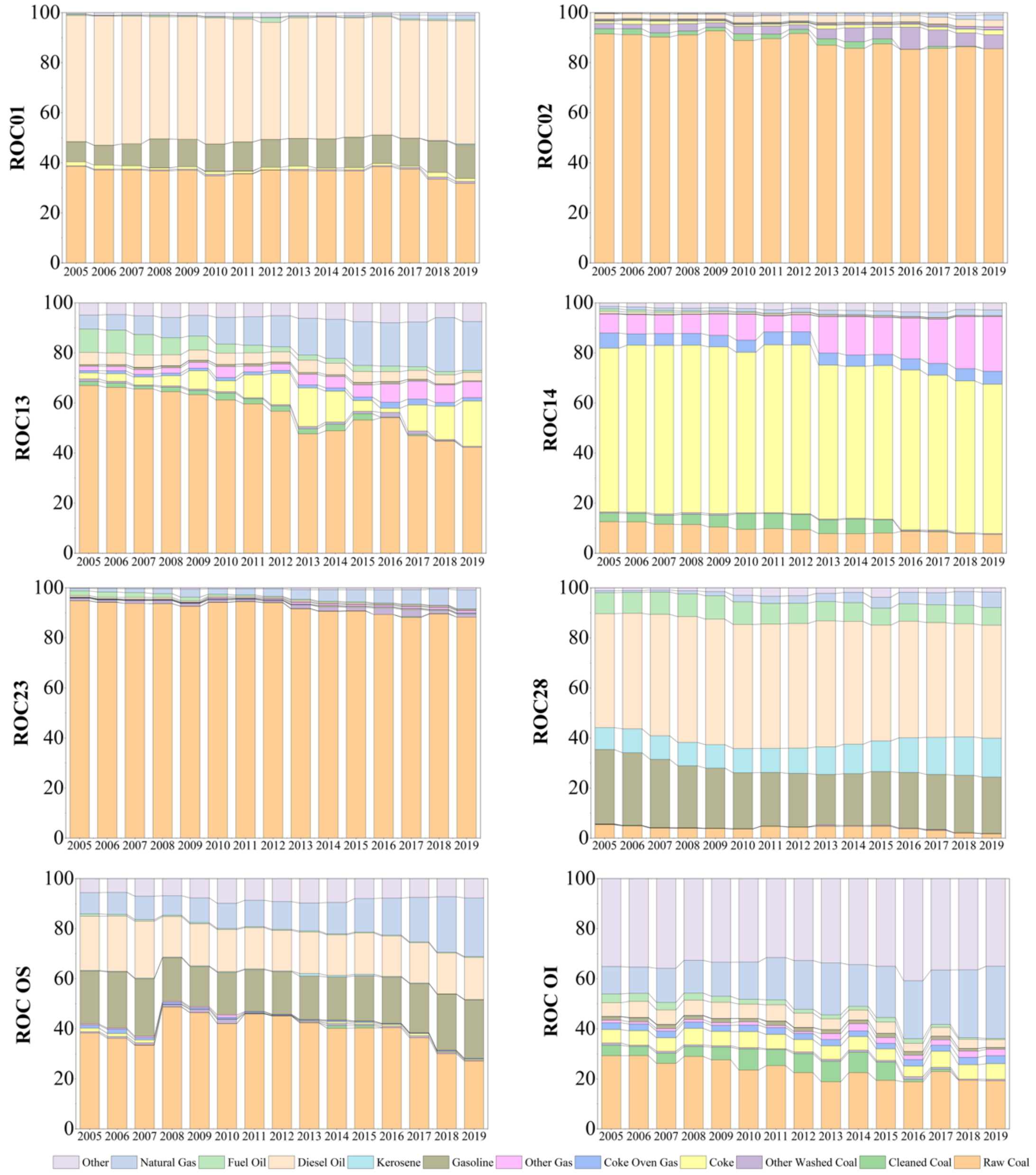


Fig.4-A3 Energy consumption structure of main upstream sectors (ROC)

Reference

Abu Dabous, S., Shanableh, A., Al-Ruzouq, R., Hosny, F., & Khalil, M. A. 2022. A spatio-temporal framework for sustainable planning of buildings based on carbon emissions at the city scale. Sustainable Cities and Society, 82, 103890. https://doi.org/10.1016/j.scs.2022.103890.

AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability — IPCC, 2022.

Cang, Y., Yang, L., Luo, Z., & Zhang, N. (2020). Prediction of embodied carbon emissions from residential buildings with different structural forms. Sustainable Cities and Society, 54, 101946.

Chang, Y., Ries, R.J., Wang, Y., 2010. The embodied energy and environmental emissions of construction projects in China: An economic input–output LCA model. Energy Policy, Energy Efficiency Policies and Strategies with regular papers. 38, 6597–6603. https://doi.org/10.1016/j.enpol.2010.06.030

Cherni, J. A., & Kentish, J. (2007). Renewable energy policy and electricity market reforms in China. Energy Policy, 35(7), 3616-3629.

Chen, J., Shi, Q., Shen, L., Huang, Y., & Wu, Y. (2019). What makes the difference in construction carbon emissions between China and USA?. Sustainable Cities and Society, 44, 604-613.

Development WBCFS, Institute WR, 2012. The Greenhouse Gas Protocol: a Corporate Accounting and Reporting Standard. World Resources Inst.

Ding, yiting, 2021. Strive to achieve carbon peak by 2030 and carbon neutral by 2060 -- winning the battle of low-carbon transition. People’s Daily

Du, Q., Shao, L., Zhou, J., Huang, N., Bao, T., & Hao, C. (2019). Dynamics and scenarios of carbon emissions in China’s construction industry. Sustainable Cities and Society, 48, 101556.

Du, Q., Zhou, J., Pan, T., Sun, Q., Wu, M., 2019. Relationship of carbon emissions and economic growth in China’s construction industry. J. Clean. Prod. 220, 99–109. https://doi.org/10.1016/j.jclepro.2019.02.123

Fan, J., Wan, X., 2007. Input-output table and social accounting matrix updating: a review. J. Quant. Tech. Econ. 151–160.

Fan, J. S., & Zhou, L. 2019. Impact of urbanization and real estate investment on carbon emissions: Evidence from China’s provincial regions. Journal of cleaner production, 209, 309-323.

Gilles, E., Ortiz, M., Cadarso, M.-Á., Monsalve, F., Jiang, X., 2021. Opportunities for city carbon footprint reductions through imports source shifting: The case of Bogota.

Resour. Conserv. Recycl. 172, 105684. https://doi.org/10.1016/j.resconrec.2021.105684

Guan, Y., Shan, Y., Huang, Q., Chen, H., Wang, D., Hubacek, K., 2021. Assessment to China's Recent Emission Pattern Shifts. Earths Future 9, e2021EF002241. https://doi.org/10.1029/2021EF002241

Hangzhou Bureau of Statistics. (2006-2020). Hangzhou Statistical Yearbook 2005-2019. China statistics press.

Hangzhou Municipal Government, 2015. Hangzhou 2015 Air Pollution Prevention and Control implementation plan. Hangzhou Municipal Government.

Hangzhou Municipal Government, 2014. Hangzhou Air Pollution Prevention and Control Action Plan (2014-2017). Hangzhou Municipal Government.

He, J., Yue, Q., Li, Y., Zhao, F., Wang, H., 2020. Driving force analysis of carbon emissions in China's building industry: 2000–2015. Sustain. Cities Soc. 60, 102268. https://doi.org/10.1016/j.scs.2020.102268

Hong, J., Shen, G.Q., Feng, Y., Lau, W.S., Mao, C., 2015. Greenhouse gas emissions during the construction phase of a building: a case study in China. J. Clean. Prod., Carbon Emissions Reduction: Policies, Technologies, Monitoring, Assessment and Modeling 103, 249–259. https://doi.org/10.1016/j.jclepro.2014.11.023

Hu, Y., Zhu, D., 2015. Disconnect analysis between CO_2 emission output value and energy consumption of China. Chinas Popul. Resour. Environ. 25, 50–57. (In Chinese)

Hung, C.C.W., Hsu, S.-C., Cheng, K.-L., 2019. Quantifying city-scale carbon emissions of the construction sector based on multi-regional input-output analysis. Resour. Conserv. Recycl. 149, 75–85. https://doi.org/10.1016/j.resconrec.2019.05.013

Intelligent research consulting, 2021. Market operation status and development prospect forecast report of China's construction machinery industry from 2021 to 2027. Intelligent research consulting.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, IGES, Japan.

KAYA, Y., 1989. Impact of carbon dioxide emission control on GNP growth : Interpretation of proposed scenarios. Intergov. Panel Clim. Chang. Strateg. Work. Group May.

Lee, B., Trcka, M., & Hensen, J. L. (2011). Embodied energy of building materials and green building rating systems—a case study for industrial halls. Sustainable Cities and Society, 1(2), 67-71.

Leontief, W.W., 1936. Quantitative Input and Output Relations in the Economic Systems of the United States. Rev. Econ. Stat. 18, 105–125. https://doi.org/10.2307/1927837

Li, D., Huang, G., Zhang, G., Wang, J., 2020. Driving factors of total carbon emissions from the construction industry in Jiangsu Province, China. J. Clean. Prod. 276, 123179. https://doi.org/10.1016/j.jclepro.2020.123179

Li, D., Huang, G., Zhu, S., Chen, L., Wang, J., 2021. How to peak carbon emissions of provincial construction industry? Scenario analysis of Jiangsu Province. Renew. Sustain. Energy Rev. 144, 110953. https://doi.org/10.1016/j.rser.2021.110953

Li, L., Yang, J., 2020. A new method of energy-related carbon dioxide emissions estimation at the provincial-level: A case study of Shandong Province, China. Sci. Total Environ. 700, 134384. https://doi.org/10.1016/j.scitotenv.2019.134384

Liu, W., Zhan, J., Zhao, F., Wei, X., & Zhang, F. (2021). Exploring the coupling relationship between urbanization and energy eco-efficiency: A case study of 281 prefecture-level cities in China. Sustainable Cities and Society, 64, 102563.

Lu, Y., Cui, P., Li, D., 2016. Carbon emissions and policies in China’s building and construction industry: Evidence from 1994 to 2012. Build. Environ. 95, 94–103. https://doi.org/10.1016/j.buildenv.2015.09.011

Luo, W., Zhang, Y., Gao, Y., Liu, Y., Shi, C., & Wang, Y. (2021). Life cycle carbon cost of buildings under carbon trading and carbon tax system in China. Sustainable Cities and Society, 66, 102509.

Ma, M., Cai, W., 2019. Do commercial building sector-derived carbon emissions decouple from the economic growth in Tertiary Industry? A case study of four municipalities in China. Sci. Total Environ. 650, 822–834. https://doi.org/10.1016/j.scitotenv.2018.08.078

MHURD, 2011. Code for winter construction of construction engineering, JGJ/T104-2011.

Minx, J.C., Baiocchi, G., Peters, G.P., Weber, C.L., Guan, D., Hubacek, K., 2011. A “Carbonizing Dragon”: China’s Fast Growing CO_2 Emissions Revisited. Environ. Sci. Technol. 45, 9144–9153. https://doi.org/10.1021/es201497m

National Bureau of Statistics PRC. (2006a-2020a). China Statistical Yearbook 2005-2019 (Chinese-English Edition). China statistics press, Beijing.

National Bureau of Statistics PRC. (2006b-2020b). China Energy Statistical Yearbook 2005-2019 (Chinese-English Edition). China statistics press, Beijing.

Naughton, B., 2007. the Chinese Economy: Transitions and Growth. MIT press.

Nie, H., Kemp, R., Vivanco, D.F., Vasseur, V., 2016. Structural decomposition analysis of energy-related CO_2 emissions in China from 1997 to 2010. Energy Effic. 9, 1351–1367. https://doi.org/10.1007/s12053-016-9427-x

Pan, W., Pan, M., 2018. A dialectical system framework of zero carbon emission building policy for high-rise high-density cities: Perspectives from Hong Kong. J. Clean. Prod. 205, 1–13. https://doi.org/10.1016/j.jclepro.2018.09.025

Popita, G.-E., Frunzeti, N., Ionescu, A., Lazar, A.-L., Baciu, C., Popovici, A., Pop, C., Faur, V.-C., Proorocu, M., 2015. Evaluation of carbon dioxide and methane emission from cluj-napoca municipal landfill, romania. Environ. Eng. Manag. J. 14, 1389–1398.

R, S., 1962. Multiple classification in social accounting. Bull. L' Inst. Int. Stat. 215～233.

Ruddiman, W.F., 2014. Earth's Climate: past and future (Third Edition). Macmillan.

Schuh, A.E., Otte, M., Lauvaux, T., Oda, T., 2021. Far-field biogenic and anthropogenic emissions as a dominant source of variability in local urban carbon budgets: A global high-resolution model study with implications for satellite remote sensing. Remote Sens. Environ. 262, 112473. https://doi.org/10.1016/j.rse.2021.112473

Shan, Y., Guan, D., Liu, Jianghua, Mi, Z., Liu, Z., Liu, Jingru, Schroeder, H., Cai, B., Chen, Y., Shao, S., Zhang, Q., 2017. Methodology and applications of city level CO_2 emission accounts in China. J. Clean. Prod. 161, 1215–1225. https://doi.org/10.1016/j.jclepro.2017.06.075

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., Mi, Z., Liu, Z., Zhang, Q., 2018. China CO_2 emission accounts 1997–2015. Sci. Data 5, 170201. https://doi.org/10.1038/sdata.2017.201

Shan, Y., Huang, Q., Guan, D., Hubacek, K., 2020. China CO_2 emission accounts 2016–2017. Sci. Data 7, 54. https://doi.org/10.1038/s41597-020-0393-y

Shan, Y., Liu, J., Liu, Z., Xu, X., Shao, S., Wang, P., Guan, D., 2016. New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors. Appl. Energy 184, 742–750. https://doi.org/10.1016/j.apenergy.2016.03.073

Shi, Q., Chen, J., Shen, L., 2017. Driving factors of the changes in the carbon emissions in the Chinese construction industry. J. Clean. Prod. 166, 615–627. https://doi.org/10.1016/j.jclepro.2017.08.056

Statistical Review of World Energy, 2021. bp p.l.c.

Trinh, B., Phong, N. V., 2013. A short note on RAS method. Advances in Management and Applied Economics, 3(4), 133.

UNEP, UNEP DTU Partnership, 2021. Emissions Gap Report 2021. UNEP.

Wang, G., Chen, X., Zhang, Z., Niu, C., 2015. Influencing factors of energy-related CO_2 emissions in China: A decomposition analysis. Sustain. Switz. 7, 14408–14426. https://doi.org/10.3390/su71014408

Wang, H., Zhang, Y., Gao, W., Kuroki, S., 2020. Life Cycle Environmental and Cost Performance of Prefabricated Buildings. Sustainability 12, 2609. https://doi.org/10.3390/su12072609

Wang, L., 2021. Hangzhou will promote "new urban construction" from a high starting point to help build a benchmark of "Made in China." Hangzhou Dly.

Wang, M., Feng, C., 2018. Exploring the driving forces of energy-related CO_2 emissions in China’s construction industry by utilizing production-theoretical decomposition analysis. J. Clean. Prod. 202, 710–719. https://doi.org/10.1016/j.jclepro.2018.08.152

Wu, P., Song, Y., Zhu, J., Chang, R., 2019. Analyzing the influence factors of the carbon emissions from China’s building and construction industry from 2000 to 2015. J. Clean. Prod. 221, 552–566. https://doi.org/10.1016/j.jclepro.2019.02.200

Wu, Y., Sharifi, A., Yang, P., Borjigin, H., Murakami, D., Yamagata, Y., 2018. Mapping building carbon emissions within local climate zones in Shanghai. Energy Procedia, Cleaner Energy for Cleaner Cities 152, 815–822. https://doi.org/10.1016/j.egypro.2018.09.195

Xu, J., Deng, Y., Shi, Y., & Huang, Y. (2020). A bi-level optimization approach for sustainable development and carbon emissions reduction towards construction materials industry: A case study from China. Sustainable Cities and Society, 53, 101828. https://doi.org/10.1016/j.scs.2019.101828

Xu, L., Yi, W., Wu, G., 2006. Parameter identification of a model concrete frame structure. J. Earthq. Eng. Eng. Vib. 26, 121–126.

Xu, W., 2013. Zhejiang completely withdrew from coal production. National Energy Administration.

Yu, Y., Li, S., Sun, H., Taghizadeh-Hesary, F., 2021. Energy carbon emission reduction of China’s transportation sector: An input–output approach. Econ. Anal. Policy 69, 378–393. https://doi.org/10.1016/j.eap.2020.12.014

Yuan, H., 2014. More than 200 enterprises in Hangzhou have been closed and relocated, including Hangzhou Steel Refinery. Zhejiang Daily.

Zhang, N., Luo, Z., Liu, Y., Feng, W., Zhou, N., & Yang, L. (2022). Towards low-carbon cities through building-stock-level carbon emission analysis: A calculating and mapping method. Sustainable Cities and Society, 78, 103633.

Zhang, X., Liu, K., Zhang, Z., 2020. Life cycle carbon emissions of two residential buildings in China: Comparison and uncertainty analysis of different assessment methods. J. Clean. Prod. 266, 122037. https://doi.org/10.1016/j.jclepro.2020.122037

Zhejiang D&RC, 2021. Zhejiang Province renewable energy development “14th five-year plan.” Zhejiang Development and Reform Commission.

Zhejiang D&RC, 2018. Implementation plan for Zhejiang Province to further strengthen “dual control” of energy and promote high-quality development (2018-2020). Zhejiang Development and Reform Commission.

Zhejiang Provincial Bureau of Statistics. (2006-2020). Zhejiang Statistical Yearbook 2005-2019. China statistics press.

Zhejiang Provincial Bureau of Statistics. 2021. Zhejiang Statistical Yearbook 2020. China statistics press.

Zheng, H., Többen, J., Dietzenbacher, E., Moran, D., Meng, J., Wang, D., Guan, D., 2021. Entropy-based Chinese city-level MRIO table framework. Econ. Syst. Res. 0, 1–26. https://doi.org/10.1080/09535314.2021.1932764

Zhou, Y., Liu, W., Lv, X., Chen, X., Shen, M., 2019. Investigating interior driving factors and cross-industrial linkages of carbon emission efficiency in China's construction industry: Based on Super-SBM DEA and GVAR model. J. Clean. Prod. 241, 118322. https://doi.org/10.1016/j.jclepro.2019.118322

Chapter 5

SYNERGISTIC DECARBONIZATION POTENTIAL OF THE CONSTRUCTION AND UPSTREAM SECTORS

CHAPTER 5: SYNERGISTIC DECARBONIZATION POTENTIAL OF THE CONSTRUCTION AND UPSTREAM SECTORS

Contents

5.1 Content

The indirect emissions from the upstream sector of the construction industry account for about 97% of the carbon emissions in Hangzhou's construction industry. Researching the synergistic decarbonization potential and reduction pathways of the construction industry and upstream sectors can help guide the sustainable development of Hangzhou's construction industry. This chapter proposes a bottom-up carbon accounting model for the construction industry, based on a system dynamics and process-based life cycle assessment model. The model simulates the carbon emissions of Hangzhou's construction industry in the materialization stage under different scenarios until 2060. A decomposition model is used to explore the reduction potential of various factors. The results indicate that (1) without control measures, carbon emissions in Hangzhou's construction industry will continue to rise, with annual emissions reaching a maximum of 27.6 million tons and a huge scale of 14.9 million tons remaining in 2060. (2) Under the optimal scenario, the cumulative reduction potential over the next 40 years can reach 366.1 million tons, but there will still be a need to compensate for 3.7 million tons of CO_2 through carbon trading or carbon removal methods by 2060. (3) The potential for decarbonization in the construction industry mainly comes from carbon emission reduction in the material production process and controlling the area of new construction, which contribute 43.2% and 40.7%, respectively, to the cumulative carbon reduction. Therefore, controlling the construction scale and reducing material carbon emissions will be key strategies for decarbonization in the construction industry.

5.2 Introduction

The global climate crisis is one of the greatest challenges facing humanity today. Climate change has already caused problems such as rising sea levels, frequent extreme weather events, and loss of biodiversity. If swift action is not taken to reduce greenhouse gas emissions, global temperatures could rise by more than 2°C in the coming decades, leading to even more catastrophic consequences. (*AR6 Climate Change*, 2022).

The construction industry is one of the important sources of global greenhouse gas emissions, accounting for 39% of the total emissions. Carbon emissions from construction and operation account for over 93% of the entire building industry emissions (UNEP, 2017). China has made a "dual-carbon" commitment to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 (Xi, 2022). Unlike developed countries, China is currently in a critical moment of urbanization, and the building stock is expected to continue to grow in the foreseeable future. Therefore, the construction industry will play a crucial role in achieving this goal. Currently, the construction industry's carbon emissions account for about half of China's total emissions, making decarbonization and emissions reduction in the construction industry a major challenge facing China.

The construction industry is highly dependent on resource inputs from upstream industries and bears the carbon emissions responsibility of the upstream sectors. This means that decarbonization efforts in the construction industry rely on support from upstream industries. As early as 2007, the *National Comprehensive Work Plan for Energy Conservation and Emission Reduction* pointed out the need to strengthen research and application of building material technologies, enforce mandatory standards and technical specifications, and encourage the use of green building materials (NDRC, 2007). The *Green Building Evaluation Standard* also lists “resource conservation” as one of the definitions of green buildings and considers resource utilization evaluation as a necessary part of green building assessment (CABR, 2019a). The *Implementation Plan for Synergy in Pollution Reduction, Carbon Reduction, and Efficiency Increase* requires the construction industry to promote high-efficiency energy-saving building technologies and products and encourages the use of low-carbon building materials and equipment(MEE, 2022). It has become a consensus that carbon reduction efforts in the construction industry need to be carried out in coordination with upstream industries(Zhao et al., 2023).

Research on carbon emissions in the construction industry has been widely conducted at the national or provincial level. However, at the city scale, which is the fundamental unit of carbon accounting, there is still a research gap. Hangzhou, as the capital city of Zhejiang Province and one of the core cities in the southeast coastal region of China and the Yangtze River Delta, has experienced a rapid increase in building stock due to the continuous influx of population in recent years, which has led to a significant consumption of building materials and a continuous increase in carbon emissions from both the materials and construction sectors, thus driving the rapid growth of carbon emissions in Hangzhou.

There is a strong link between the construction industry in Hangzhou and the upstream sectors. This chapter will select Hangzhou as the research object to carry out joint carbon emission accounting and decarbonization prediction for the construction industry and upstream sectors at the city scale. Specifically, this chapter will conduct research on the three stages closely linked between the construction industry and upstream sectors, namely the production stage of building materials, transportation stage of materials, and construction stage of buildings, which are collectively referred to as the materialization stage of building.

The main purpose of this chapter is to analyze the future carbon emission trend of the construction industry in Hangzhou city and the potential joint decarbonization of the construction industry and upstream sectors by 2060. Factors that may affect the future carbon emissions of the construction industry, such as population growth, per capita floor area demand, material CI, and material demand intensity, are divided into two types: development mode and policy control, with three development paths for each type, resulting in nine scenarios. A system dynamics model is then used to construct a building stock flow model, estimate building demand and new building area in different scenarios, and use a process-based life cycle assessment method to calculate Materialization Stage Carbon Emissions (MSCE) in construction industry. Finally, the Logarithmic Mean Divisia Index method (LMDI) is used to decompose the carbon emission differences among different scenarios, identify the core influence factors of MSCE, and explore the possibility of decarbonization of the construction industry.

5.3 Method and models

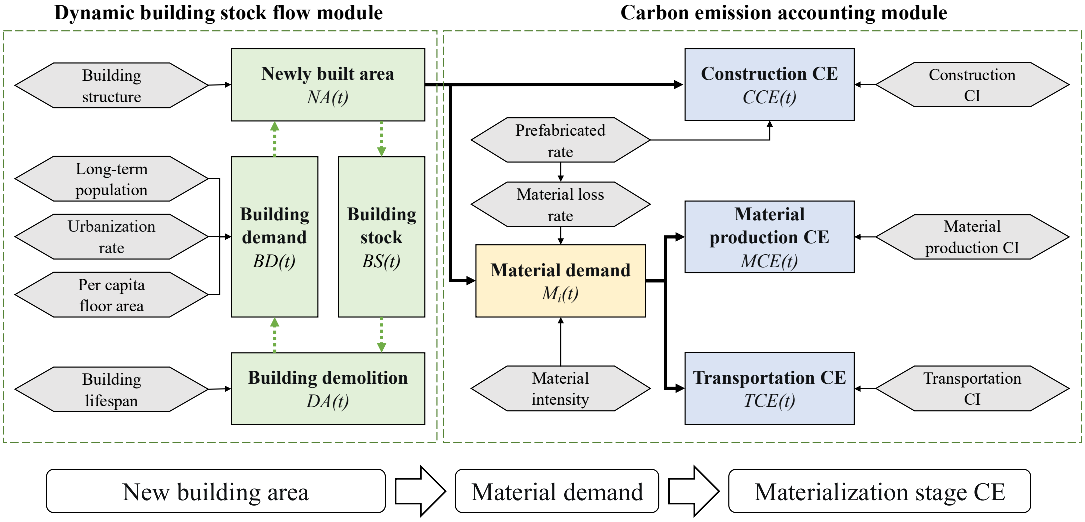


Fig. 5-1 The bottom-up materialization stage CE model framework

The Figure 5-1 presents the bottom-up approach for carbon accounting and forecasting in the construction industry developed in this paper. The model consists of two modules: a dynamic building stock flow model used to determine the annual new building area, and a carbon accounting module that calculates the construction emissions and material demand based on the new building area, followed by calculating the carbon emissions from material production and transportation based on the material demand.

5.3.1 Research scope

Carbon emissions from the production of building materials, transportation of materials, and building construction are within the scope of carbon accounting in this chapter. The year 2020 will be used as the base year, and the synergistic decarbonization effects between the construction industry and upstream sectors will be predicted from 2021 to 2060.

The scope of this study includes residential buildings and public buildings, i.e., non-productive civil buildings. Public buildings include office buildings, commercial buildings, medical buildings, scientific research and education buildings, and municipal buildings, etc.

Due to the significant differences in urban and rural construction and development in China, there are differences in building function and structure between urban and rural areas. The differences in building function and structure have a significant impact on the demand for building materials. Therefore, this study classifies buildings into three levels: region, function, and structure.

As shown in Figure 5-2, the region is divided into urban and rural areas, building function is divided into residential and public buildings, and structure is divided into brick and wood buildings (BW), brick and concrete buildings (BC), reinforced concrete buildings (RC), steel structure buildings, timber structure buildings, and others. Others refer to early building structures used in Hangzhou, such as rammed earth buildings and earth blocks with bamboo frame buildings, which existed for a short period of time. Considering the accuracy and simplicity of the accounting process, the carbon emissions of seven major building materials are calculated, namely steel, cement, brick, wood, aluminum, glass, and insulation, whose carbon emissions account for over 90% of the related carbon emissions of building materials (Kumanayake et al., 2018).

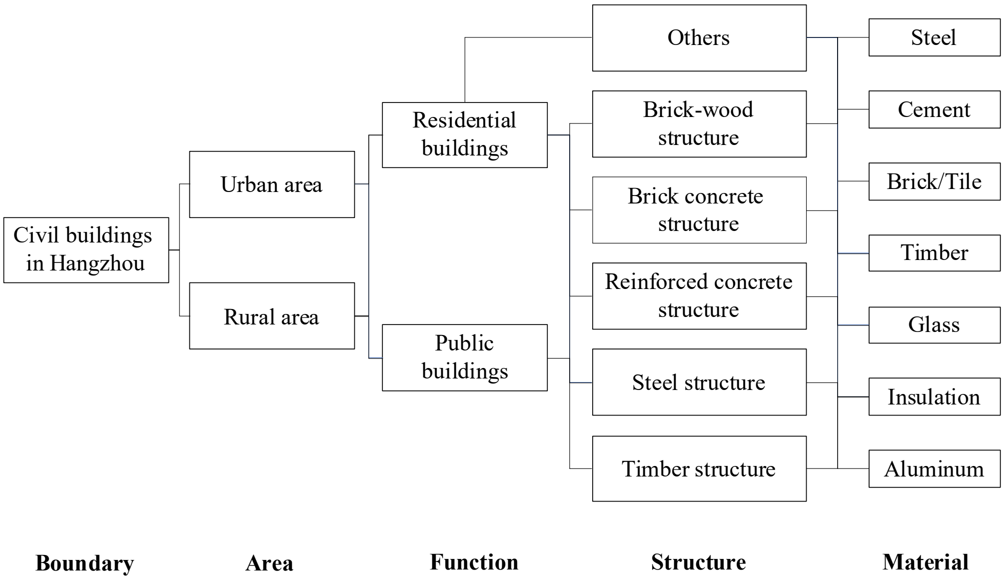


Fig. 5-2 Classification of buildings and materials

5.3.2 Building stock-flow model

The trajectory of building stock evolution refers to the ongoing process of new buildings being constructed as inflow, existing buildings in stock aging, and old buildings reaching the end of their life being demolished as outflow(W. Zhou et al., 2020). This process is fueled by the social demand for a diverse range of building stocks. The building demand can be estimated through Eq. (5-1).

$$BD_{l,f}(t) = P_l(t) * PA_{l,f}(t) \tag{5-1}$$

Where, l denotes the location (urban or rural); f denotes the building function (residential or public buildings); $BD_{l,f}(\mathrm{t})$ denotes the demand of building f in area l in year t (million m^2); $\mathrm{P}_l(\mathrm{t})$ is the population in area l in year t (million people); and $\mathrm{PA}_{l,f}(\mathrm{t})$is the per capita floor area of building f in area l in year t. (m^2).

In this study, it is assumed that the building stock is equal to the building demand, such as Eq. (5-2). Constructing new buildings can compensate for the insufficient demand caused by demolishing outdated buildings and the continuously increasing social demand for buildings. The quantity of newly erected buildings can be computed by utilizing Eq. (5-3) and Eq. (5-4).

$$BS_{l,f}(t) = BD_{l,f}(t) \tag{5-2}$$

$$NA_{l,f}(t) = BS_{l,f}(t) - BS_{l,f}(t-1) + DA_{l,f}(t) \tag{5-3}$$

$$NA_{l,f,s}(t) = NA_{l,f}(t) * ST_{l,f,s}(t) \tag{5-4}$$

Where, $BS_{l,f}(\mathrm{t})$ denotes the stock of building f in area l in year t (million m^2); $NA_{l,f}(t)$ denotes the new construction building f in area l in year t (million m^2); $DA_{l,f}(t)$ is the buildings f in area l demolished in year t (million m^2); s represents the building structure type, $NA_{l,f,s}(t)$ is the f type new building area of s structure in Area l in year t; $ST_{l,f,s}(t)$ denotes the proportion of f type new buildings of s structure in Area l in year t.

The total number of demolished buildings in a particular year (t) can be calculated by summing up all the buildings that have completed their expected lifespan by that year, which is determined by their age and lifespan distribution profile, such as Eq. (5-5) and Eq. (5-6). The uncertainty in the lifespan of a building constructed in a given year can be represented by a probability density function, which is a key concept in survival analysis. In this study, we have selected the normal distribution function as the probability density function to model the lifespan of buildings, which has been shown to be applicable in many previous studies.(Hong et al., 2016)

$$DA_{l,f}(t) = \sum_s \sum_{\mathrm{t0}}^{\mathrm{t'}} \mathrm{L}_{l,f,s}(\mathrm{t},\mathrm{t'}) * NA_{l,f,s}(t) \tag{5-5}$$

$$\mathrm{L}_{l,f,s}(\mathrm{t},\mathrm{t'}) = \frac{1}{\sqrt{2\pi}\sigma_{l,f,s}} * \mathrm{e}^{\frac{-(\mathrm{t}-\mathrm{t'}-\mu_{l,f,s})^2}{2\sigma_{l,f,s}}} \tag{5-6}$$

Where, t denotes the time series 1949-2100; t0 denotes the initial year 1949; t' denotes the target year; L(t, t') denotes building life distribution; μ denotes building life; σ denotes standard deviation of normal distribution and is assumed to be $\mu/2$.

5.3.3 Carbon emissions Accounting

The MSCE will be comprised of carbon emissions from material production, material transportation, and construction activities, as shown in Eq. (5-7).

$$CE(t) = MCE(t) + TCE(t) + CCE(t) \tag{5-7}$$

Where, $CE(t)$ Where, the total carbon emissions within the accounting scope in year t (tons CO_2), $MCE(t)$ denotes the carbon emissions from the production of building materials in year t (tons CO_2), $TCE(t)$ denotes the carbon emissions from the transportation of building materials in year t (tons CO_2), $CCE(t)$ denotes the carbon emissions from the construction of buildings in year t (tons CO_2).

The carbon emission intensity method is often used to account for the carbon emissions in the production of building materials(Z. Zhang & Wang, 2016). This method assumes that the carbon emissions from the production of materials are stable, and that the carbon emissions are determined by the material consumption and the carbon emission intensity (CI), as shown in Eq. (5-8). The material consumption is determined by the material demand intensity (MI) of different building structures and the area of new construction. In the construction process, there is also material loss(Dixit et al., 2013). Prefabricated construction can effectively reduce on-site construction, thereby reducing about 70% of material loss in the construction process (Zhu et al., 2022). The calculation of material consumption is shown in Eq. (5-9).

$$MCE(t) = \sum_i M_i(t) \times CI_i(t) \tag{5-8}$$

$$M_i(t) = \sum_l \sum_f \sum_s \sum_i NA_{l,f,s}(t) \times MI_{l,f,s,i}(t) \times \left(1 + \omega_i \times \left(1 - \alpha \times \beta_{l,f,s}(t)\right)\right) \tag{5-9}$$

Where, i denotes different building materials, $M_i(t)$ denotes the consumption of material i in year t (tons), $CI_i(t)$ denotes the carbon emission intensity of material i in year t (tons CO_2/t), $MI_{l,f,s,i}(t)$ denotes the material demand intensity of building i with function s and structure f in region l in year t (tons/ m^2), ω_i denotes the loss rate of material i during the construction process (%) (*Building Construction Handbook-5th Edition*, 2012; Dixit et al., 2013), α denotes the reduction rate of material loss in prefabricated buildings, which is 70% in this study, $\beta_{l,f,s}$ denotes the prefabrication rate of new buildings (%).

The carbon emissions from transportation and construction can also be calculated using the carbon emission intensity method, as shown in equations (5-10) and (5-11). Prefabricated buildings can reduce carbon emissions at the construction site by about 25% (Cao et al., 2015; X. Li et al., 2022).

$$TCE(t) = \sum_i M_i(t) \times CI_{trans}(t) \times TD_i \tag{5-10}$$

$$CCE(t) = \sum_l \sum_f \sum_s NA_{l,f,s}(t) \times CI_{con}(t) \times \left(1 - \gamma \times \beta_{l,f,s}(t)\right) \tag{5-11}$$

Where, $CI_{trans}(t)$ denotes the carbon emission intensity of transportation in year t (tons CO_2/t·km), TD_i denotes the average transportation distance for material i (km), which is set to 500 km due to Hangzhou relies heavily on external material inputs(CABR, 2019b), $CI_{con}(t)$ denotes the carbon emission intensity of construction process in year t (tons CO_2/m^2), γ denotes the reduction ratio of EI_{con} due to prefabricated construction, which is set to 25%.

5.3.4 Decomposition of decarbonization potential

In order to identify the primary determinants of carbon emissions, it is common practice to decompose the carbon emission potential(B. Lin & Liu, 2015). The LMDI decomposition method is utilized, which is a type of IDA approach that offers advantages such as simplicity, efficiency, and no decomposition residuals(D. Li et al., 2020). The process can be expressed by Eq. (5-12).

$$\begin{aligned} &\Delta EC(t) \\ &\quad = EC_a(t) - EC_b(t) \\ &\quad = \left(MEC_a(t) + TEC_a(t) + CEC_a(t)\right) - \left(MEC_b(t) + TEC_b(t) + CEC_b(t)\right) \\ &\quad = \Delta MEC(t) + \Delta TEC(t) + \Delta CEC(t) \end{aligned} \tag{5-12}$$

Where, a and b denote different scenario, $\Delta EC(t)$ denotes total carbon emission difference of scenario a and b in year t (tons CO_2), $\Delta MEC(t)$, $\Delta TEC(t)$ and $\Delta CEC(t)$ denotes material production, transportation, and construction carbon emission difference of scenario a and b in year t (tons CO_2).

By using the calculation formulas for MEC, TEC, and CEC, the factors affecting carbon emission potential can be classified as controlling the new building area, the distribution of building structures, reducing MI, material CI, transportation CI, construction CI, and reducing material waste by prefabricated construction, as well as saving construction energy consumption by prefabricated construction, as shown in formulas (5-13) to (5-15).

$$\Delta MEC(t) = \Delta NA(t) + \Delta ST(t) + \Delta MI(t) + \Delta CI_{mat}(t) + \Delta Pr(t) \tag{5-13}$$

$$\Delta TEC(t) = \Delta NA(t) + \Delta ST(t) + \Delta MI(t) + \Delta CI_{trans}(t) + \Delta Pr(t) \tag{5-14}$$

$$\Delta CEC(t) = \Delta NA(t) + \Delta CI_{con}(t) + \Delta Pr(t) \tag{5-15}$$

Where, $\Delta NA(t)$, $\Delta ST(t)$, $\Delta MI(t)$, $\Delta CI_{mat}(t)$, $\Delta CI_{trans}(t)$, $\Delta CI_{con}(t)$ and $\Delta Pr(t)$ denote the carbon emission difference due to control of new building area, the distribution of building structures, reducing MI, material CI, transportation CI, construction CI and the spread of prefabricated buildings.

The carbon emissions caused by controlling the new construction area can be calculated using equations 5-16 and 5-17. Other variables can be calculated using similar methods. It should be noted that since this chapter did not make scenario assumptions for building structure and construction carbon emissions, these two factors will not cause carbon emissions differences between scenarios, that is, $\Delta ST(t) = 0$ and $\Delta CI_{con}(t) = 0$.

$$\Delta NA(t) = \sum_{l,f,s,i} \omega_{l,f,s,i}^{MEC}(t) ln(\frac{NA_{l,f}^{a}(t)}{NA_{l,f}^{b}(t)}) \tag{5-16}$$

$$\omega_{l,f,s,i}^{MEC}(t) = \frac{MEC_{l,f,s,i}^{a}(t) - MEC_{l,f,s,i}^{b}(t)}{lnMEC_{l,f,s,i}^{a}(t) - lnMEC_{l,f,s,i}^{b}(t)} \quad \text{for } MEC_{l,f,s,i}^{a}(t) \neq MEC_{l,f,s,i}^{b}(t)$$

$$\tag{5-17}$$

$$\omega_{l,f,s,m}^{MEC}(t) = MEC_{l,f,s,m}^{a}(t) \quad \text{for } MEC_{l,f,s,i}^{a}(t) = MEC_{l,f,s,i}^{b}(t)$$

5.4 Development path and scenario design

To explore the collaborative emission reduction capabilities of the construction industry and its upstream sectors under different scenarios, it is necessary to make assumptions about the future development paths of key factors. The carbon emission contributions of the construction industry and the building material industry are the focus of this study. As shown in Table 5-1, the factors that affect the development of carbon emissions, such as building lifespan, per capita floor area, CI, and MI, are divided into two categories: Development mode and Policy driven. Three development paths are defined for each category of influencing factors. The future development scenario is composed of different combinations of these development paths. In addition, the long-term population and building structure will also affect future carbon emissions of the construction industry, and the development paths of these two factors are also assumed.

Table 5-1 Path and scenario design

Influencing factor	Development path	Description
Development mode	Unsustainable development path (UD)	Large-scale construction activities, with per capita floor area reaching the level of developed American countries. The construction pattern is sloppy, and a large number of buildings are demolished before reaching design lifespan.
	Moderate development path (MD)	The building stock follows current trends, with per capita floor area reaching the level of developed European countries. Construction patterns are improved, and buildings are demolished when reaching design lifespan.
	Sustainable development path (SD)	The building stock is well planned, and the per capita floor area exceeds the level of developed Asian countries. The adoption of refined construction, advances in building technology and extended building life.
Policy driven	Baseline path (BS)	Technology develops according to the current trend, prefabricated buildings are popularized according to the national plan, material CI decreases according to the current trend, and MI remains unchanged.
	Moderate control path (MC)	Promoted by policy, prefabricated buildings are popularized by regional plan, carbon emission reduction in material industry is accelerated, material performance is improved, and the MI is reduced.
	Strict control path (SC)	Under strict policy restrictions, prefabricated buildings are rapidly gaining popularity and the materials industry is making breakthroughs in carbon reduction technology and material performance.

5.4.1 Population and urbanization rate development

Population change is an important driving force for changes in building demand. Hangzhou is currently experiencing rapid population growth, with a continuously expanding population. By the end of 2020, the city's registered population had reached 8.14 million, an increase of 12.5% compared to 2015. In 2022, the city's long-term population has already reached 12.4 million, with a population growth of 3.6 million and 40.6% over the past decade (Hangzhou MBS, 2022).

Over the next 15 years, the population of Hangzhou is expected to continue to grow, reaching 13.7 million and 15.0 million by 2025 and 2035, respectively. It is believed that the city will eventually be able to accommodate about 18 million people (Hangzhou DRC, 2021). The logistic growth model is often used to describe population growth patterns under conditions of limited resources. As shown in Figure 5-3, this study used the logistic growth function to establish a model of the development of the long-term population in Hangzhou to predict its future population growth.

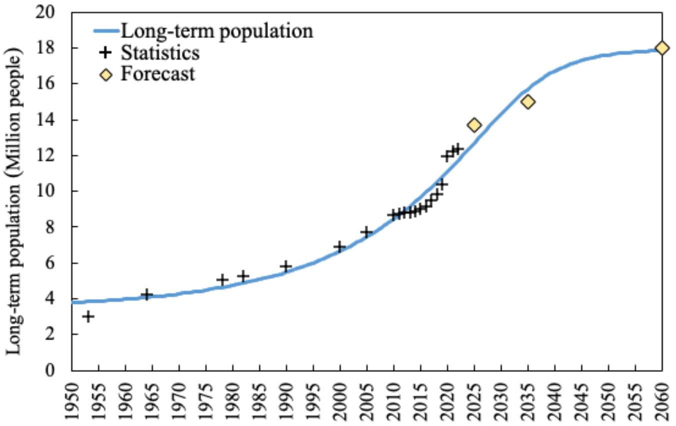


Fig. 5-3 Population development of Hangzhou

The population development plan for the "14th Five-Year Plan" in Hangzhou pointed out that the fertility rate in Hangzhou urban is declining, the natural population growth rate is slowing down, and the population growth momentum has shifted to the mechanical growth mode of population migration. The indicator of the urbanization rate of the long-term population is introduced to distinguish between urban and rural populations.

In recent years, with the development and expansion of Hangzhou city, the urbanization rate has continued to rise. By 2022, the urbanization rate has reached 84.0%, and the urbanization rate of districts such as Shangcheng, Gongshu, and Binjiang has reached 100%. Hangzhou aims to achieve an urbanization rate of 85% by 2025 as a short-term goal (Hangzhou DRC, 2021). Based on this, this study predicts the trend of urbanization rate growth in Hangzhou, as shown in Figure 5-4.

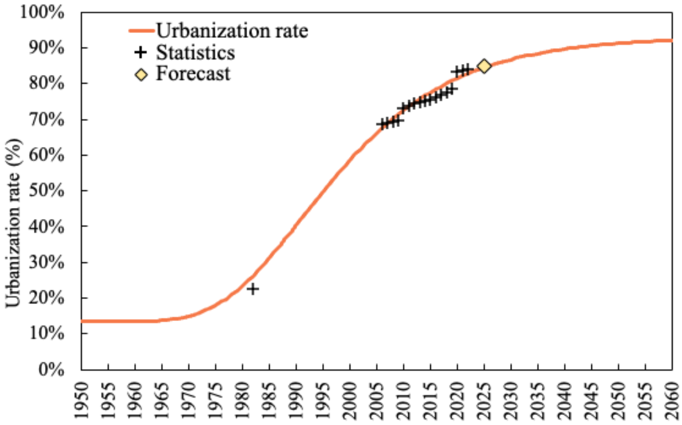


Fig. 5-4. Urbanization rate forecast of Hangzhou

Figure 5-5 shows the development curves of urban and rural populations in Hangzhou predicted based on the Hangzhou long-term population development model and the urbanization rate growth model, with statistical data for validation. This study believes that the predicted model is accurate and reliable.

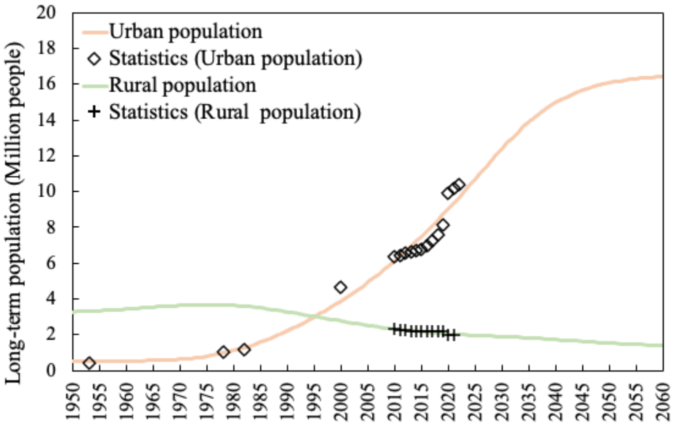


Fig. 5-5. Urban and Rural Long-term Population Forecast

The predicted data for the urban and rural long-term population in Hangzhou are shown in Table 5-2.

Table 5-2 Long-term Population Forecast (million people)

	2020	2030	2040	2050	2060
Long-term Population	11.94	14.30	16.69	17.61	17.84
Urbanization rate	83.3%	86.7%	89.6%	91.2%	92.1%
Urban Long-term Population	9.94	12.39	14.96	16.07	16.43
Rural Long-term Population	1.99	1.90	1.73	1.55	1.41

5.4.2 Proportion of building structure

The building structure of Hangzhou has undergone an evolution from primarily using bamboo, straw, and earthen materials to BW structure, and then to BC structure and RC structure (Zhejiang PBS, 2022). Different building structures have different material demands, and how to simulate the development of Hangzhou's building structure is one of the issues addressed in this study. As shown in Figures 5-6, 5-7, 5-8, and 5-9, based on statistical data, and current policies, and by referencing existing research (Zhu et al., 2022), this study used functions such as the logistic function, polynomial function, and exponential function to fit curves and simulate the changes in the proportion of urban and rural residential and public buildings' structures in Hangzhou from 1949 to 2060.

From 1949 to 1958, Hangzhou's urban construction mainly consisted of BW buildings that used wooden frameworks and clay bricks as building materials, with some public buildings using BC structures. With technological innovation in 1959, silicate blocks and cement prefabricated components were used in residential buildings, leading to the development of BC housing (Live in Hangzhou, 2015). In 1978, spurred by an increase in residential demand and urban development policies, Hangzhou began a wave of residential construction, with 6-story BC multi-story residential buildings rapidly replacing BW buildings as the mainstream (Hangzhou MBS, 1987).

In the 1980s, reinforced concrete was introduced to China and quickly applied in urban public buildings (Zhu et al., 2022) After 2000, the housing demand in Hangzhou grew rapidly and the real estate market boomed. A large number of RC high-rise residential buildings were constructed, and the proportion of RC residential buildings increased from 5.6% in 2000 to 71.8% of all existing residential buildings in 2020 (China NBS, 2001, 2021). RC structures replaced BC structures as the main trend in residential construction. In 2019, Hangzhou became a pilot city for steel-structure prefabricated housing, with a target of building 1.6 million m^2 of such housing in the urban area between 2020 and 2022 (Hangzhou Municipal Government, 2019), accounting for 5.3% of the total new housing area in the same year (Hangzhou MBS, 2022). The target was achieved with an overachievement of 54% (Hangzhou Daily, 2022).

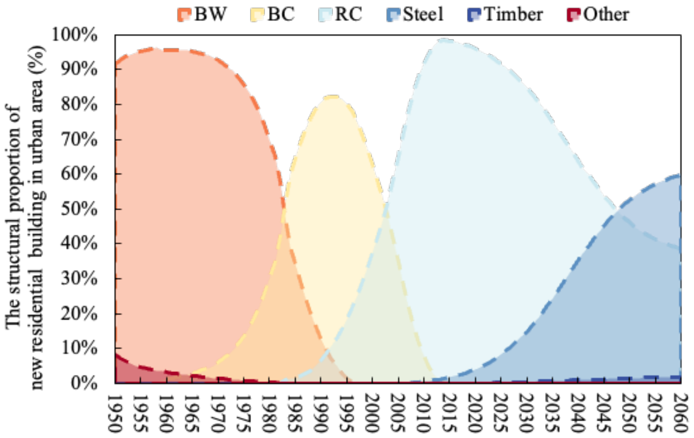


Fig. 5-6 Evolution of urban residential building structure type

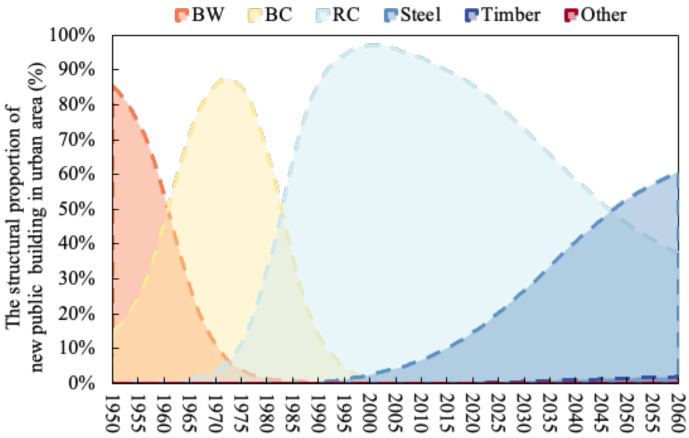


Fig. 5-7 Evolution of urban public building structure type

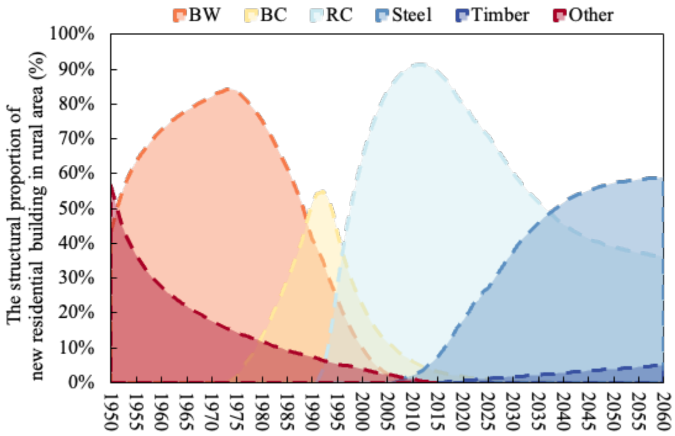


Fig. 5-8 Evolution of rural residential building structure type

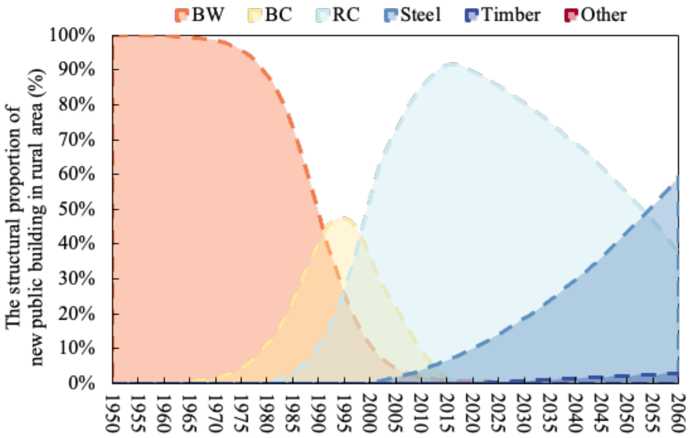


Fig. 5-9 Evolution of rural public building structure type

Initially, the rural building structures were dominated by other and BW structures, while other structures were quickly replaced by BW and BC structures. In 1985, other structures, BW structure, and BC structure accounted for 8.6%, 64.5%, and 26.9% of new rural buildings, respectively (Zhejiang PBS, 1986). With the application of concrete block and reinforced concrete technologies in rural housing, other structures accounted for only 2.7% of new rural housing in 1990, and BW structure decreased to 48.9%. By 1999, BW structure accounted for only 7.1% (Zhejiang PBS, 1991, 2000). The stock of BW housing buildings decreased rapidly, from 48.4% in 2000 to 12.4% in 2022 (Zhejiang PBS, 2022), and BW housing buildings have been eliminated.

BC and RC structures replaced BW structures as the mainstream around 1995, with a total share of 72.5% of total new building house area that year. These two structures reached their peak around 2012, accounting for 98.7% of new building house area and 98.3% of new building public area (China NBS, 1995, 2012). Since then, light steel structure technology has become popular in rural areas. From 2020 to 2022, more than 0.2 million m^2 of rural steel structure prefabricated houses have been started in construction (Hangzhou Daily, 2023), accounting for approximately 19.1% of the incremental rural housing (Hangzhou MBS, 2022).

Hangzhou is vigorously promoting construction industrialization and has the advantage of agglomeration of the steel structure industry. Along with the target set to build 3.5 million m^2 of steel structure prefabricated houses by 2025 and the policy requiring the use of steel structure prefabrication in the construction of public buildings larger than 20,000 m^2 (Hangzhou URCC, 2022), steel structure prefabricated buildings will be the development direction of Hangzhou's urban transformation and upgrading.

5.4.3 Development mode

(1) Building lifespan

The reasons for the short lifespan of buildings in China, which is less than 30 years on average and even shorter for rural buildings, include poor quality, lack of maintenance, urban planning adjustments, and functional mismatch (Cai et al., 2015). Huang suggested that buildings constructed before 2015 had a lifespan of only 20-30 years(Huang et al., 2017). Zhu categorized the lifespan of urban BW, BC, RC, steel, and wood structure buildings built before 2020 as 10, 25, 30, 50, and 50 years, respectively. Zhu also noted that the lifespan of rural BC buildings is shorter than that of urban buildings, at 20 years (Zhu et al., 2022).

Hangzhou is currently in a stage of rapid development, but premature demolition of buildings is also a problem that Hangzhou faces. Before the merger of Xiaoshan and Yuhang into Hangzhou in 2001, the limited urban space resources had been an important factor restricting the development of Hangzhou (Hangzhou BPNR, 2001). In 1982 and 1992, the Hangzhou carried out the *Zhongdong River Comprehensive Management Project* and *the Qingchun Road Comprehensive Transformation*, demolishing a large number of buildings that were less than 25 years old. In 2013, Zhejiang Province began a comprehensive campaign to renovate old and illegal buildings. As of 2019, Hangzhou had demolished 145.1 million m^2 of buildings (Hangzhou Daily, 2019). These demolitions resulting from planning adjustments have limited the lifespan of buildings in Hangzhou. Based on relevant policies and historical data in Hangzhou, this study makes assumptions about the lifespan of buildings in Hangzhou, as shown in Table 5-3.

Table 5-3 Building lifespan assumption

	Structure types	Before 2020	UD	MD	SD
Urban area	Others	10	10	-	-
	BW	20	20	30	40
	BC	30	30	40	50
	RC	30	30	50	60
	Steel	50	50	50	80
	Timber	50	50	50	60
Rural area	Others	10	10	-	-
	BW	15	15	25	40
	BC	30	30	40	50
	RC	40	40	50	60
	Steel	50	50	50	80
	Timber	50	50	50	60

In the future scenario design, the UD path assumes that the building lifespan will remain unchanged, and that the city will continue to adopt an extensive urban planning model, resulting in most buildings being demolished before reaching their designed lifespan. In the MD path, the building lifespan is set according to *the Unified Design Standard for Civil Buildings*, which stipulates a design lifespan of 50 years for ordinary buildings (MOHURD, 2019). Considering the lower construction and material quality of BW and BC buildings, their lifespan is set to the average of UD and SD paths. In the SD path, the lifespan of buildings is set based on the economic durability-related indicators of buildings (Lu, 2010), which are used to calculate the residual value of buildings in the real estate sector.

(2) Floor space per capita

Between 1983 and 2021, the per capita living space in Hangzhou increased from 11.7 m2 to 40.2 m^2, while the per capita living space in rural areas increased from 29.9 m^2 to 77.1 m^2. Both resident demand and social supply can influence this variable. From the perspective of economic development stages, Hangzhou City has entered a phase of high-level mass consumption and pursuit of quality of life, with accelerated upgrading and transformation of residents' consumption demands for more comfortable living conditions and richer family activities, leading to an increase in demand for housing.

There is a strong positive correlation between per capita housing area and GDP (Y. Zhang et al., 2022). As Hangzhou is in a period of rapid development, the demand for per capita building area, including housing and public buildings, will continue to rise in the foreseeable future. This is an inevitable result of economic development. Hangzhou is one of the core cities in Zhejiang Province and the Yangtze River Delta region, and it is attracting a fast influx of migrants, making per capita land resources scarce. Solving the contradiction between the rapid growth of the permanent population and the shortage of housing demand has become a major issue facing Hangzhou. Hangzhou has proposed goals such as accelerating the development of the housing rental market and vigorously developing guaranteed rental housing to address this issue. In the next five years, there will be 800,000 affordable housing with an average building area of about 68m^2 supplied to the society (Hangzhou HSB, 2022).

This implies that the building scale in Hangzhou will continue to grow driven by economic development. However, due to resource scarcity, planning controls, and government policies, the per capita residential area in the city may not reach the level of developed American countries such as the US (67m^2) and Canada (57m^2). It may be possible to achieve the level of developed European countries represented by France and Germany (40-50m^2) and exceed the national average level of developed Asian countries such as South Korea and Japan (35-40 m^2). Based on this, the present study makes assumptions about the per capita residential area for urban and rural areas in Hangzhou using the logistic growth model, as shown in Figures 5-10 and 5-11.

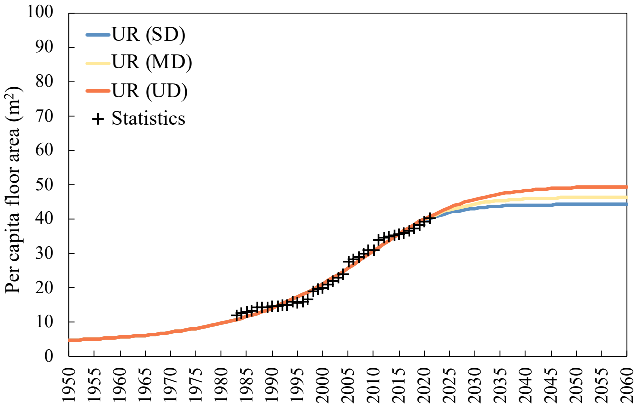


Fig. 5-10 Urban residential area per capita in different paths

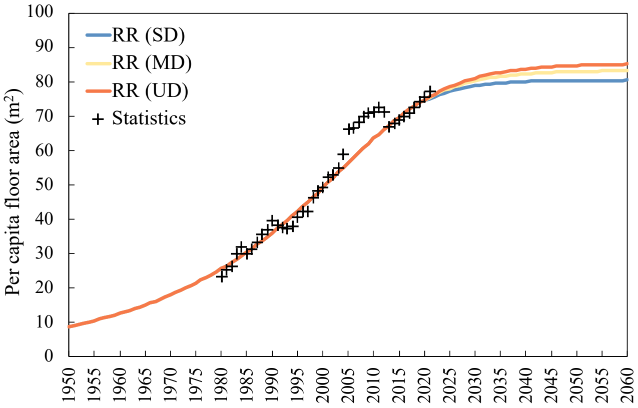


Fig. 5-11 Rural residential area per capita in different paths

The per capita public building area in China is small and unevenly distributed. In 2019, it was around 3.1m^2 in rural areas and 14.1m^2 in urban areas(MOHURD, 2020). Hangzhou leads the country in per capita public building area, with around 17.7m^2 in urban areas in 2021 (Hangzhou MBS, 2022; MOHURD, 2022a). Since the launch of the new rural construction plan in Zhejiang province in 2007, the per capita public building area in rural Hangzhou has grown rapidly, from 3.2 m^2 in 2006 to 6.6 m^2 in 2022, a growth rate of 106% (MOHURD, 2022a; Zhejiang PBS, 2022).

With the implementation of the Zhejiang rural revitalization strategy, the per capita public building area in rural areas is expected to continue to grow rapidly. Compared to developed countries, Hangzhou still has a large gap in public building stock, with the US at around 28m^2 and Germany at around 22m^2. This indicates that with the flourishing development of the tertiary industry and the continuous improvement of public service demand and quality, there is great potential for an increase in the stock of public buildings. Referring to the levels in developed countries, this paper proposes hypotheses for per capita public building area as shown in Figure 5-12 and 5-13.

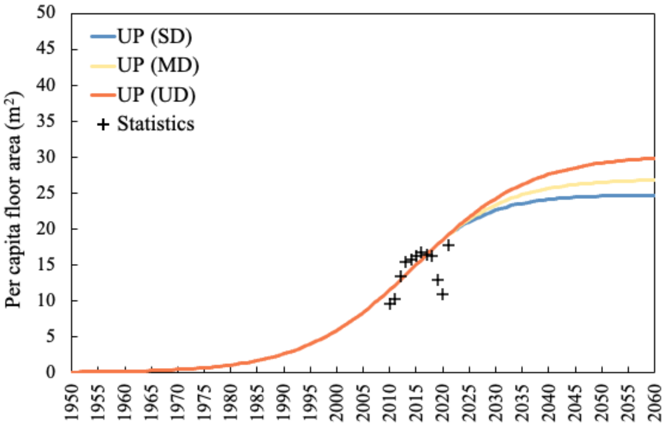


Fig. 5-12 Urban public building area per capita in different paths

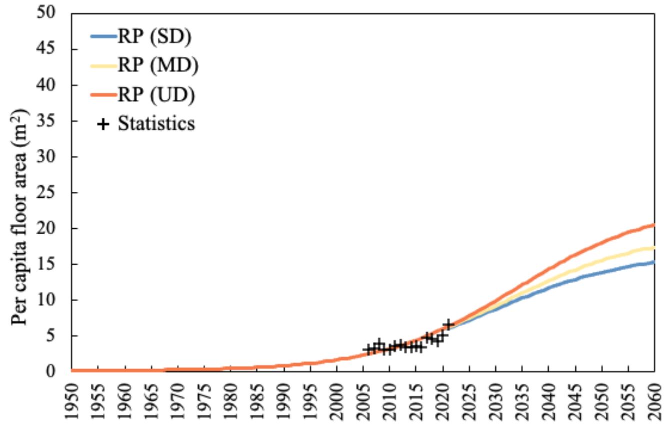


Fig. 5-13 Rural public building area per capita in different paths

5.4.4 Policy driven

(1) Material demand intensity

Due to differences in construction technology, material performance, and spatial function, different buildings have different material demands. Urban public buildings, due to their functional and aesthetic requirements, often have complex spatial structures and large spans, requiring more steel and glass (Lou et al., 2011). Urban residential buildings typically take the form of apartment complexes, with smaller spatial divisions requiring more bricks and wood. Rural public buildings serve a single target audience, have simple forms, have significantly different building material demands than urban buildings. Therefore, the demand intensity of building materials is distinguished in this study according to the building function and regional differences.

The implementation of green building evaluation standards, carbon emission accounting systems, and other policy regulations will promote the development of building design concepts and material technologies. More reasonable building space layouts and high-strength new materials will be applied, and the building industry is moving towards lightweight development (Zhong et al., 2021). An increase of 100 MPa in the yield strength of steel materials can reduce steel consumption by 6%-20% (Fu, 2020; Y. Zhang & Yu, 2017). The use of fly ash and water-reducing agents instead of cement can reduce cement consumption by 15%-30% without affecting the performance of concrete (H. Lin et al., 2022). The widespread use of lightweight and high-strength wall materials can save wall materials such as bricks (Malmqvist et al., 2018). In addition, the replacement of wooden formwork with reusable metal formwork during the construction process has become a trend, which can save about 35%-60% of wood consumption (Han, 2010).

In addition, with the improvement of building energy efficiency standards, the demand for glass and insulation materials will show an upward trend (Azari & Abbasabadi, 2018). With the requirements for energy saving and the implementation of green building standards, double or triple glazed window systems will be more widely used, and the demand intensity for glass will increase by 15%-30%. Aluminum is encouraged to replace traditional materials due to its strength, lightweight, easy processing, corrosion resistance, and recyclability, assuming its demand intensity will increase by 20%-40% in the future.

Based on the benchmark year of 2020, the demand intensity of building materials in the benchmark year was collected by Zhu using construction engineering lists, design drawings, asset assessment parameter manuals, and literature (Zhu et al., 2022). This study calculated the data for various paths in 2060 based on the trend of building material demand mentioned above, as shown in Table 5-4. The BS path assumes that the MI remains unchanged at the benchmark year level, while the remaining year’s data in the MC and SC scenarios are obtained through linear fitting.

Table 5-4 Building materials intensity in different scenario (kg/m^2)

		Base year & BS path			MC path (2060)			SC path (2060)		
		UR	UP	RR&RP	UR	UP	RR&RP	UR	UP	RR&RP
Other	Steel	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Cement	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Brick/Tile	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Timber	86.0	86.0	86.0	55.9	55.9	55.9	34.4	34.4	34.4
	Aluminum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Glass	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2
	Insulation	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BW	Steel	10.0	12.1	10.0	9.0	10.9	9.0	8.0	9.7	8.0
	Cement	27.1	29.9	112.0	21.7	23.9	89.6	17.6	19.4	72.8
	Brick/Tile	736.0	1059.1	771.3	515.2	741.4	539.9	368.0	529.6	385.7
	Timber	59.6	20.1	107.0	38.7	13.1	69.6	23.8	8.0	42.8
	Aluminum	2.9	0.6	0.0	3.4	0.7	0.0	4.0	0.8	0.0
	Glass	1.3	1.5	0.3	1.5	1.7	0.3	1.7	2.0	0.3
	Insulation	0.9	1.4	0.0	2.0	2.0	1.4	4.1	4.1	2.7
BC	Steel	66.0	70.0	40.0	59.4	63.0	36.0	52.8	56.0	32.0
	Cement	151.1	161.7	172.0	120.9	129.4	137.6	98.2	105.1	111.8
	Brick/Tile	530.7	406.6	672.2	371.5	284.6	470.5	265.4	203.3	336.1
	Timber	17.7	33.6	24.0	11.5	21.8	15.6	7.1	13.4	9.6
	Aluminum	0.6	0.6	0.6	0.7	0.7	0.7	0.8	0.8	0.8
	Glass	1.6	2.0	1.3	1.8	2.3	1.5	2.1	2.6	1.7
	Insulation	0.9	1.4	0.0	2.0	2.0	1.4	4.1	4.1	2.7
RC	Steel	172.0	172.0	95.0	154.8	154.8	85.5	137.6	137.6	76.0
	Cement	217.3	278.7	238.0	173.8	223.0	190.4	141.2	181.2	154.7
	Brick/Tile	146.8	149.4	16.0	102.8	104.6	11.2	73.4	74.7	8.0
	Timber	17.4	33.6	26.0	11.3	21.8	16.9	7.0	13.4	10.4
	Aluminum	9.6	9.6	8.6	11.5	11.5	10.3	13.4	13.4	12.0
	Glass	4.0	4.5	2.0	4.6	5.2	2.3	5.2	5.9	2.6
	Insulation	0.7	0.9	0.5	1.4	1.4	0.7	2.7	2.7	1.4
Steel	Steel	188.0	202.0	120.0	169.2	181.8	108.0	150.4	161.6	96.0
	Cement	185.7	159.0	85.5	148.6	127.2	68.4	120.7	103.4	55.6
	Brick/Tile	105.9	163.7	105.9	74.1	114.6	74.1	53.0	81.9	53.0
	Timber	31.8	32.4	20.0	20.6	21.1	13.0	12.7	13.0	8.0
	Aluminum	9.6	9.6	8.6	11.5	11.5	10.3	13.4	13.4	12.0
	Glass	4.3	5.0	2.2	4.9	5.8	2.5	5.6	6.5	2.9
	Insulation	0.7	0.9	0.7	1.5	1.5	1.0	2.0	2.0	1.4
Timber	Steel	5.9	5.9	5.9	5.3	5.3	5.3	4.7	4.7	4.7
	Cement	18.5	18.5	18.5	14.8	14.8	14.8	12.0	12.0	12.0
	Brick/Tile	1.7	1.7	1.7	1.2	1.2	1.2	0.8	0.8	0.8
	Timber	410.3	410.3	410.3	266.7	266.7	266.7	164.1	164.1	164.1
	Aluminum	9.6	9.6	8.6	11.5	11.5	10.3	13.4	13.4	12.0
	Glass	4.3	4.3	2.2	4.9	4.9	2.5	5.6	5.6	2.9
	Insulation	0.3	0.4	0.3	0.5	0.5	0.3	0.6	0.6	0.4

(2) Popularization of prefabricated buildings

The RC structure is the most used structure in Hangzhou. The traditional cast-in-place construction mode was formed in the 1980s, and it has the disadvantages of extensive construction, difficult to ensure building quality, excessive consumption of steel, cement, and other building materials. Prefabricated buildings have advantages in water, energy and material saving (H. Wang et al., 2020), and can also reduce carbon emissions during the construction process. The popularization of this technology is an inevitable trend.

The promotion of prefabricated buildings is a key part of the transformation and upgrading of Hangzhou's construction industry. Hangzhou actively constructs a prefabricated building industry system, and the development of prefabricated buildings in China is in a leading position (Hangzhou GPNCI, 2019). Hangzhou has built a total of 130 million m^2 of prefabricated buildings. In 2020, 25.5 million m^2 of new prefabricated buildings were started, and the proportion of new buildings constructed with prefabricated building technology increased from 8% in 2017 to 33% in 2022. Hangzhou aims to achieve a target of 35% of new building area using prefabricated building technology by 2025, to promote the popularity of prefabricated buildings (Hangzhou Daily, 2023).

Table 5-5 shows the prediction of the development of prefabricated buildings in Hangzhou. As the popularization rate of prefabricated buildings in Hangzhou is faster than the national average, this study adopts the China's prefabricated building popularization target (MOHURD, 2022b) as the assumption for the UD pathway. For the MD pathway, the development target for prefabricated buildings in *Hangzhou's Green Building Special Plan* is used as the basis (Hangzhou URCC, 2022; Zhejiang MOHURD, 2021). The SD pathway assumes rapid development of prefabricated buildings, with a popularization rate faster than the expected target in Hangzhou.

Common prefabricated buildings can be classified into RC, steel, and timber structures. In 2020, steel prefabricated buildings accounted for over 12% of all prefabricated buildings in Hangzhou, while in rural areas, the proportion exceeded 20% (Hangzhou Daily, 2023). Based on the *Hangzhou Pilot Work Plan for Promoting Steel Structure Prefabricated Housing*, this study assumed that all newly built steel and timber buildings will be constructed using prefabrication mode (Hangzhou GPNCI, 2019), and the proportion of prefabricated RC buildings is estimated and presented separately.

Table 5-5 The share of prefabricated buildings in new construction buildings

Region	Type	Path	2020	2030	2040	2050	2060
Urban	Total	BS	31%	44%	65%	97%	100%
		MC	31%	54%	94%	100%	100%
		SC	31%	70%	100%	100%	100%
	RC	BS	28%	41%	62%	95%	100%
		MC	28%	50%	89%	100%	100%
		SC	28%	65%	100%	100%	100%
Rural	Total	BS	8%	31%	56%	81%	100%
		MC	8%	37%	68%	98%	100%
		SC	8%	53%	98%	100%	100%
	RC	BS	6%	28%	53%	78%	100%
		MC	6%	34%	65%	96%	100%
		SC	6%	46%	87%	100%	100%

(3) Carbon emission intensity of materials

Under the influence of China's energy policies and carbon emission targets, the energy consumption and carbon emissions per unit of materials production have shown a clear downward trend. The elimination of outdated production capacity in the steel industry has achieved significant results, with 6,836 enterprises shut down by 2020, leaving a remaining 5,307 steel industry production enterprises (CISA, 2021). The elimination of outdated production capacity in the steel industry has achieved significant results, with 6,836 enterprises shut down by 2020, leaving a remaining 5,307 steel industry production enterprises (W. Wang, 2022). Carbon emissions from the cement industry are one of the key areas for emissions reduction in China. In 2022, China’s comprehensive energy consumption for cement clinker production was 86.76 kgce/t, which was 24.5% lower than the national average in 2010 (China MIIT, 2023). The average energy consumption per unit of glass production has decreased from 16.09 kgce/weight case in 2012 to 12.74 kgce/weight case in 2020 (China MIIT, 2022). The average comprehensive AC power consumption in China’s electrolytic aluminum industry was 13,543 kWh per ton in 2021, which was approximately 500 kWh lower than in 2013, reaching an internationally advanced level (NDRC, 2021).

However, compared with international leading levels, China’s building materials manufacturing still has a long way to go in terms of product structure, energy structure, resource utilization, and other aspects. For metal materials, recycled materials have much smaller carbon emissions than primary materials (Ogawa & Gao, 2006). In 2020, China’s production of primary aluminum was about 7.6 million tons, accounting for 20.4% of the total aluminum production, which is lower than the international average level (32.8%) and the level of developed countries (100% in Japan, 81% in the United States) (CNMIA, 2021). China’s steel industry has not yet reached the carbon peak and has great potential for emission reduction. Under the conditions of full utilization of waste steel resources, widespread use of electric furnace technology, and so on, the energy intensity of China's steel industry can be reduced by 30%-50% by 2050, and the total carbon emissions can be reduced by 60%-80% compared to the peak (J. Li et al., 2022). With the development of clean energy, the CI will decrease.

The energy intensity and carbon emissions intensity of building materials have always been a hot research topic, and many research institutions and regulatory agencies have conducted predictive studies (Agency, 2021; N. Zhou et al., 2019). The Energy Research Institute of the National Development and Reform Commission utilized the China Long-term Low Carbon and Energy Saving Analysis Model to set three paths (business-as-usual, policy deployment, and enhanced low-carbon) and analyzed possible low-carbon development paths for different industries (Dai et al., 2017). As Dai's research is authoritative and applicable, the relevant results were adopted in this study, as shown in Table 5-6.

Table 5-6 Building materials CI in different scenario (tCO_2/t)

		2020	2030	2040	2050	2060
BS Path	Steel	2.02	1.83	1.66	1.50	1.35
	Cement	0.25	0.24	0.23	0.22	0.21
	Brick/Tile	0.24	0.22	0.21	0.19	0.18
	Timber	0.10	0.10	0.09	0.09	0.09
	Aluminum	9.47	7.15	5.51	4.31	3.31
	Glass	0.66	0.58	0.49	0.41	0.35
	Insulation	2.99	2.73	2.56	2.40	2.23
MC Path	Steel	2.02	1.76	1.49	1.22	1.04
	Cement	0.25	0.22	0.20	0.18	0.17
	Brick/Tile	0.24	0.20	0.18	0.15	0.13
	Timber	0.10	0.09	0.09	0.08	0.08
	Aluminum	9.47	6.19	4.00	2.48	1.63
	Glass	0.66	0.53	0.43	0.34	0.27
	Insulation	2.99	2.53	2.19	1.84	1.59
SC Path	Steel	2.02	1.69	1.32	0.94	0.74
	Cement	0.25	0.20	0.18	0.16	0.14
	Brick/Tile	0.24	0.18	0.14	0.10	0.07
	Timber	0.10	0.09	0.08	0.08	0.07
	Aluminum	9.47	4.53	1.92	0.60	0.27
	Glass	0.66	0.46	0.37	0.27	0.20
	Insulation	2.99	2.25	1.68	1.21	0.92

Note: The CI of cement here does not include the chemical reaction emissions in the production process.

(4) Material transport

The transportation carbon emissions intensity is determined by the transportation structure and energy efficiency (N. Zhou et al., 2019). Building materials usually adopt a transportation structure that combines railway and road transport. Materials in Hangzhou mainly come from other cities in Zhejiang Province (Zhao et al., 2023), and the transportation structure is estimated using the turnover of goods in Zhejiang. Road transportation accounts for 90.7% of the land transport turnover in Zhejiang (Zhejiang PBS, 2022). The future transport structure is linearly fitted using historical data.

The transportation industry is a key sector for energy conservation and emission reduction, and non-compliant diesel trucks will be phased out and replaced by 2025, with a target to accelerate the green transportation of new energy vehicles (Zhejiang DRC, 2021). It is expected that the carbon emissions intensity of road freight transportation will show a downward trend.

Table 5-7 shows the transportation carbon emissions intensity under different paths. The baseline year data comes from sources such as the *China Statistical Yearbook, China Transport Statistical Yearbook, Statistical Bulletin of Transport Industry Development, and China Railway Statistical Bulletin*. Future data references authoritative research reports from the National Development and Reform Commission Energy Research Institute (Dai et al., 2017) and the China Academy of Transportation Sciences (ICCSD, 2021).

Table 5-7 Transportation emission intensity in different scenario (10^{-6} tonsCO_2/ t·km)

	2020	2030	2040	2050	2060
BS Path	148.7	144.4	135.6	126.9	118.2
MC Path	148.7	141.1	131.5	121.9	111.4
SC Path	148.7	137.9	127.5	117.0	105.6

5.5 Result

5.5.1 Building stock and flow

According to Figure 5-14, the total stock of residential and public buildings in Hangzhou was about 694 million m^2 in 2020. The demand for building stock varies greatly under the three development paths of per capita building area. As the population grows, the building stock will continue to increase, and the growth rate will slow down around 2040. By 2060, under the UD, MD, and SD paths, the building stock in Hangzhou could reach 1.45 billion m^2, 1.34 billion m^2, and 1.27 billion m^2, respectively. This means that the building stock in Hangzhou will increase by 83.0%-109.0% in the next 40 years.

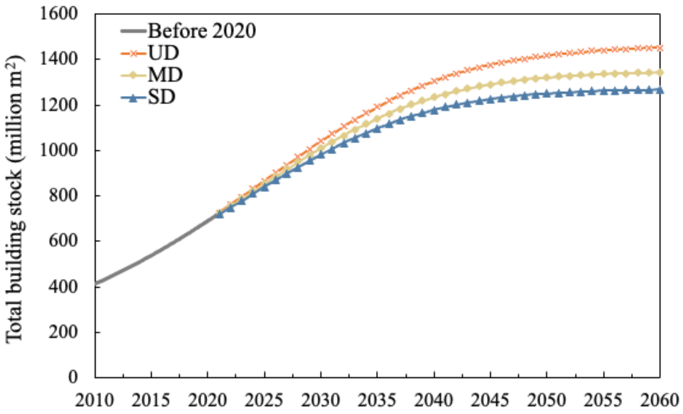


Fig. 5-14 Building stock in different scenarios

Figure 5-15 shows the composition of building stock under the MD scenario in Hangzhou. Urban buildings are the main driving force behind the growth of building stock, with their proportion continuously increasing from 76% in 2020 to 89.4% in 2060. Under the combined effect of rapid influx of migrants and increasing demand for per capita floor area, the demand for urban residential buildings in Hangzhou will increase from 359.1 million m^2 in 2020 to 761.3 million m^2 in 2060, representing an increase of 112.0%. Demand for urban public buildings will also increase significantly, from 166.9 million m^2 to 440.4 million m^2, an increase of 163.9%. As urbanization accelerates, the rural population will decline, and demand for rural residential buildings will begin to decrease from 2024, with the demand decreasing from its peak of 154.1 million m^2 in 2024 to 117.4 million m^2 in 2060. However, driven by policies for *Coordinated Urban-Rural Development* and *New Rural Construction*, demand for rural public buildings will grow and reach 24.5 million m^2, about 2.04 times that of 2020.

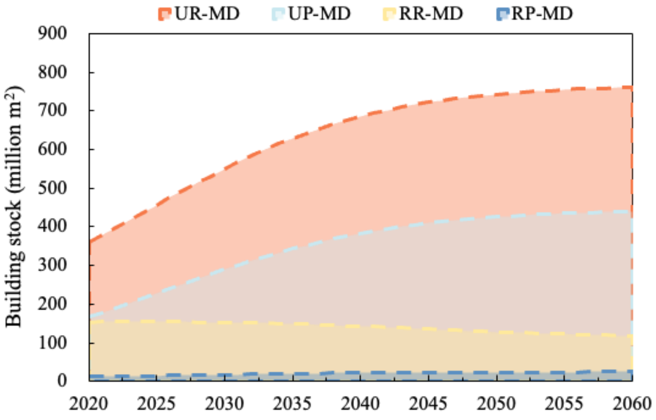


Fig. 5-15 The composition of the building stock in the MD path

The Figure 5-16 presents the increment of different types of buildings under the three paths. Urban residential buildings will increase by 450 million m^2, 402 million m^2, and 372 million m^2 respectively. Urban public buildings will increase by 324 million m^2, 274 million m^2, and 239 million m^2 respectively. Rural residential buildings will decrease by 33.7 million m^2, 36.1 million m^2, and 39.5 million m^2 respectively, while rural public buildings will increase by 16.7 million m^2, 12.6 million m^2, and 9.8 million m^2 respectively. Overall, the increment of building stock under the UD path is approximately 1.3 times that under the SD path.

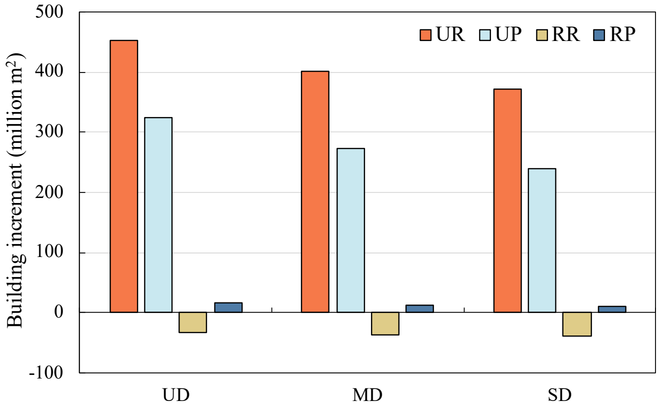


Fig. 5-16 The increment of different types of buildings in 2020-2060

The figure 5-17 displays the dynamic of construction activities in Hangzhou's construction industry under three different scenarios, i.e., the construction and demolition of buildings. With the increase in building demand, the peak of building construction in each scenario is reached around 2030, followed by a decreasing trend, which eventually balances with building demolition in 2060. In the UD scenario, the short lifespan of buildings leads to a high rate of turnover, resulting in a large area of building construction. By 2060, the new building area reaches 39.1 million m^2, and the building demolition area reaches 37.4 million m^2.

In the SD scenario, the long lifespan design standard only applies to newly built buildings after the base year, which means buildings constructed around 2010 will reach their expected lifespan around 2045, and the peak of demolition, which is 23.8 million m^2, will be reached in 2049. Afterward, the demolition area will decrease due to the dual impact of decreasing building outflow and increasing building demand. Compared with the other two scenarios, the rate of decrease in building construction is faster, and the inflow of buildings is under control. By 2060, the new building area is only 23.9 million m^2, which is 61.1% of that in the UD scenario.

Building activities are concentrated in urban areas. In all three scenarios, new construction activities in urban areas account for over 85% of the total new construction, and the proportion of urban area demolition ranges from 73% to 92%. Urban residential building is the largest contributor to building activities, accounting for nearly 60% of the total new construction and over 52% of the demolition.

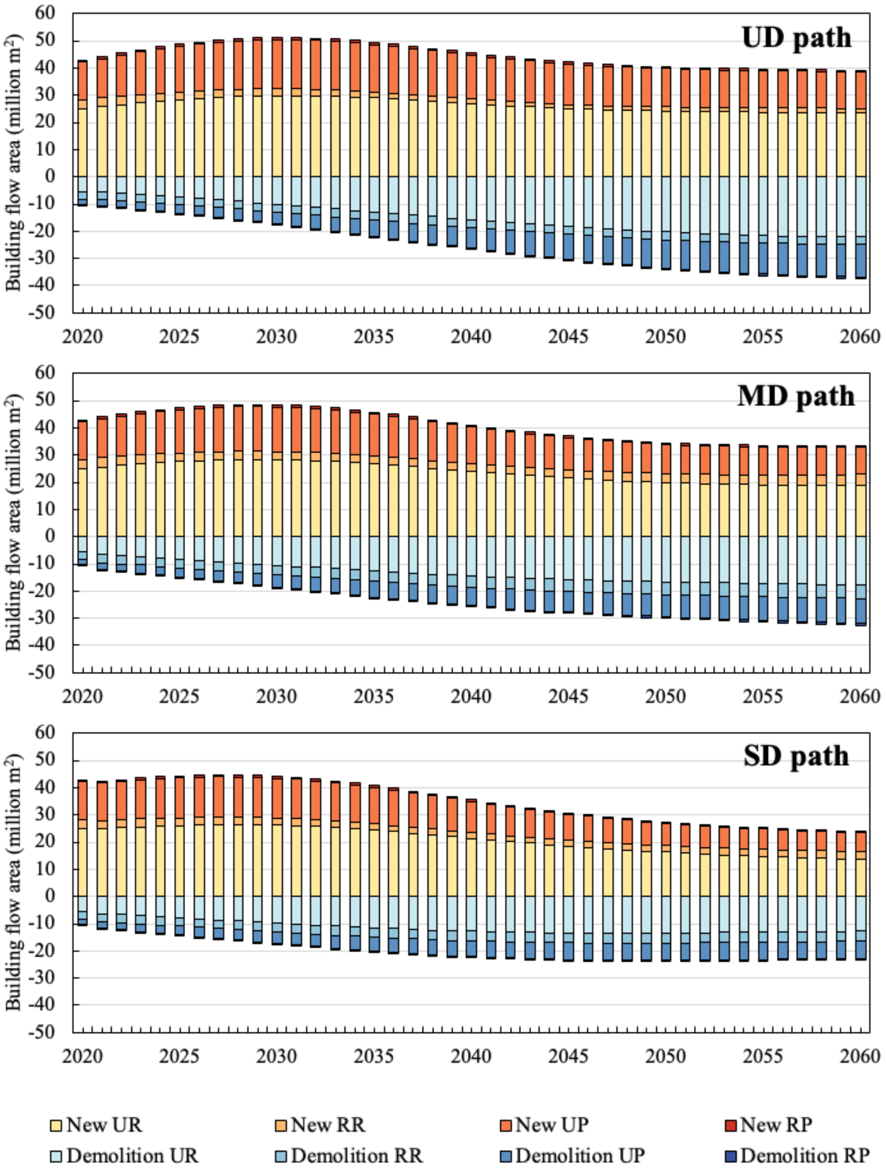


Fig. 5-17 Building inflow and outflow area in each path

5.5.2 Building materials demand

This study aims to predict the development of the construction industry in Hangzhou city by designing three hypothetical development paths for development mode and policy driven. These paths are combined to form a total of nine scenarios to demonstrate the future demand for building materials, as shown in Figure 5-18. The trend of changes in material demand is consistent with that of new building areas, showing a trend of initial increase followed by decrease. By 2060, the demand for building materials will decrease to 34.2% (SDSC) - 86.4% (UDBS) of the base year. Development mode and policy driven both affect building material demand in Hangzhou city.

The total material intensity of new buildings is declining. In the three scenarios of the BS path, the material intensity of each material remains unchanged, the reduction in total material intensity mainly depends on the proportion of building structures in new construction. As lightweight steel structures become more popular, the materials demand for buildings decreases, but the reduction in total material intensity is limited, only 5.3% (UDBS), 8.2% (MDBS), and 8.2% (SDBS). In the other scenarios, the total material intensity is influenced by the reduction in material intensity of each material, the reduction in material waste caused by the popularity of prefabricated buildings, and the change in the proportion of building structures. The total material intensity decreases significantly, with a maximum reduction of 39.7% (SDSC).

For the future total demand for building materials, when the policy driven is same, choosing the SD path as development mode can save about 183.9-232.3 million tons of building materials compared to the UD path. When the development mode is same, choosing the SC path as policy driven can save about 119.0-167.4 million tons of building materials compared to the BS path. The scenario that saves the most materials is SDSC, which requires 675.5 million tons of building materials in the next 40 years, while the material demand in the UDBS scenario is as high as 1026.8 million tons, which is 1.52 times that of the SDSC scenario.

In terms of the peak demand for building materials in the 9 scenarios, reasonable development mode and strict policy driven can effectively reduce the peak demand and bring it forward. For development mode, SD path can reach the peak 3-4 years earlier than the UD path, reducing the peak demand by about 1.2-2.3 million tons. For policy driven, SC path can bring the peak forward by 2-3 years compared to the BS path, reducing the peak demand by about 2.7-3.8 million tons. The UDBS scenario has the latest peak, which will occur in 2030 with a demand of up to 29.9 million tons, while the SDSC scenario has the smallest building material demand with a peak appearing in 2024, at 24.9 million tons. The optimal scenario reduces the peak demand by about 5 million tons compared to the worst scenario.

In terms of specific building material demand, steel, cement, and bricks/tile are the main consumables, accounting for more than 90% of the total material demand. Over the next 40 years, the cumulative demand for steel, cement, and bricks could reach as high as 315.6 million tons, 382.3 million tons, and 247.6 million tons, respectively. These three materials are all high-energy-consuming and high-carbon-emitting materials, which will exert tremendous pressure on resources and the environment. With some mitigation measures in the SDSC scenario, the cumulative demand for these three materials can be reduced by 30.1%, 34.0%, and 40.1%, respectively.

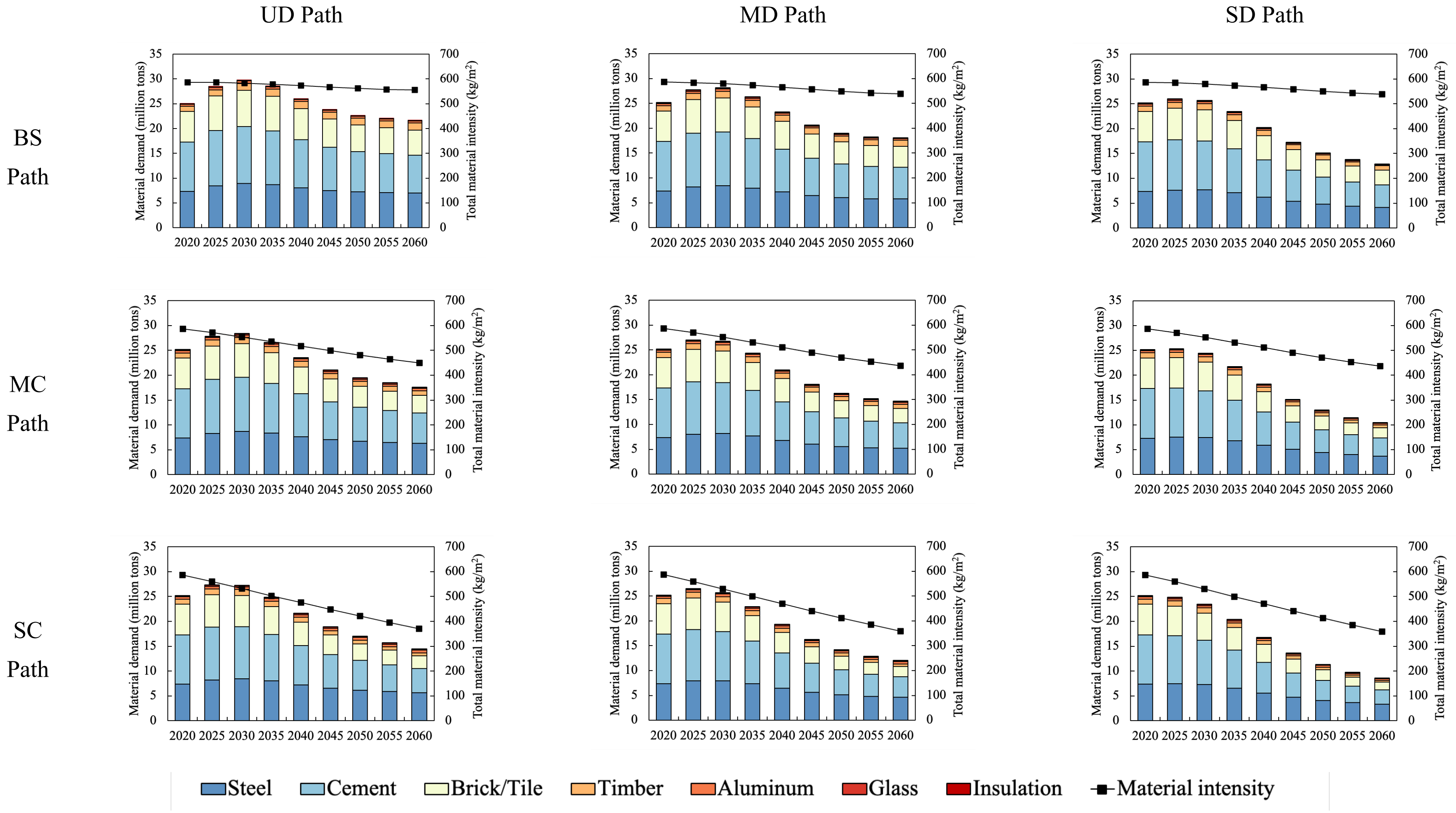


Fig. 5-18 Building material demand and total material intensity

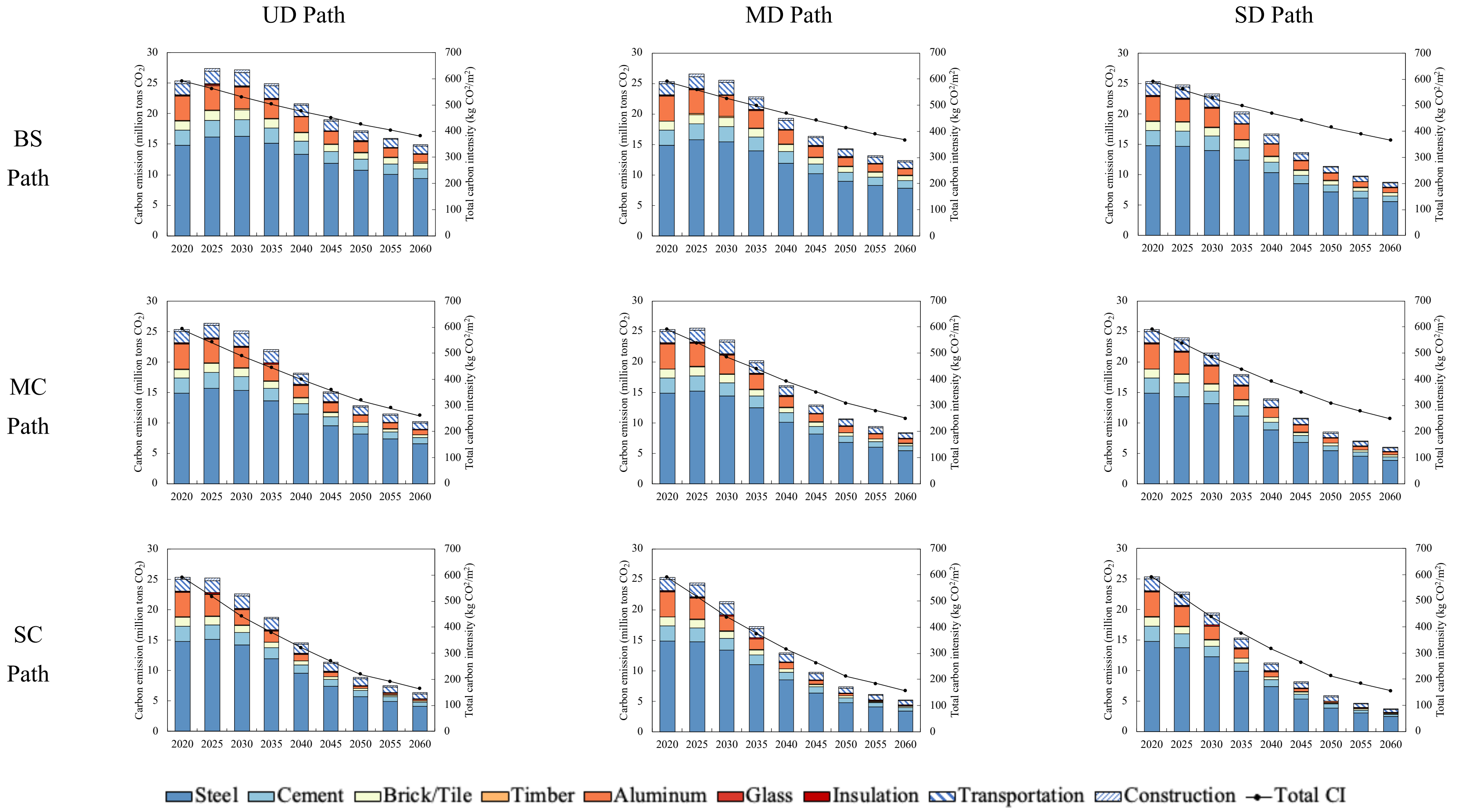


Fig. 5-20 The sources of MSCE in various scenarios

5.5.3 Carbon emissions in the materialization stage

The total carbon emissions during the materialization stage in the Hangzhou construction industry for the 9 scenarios are shown in Figure 5-19. In terms of annual carbon emissions change, the three scenarios under the SD pathway show a downward trend, while the other six scenarios show an upward trend followed by a decline, with carbon emissions peaking between 2021 and 2028. The UDBS scenario has the highest carbon emissions in the long term, with carbon emissions exceeding 27 million tons in 2024 and peaking at 27.6 million tons in 2027, followed by a decline phase, reaching 14.9 million tons by 2060. The SDSC scenario has the least carbon emissions, with 3.7 million tons in 2060, only 24.9% of the carbon emissions in the same year for the UDBS scenario, and 14.7% of the carbon emissions in 2020.

In terms of cumulative carbon emissions, policy-driven factors have a greater impact on carbon emissions. Ranked by total cumulative carbon emissions from largest to smallest, the three scenarios in the BS path are rank first (UDBS, 864.4 million tons), second (MDBS, 779.1 million tons), and fourth (SDBS, 676.6 million tons). In the MC path, the three scenarios rank third (UDMC, 738.1 million tons), fifth (MDMC, 669.6 million tons), and seventh (SDMC, 586.2 million tons). In the SC path, the three scenarios rank sixth (UDSC, 617.0 million tons), eighth (MDSC, 563.9 million tons), and ninth (SDSC, 498.3 million tons). The cumulative carbon emissions difference between scenarios can reach up to 366.1 million tons. If measured by the average carbon emissions over the next 40 years, this value is approximately equivalent to the carbon emissions in the SDSC scenario over 30 years.

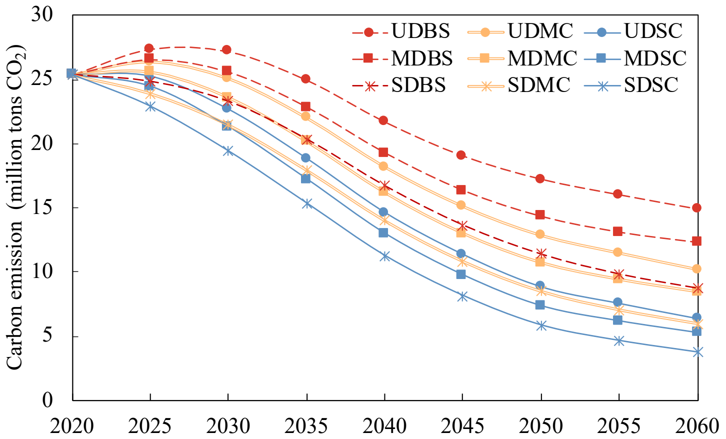


Fig. 5-19 The total MSCE in different scenarios

The sources of carbon emissions under each scenario and the predicted CI are shown in Figure 5-20. Thanks to the joint efforts of the construction sector and upstream sectors, by 2060, the CI during the materialization stage will decrease by 35.7% (BS Path), 56.0% (MC Path), and 72.4% (SC Path) compared to the baseline year of 541.4 kg CO_2/m^2.

Steel, cement, brick/tile, and aluminum are the main sources of carbon emissions, accounting for over 96.5% of the total material carbon emissions. This means that more than

80% of total carbon emissions comes from the production of these four materials. Driven by high demand and high production energy consumption, steel is the largest source of carbon emissions. Although the demand for aluminum accounts for a small proportion of total building material demand, its production process requires a large amount of energy and has a significant carbon footprint, making its carbon reduction contribution worthy of attention.

Carbon emissions from cement production also require special attention. This study only accounts for the carbon emissions produced by energy consumption in the cement production process, while the CO_2 emissions from the mineral decomposition in raw materials are not accounted for. Some studies have shown that the carbon emissions from this process account for approximately 44% of all carbon emissions from cement production (Yu et al., 2017). If the carbon emissions from mineral decomposition are included, the proportion of cement carbon emissions will be doubled.

5.6 Discussion

5.6.1 The benefits of different paths to decarbonization

To analyze the decarburization contribution of each path in the construction industry, the UDBS scenario is set as the baseline scenario. Scenarios with different development modes, policy-driven, and the combination of both are analyzed. Figure 5-21 shows the cumulative carbon emission reductions among the UDBS, MDBS, and SDBS scenarios, representing the differences in carbon reduction among different development mode. By choosing a more sustainable development mode and controlling building stock, the construction industry in Hangzhou has the potential to achieve 188.0 million tons of cumulative carbon emission reductions in the next 40 years. This carbon emission reduction potential mainly comes from the construction industry as the demand side, that is, reducing the demand for new buildings and building materials.

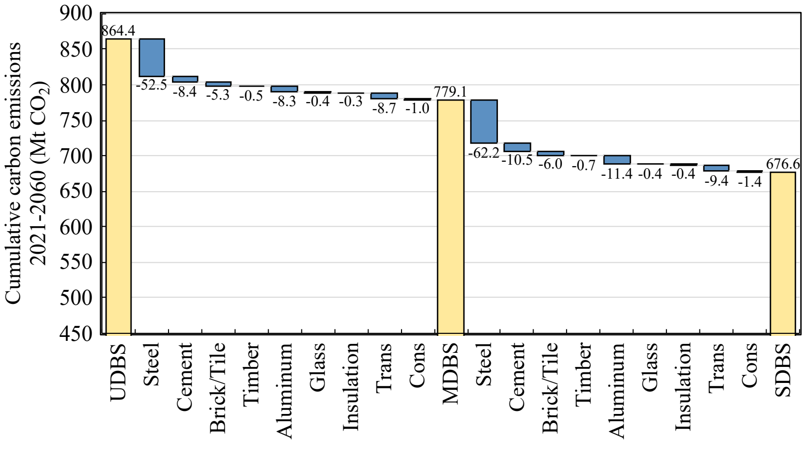


Fig. 5-21 Decarbonization potential of the development mode path

Material production, transportation and construction processes all contribute to carbon emission reductions. The UDBS scenario has a total cumulative material demand of 1026.8 million tons, while the material demand of the MDBS and SDBS scenarios is 89.7% and 77.4% of the UDBS scenario, respectively. Benefits from the reduction in material transportation, the transportation process in the SDBS scenario, which can produce up to 18.1 million tons of carbon emission reductions, accounting for 9.6% of the total reduction.

Among the materials, steel has the highest embedded carbon among building materials and the largest emission reduction potential, with a demand reduction of 72.5 million tons, which can contribute to 114.7 million tons of carbon emission reductions, accounting for 61.0% of the total reduction. The construction stage is the most direct target for carbon emission reductions, and up to 2.4 million tons of carbon can be reduced by reducing construction. By reducing new building area, the construction process can reduce carbon emissions by up to 2.4 million tons.

The cumulative carbon emissions reduction for the three scenarios, UDBS, UDMC, and UDSC, representing the differences among the three policy-driven paths, are shown in Figure 5-22. Driven by more stringent carbon emission control and green building policies, the construction industry in Hangzhou has the potential to achieve a cumulative carbon emissions reduction of 247.4 million tons over the next 40 years. This potential mainly comes from the upstream supply-side sector, which reduces fossil energy consumption in the production process, lowers the implicit carbon content of materials, and improves material performance to save materials.

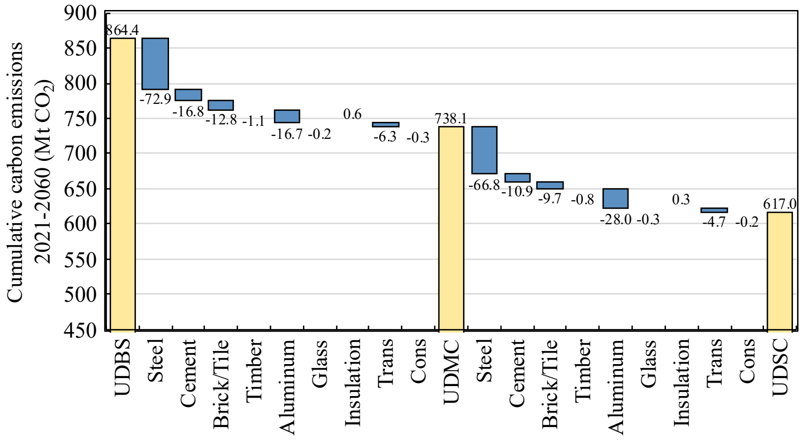


Fig. 5-22 Decarbonization potential of policy driven path

Under the dual drivers of decreasing material CI and material consumption intensity, the carbon emissions reduction potential of material production can reach up to 235.9 million tons. Steel, cement, aluminum, and brick/tile are the main contributors to carbon emissions reduction. It is worth noting that due to the increased energy-saving requirements for building operation, more insulation materials and glass will be consumed in the future. The increase in insulation material demand has a negative contribution to carbon emissions reduction. Glass is in a similar situation, but the carbon emissions reduction benefit of glass production is higher than the material demand benefit, so it still makes a positive contribution to carbon emissions reduction.

The potential for emissions reduction in the transportation stage mainly comes from the reduction of transportation weight. Compared with the UDBS scenario, the UDSC scenario can save 167.4 million tons of materials, thereby reducing transportation carbon emissions by 11.0 million tons. The rapid popularization of prefabricated buildings and the reduction of on-site construction are the reasons for the difference in carbon emissions during the construction stage. The popularization of prefabrication can provide 0.5 million tons of carbon emissions reduction, which accounts for 4.1% of the cumulative construction carbon emissions in the UDBS scenario.

Figure 5-23 shows the cumulative carbon emissions reduction in UDBS, MDMC, and SDSC, which represent the combined effects of development mode and policy-driven on carbon emissions reduction. Under more sustainable development mode and stronger policy promotion, there is a difference of 366.1 million tons of cumulative carbon emissions between the cleanest scenario, SDSC, and the baseline scenario, UDBS. It means the maximum potential for decarburization in Hangzhou's construction industry over the next 40 years is 366.1 million tons. The construction process is driven by two factors, the reduction of new construction area and the popularity of prefabricated buildings with 2.8 million tons cumulative potential. The carbon emissions reduction in transportation is driven by a combination of reduced transportation weight and lower transportation CI, with a potential reduction of 25.4 million tons. The carbon emission reduction potential of building material production is driven by the joint effect of reduced demand and decreased emission intensity in production, amounting to 337.9 million tons.

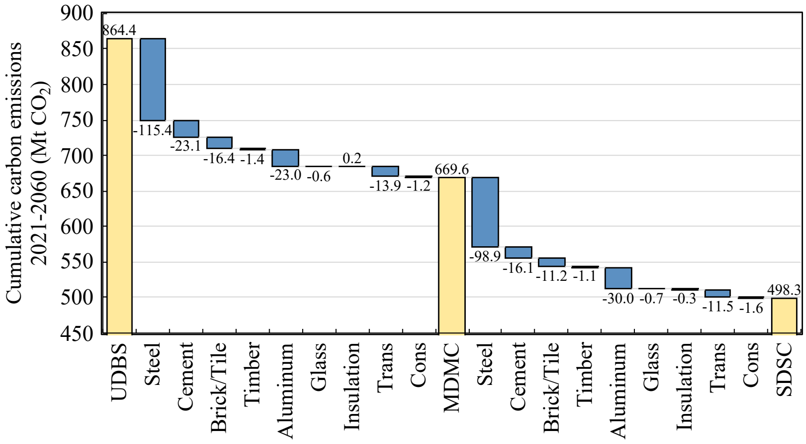


Fig. 5-23 Decarbonization potential of hybrid path

5.6.2 Decarbonization possibilities for the construction industry

When development mode and policy driven are simultaneously in effect, direct comparison cannot determine the actual impact of each path on decarburization, nor can it analyze the contribution of each influencing factor to carbon reduction. In order to quantitatively analyze, the LMDI method is introduced to decompose the cumulative carbon emission difference between the baseline scenario UDBS and the optimal scenario SDSC. According to the influencing factors and carbon emission stages, the carbon emission difference is decomposed into three stages and 10 parts, as shown in Figure 5-24.

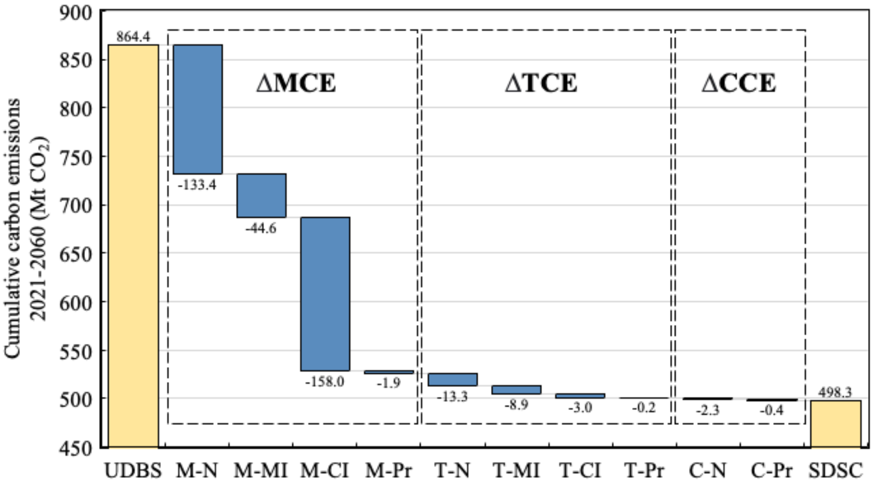


Fig. 5-24 Decomposition of cumulative emission reduction potential

Note: M, T and C denotes material production stage, transportation stage and construction stage. N, MI, CI, Pr means decarbonization potential due to reduction of new building area, reduction of MI, reduction of CI and prefabrication rate.

The material production stage contributes the greatest decarburization potential, with a cumulative reduction of 338.0 million tons of carbon emissions between 2021 and 2060. The transportation stage contributes 25.4 million tons of carbon reduction, and the construction stage has a potential for 2.8 million tons of carbon reduction.

Synergies in upstream sectors have played a critical role in decarbonizing the construction industry from the supply side. The factor that contributes the most to carbon reduction is the CI of materials. Strictly controlling the carbon emissions of material production can produce a decarbonization potential of 158.0 million tons, accounting for 43.2% of the total carbon reduction. Optimizing building design and improving material performance have reduced MI, contributing 44.6 million tons and 8.9 million tons of carbon reduction in the material production stage and transportation stage, respectively. In addition, a decrease in the CI of the transportation can also lead to 3.0 million tons of potential.

From the construction industry as demand side, controlling the new building area is an important carbon reduction measure, with a potential for 149.0 million tons of decarburization, accounting for 40.7% of the total carbon reduction. The reduction comes from the decrease in material and transportation demand, as well as the decrease in construction area. The popularization of prefabricated building technology has also contributed to carbon reduction, with a reduction of 1.9 million tons CO_2 through the reduction of material loss and 0.6 million tons of CO_2 through the reduction of construction and transportation energy consumption.

As shown in Figure 5-25, the carbon emissions differential is continued to be decomposed into annual data. Under the optimal scenario SDSC, Hangzhou's construction industry would still emit 3.7 million tons of MSCE in 2060. Although this represents a 75.0% reduction in MSCE compared to the baseline scenario UDBS, there is still a significant gap towards achieving carbon neutrality. Buying carbon credits in the carbon market or actively developing carbon removal technologies may be necessary measures for the construction industry in Hangzhou to achieve carbon neutrality.

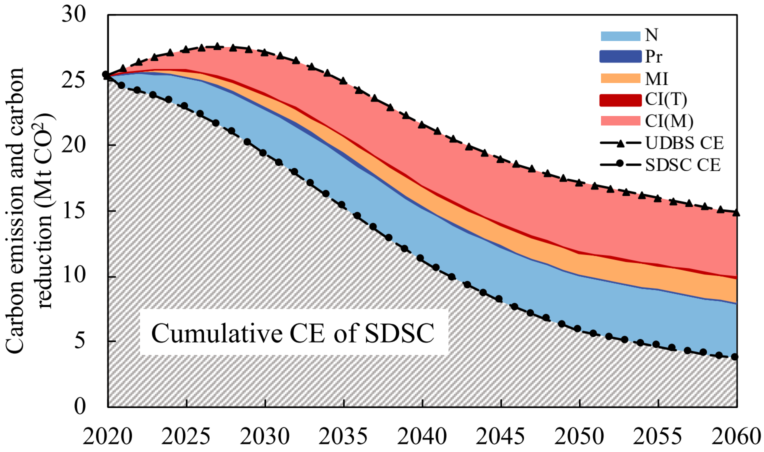


Fig. 5-25 Influencing factor emission reduction potential

Out of the 11.2 million tons of carbon emission differences between the two scenarios, controlling the area of newly built buildings, reducing the CI of material production, and lowering MI are the most effective decarbonization strategies. In 2060, controlling the area of newly built buildings can result in a reduction of 4.2 million tons MSCE, while reducing the CI of material production can contribute to a reduction of 4.9 million tons MSCE, and lowering MI can contribute to a reduction of 1.9 million tons MSCE. These three measures account for 74.3% of the decarbonization potential by the construction industry in Hangzhou.

As shown in Figure 5-26, the decarbonization potential of material production CI is further decomposed, with the steel industry having the largest carbon reduction potential, increasing every year. Over the next 40 years, the steel industry can contribute 84.1 million tons of cumulative carbon reduction to the construction industry through its own carbon reduction efforts. The aluminum industry can contribute 48.0 million tons of cumulative carbon reduction, while the cement and brick manufacturing industries can contribute 14.4 million tons and 12.1 million tons of cumulative carbon reduction, respectively.

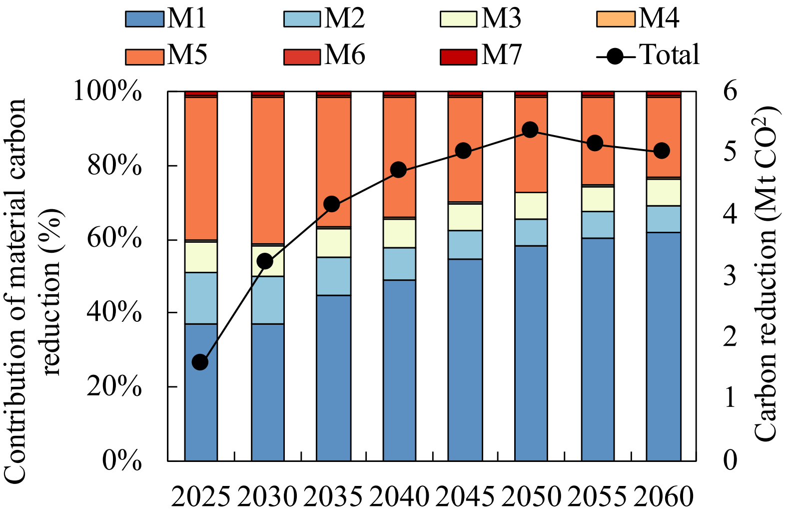


Fig. 5-26 Carbon emission reduction potential of material production CI

5.6.3 Policy implications

Based on the decomposition analysis, important factors in the joint carbon reduction process between the construction industry in Hangzhou and upstream sectors have been identified. Based on these factors, the following insights are proposed in this paper.

For demand side, that is, the Hangzhou construction industry itself, extending the lifespan of buildings, controlling per capita floor area, and avoiding unnecessary construction are key to reducing emissions. The MSCE essentially come from the new construction of buildings, which is influenced by social demand and the lifespan of buildings. From the perspective of building stock, developing the housing rental market, implementing property purchase restrictions, and real estate taxes (Hangzhou HSREA, 2022) to curb excessive investment and speculative behavior are effective ways to control building stock by reducing vacant housing. Introducing incentive policies to encourage the construction and purchase of small-sized houses (Hangzhou HSB, 2022) are effective ways to control the construction of new buildings by controlling the per capita building area.

In terms of building lifespan, for new buildings, strict adherence to green building design standards and the use of high-performance green materials should be ensured to guarantee building quality. For existing buildings, a reasonable evaluation system should be established to carry out maintenance and repairs at appropriate times and maximize the lifespan of the building. For buildings approaching the end of their lifespan, a thorough assessment should be conducted to compare the carbon footprint of demolition and reconstruction versus renovation and choose a more sustainable disposal method. In addition, urban and rural construction and development should be planned reasonably and building demolition rules and relocation management systems should be established to prevent premature demolition of buildings.

From the perspective of the supply side, i.e., the upstream sectors of the construction industry, emission reduction strategies can be implemented from two aspects: reducing the embodied carbon of materials and reducing the demand for materials. The reduction of embodied carbon of materials depends on the low-carbon efforts of the building materials industry. Carbon emissions from steel are the main source of carbon emissions in the construction industry. With the vigorous development of steel structure modular buildings in Hangzhou, reducing the emissions of steel will be particularly important. Making full use of waste steel and developing short process steelmaking will be effective measures for carbon reduction(CISA, 2021). Aluminum is a high-energy and high-carbon material. To reduce carbon emissions, low-carbon energy substitution technologies such as wind power and solar power should be promoted(NDRC, 2021). Carbon capture, utilization, and storage technologies are necessary for decarbonizing the cement industry(China MIIT, 2022). In addition, strengthening industrial carbon control, establishing and improving the carbon footprint evaluation of building materials, and fully leveraging the flexibility of carbon trading are also important means for the low-carbon transformation of the building materials industry (China MIIT, 2022).

Reducing material demand depends on the efforts of the architectural design department. Optimizing building forms and layout designs during the design phase can effectively reduce material consumption. Choosing low-carbon structures and using lightweight, high-strength green building materials can reduce emissions during production. In addition, the promotion of prefabricated and assembly-style construction should be vigorously promoted to reduce waste and emissions during the construction process.

5.7 Summary

The construction industry is a high carbon sector and reducing carbon emissions from the construction industry and its upstream sectors is crucial to achieving carbon neutrality goals. Cities have become the basic unit for achieving carbon neutrality goals. This chapter innovatively selects the city of Hangzhou, China, which is in a period of rapid development in the construction industry and rapid increase in building stock, as the research object from the city scale. It looked ahead to the carbon emissions and emission reduction potential of Hangzhou’s construction industry up to 2060.

Through the establishment of a bottom-up carbon accounting model, the possible carbon emission trajectory of Hangzhou’s construction industry was explored. The influencing factors are classified into two categories: development mode and policy driven and defining a total of nine scenarios. The building stock, building flow, material demand, and carbon emissions of each scenario are quantitatively evaluated in detail. In addition, the differences in carbon emissions between scenarios are analyzed to study the decarbonization potential of various factors and strategies. The main findings are as follows:

(1) In 2020, the total carbon emissions in the materialization stage of the construction

industry in Hangzhou city are 25.4 million tons. According to different development scenarios, carbon emissions are expected to show two patterns: first rising and then falling, or directly decreasing. Without effective emission reduction measures, under the baseline scenario (UDBS), carbon emissions will continue to increase until 2027, reaching 27.6 million tons, and a massive scale of 14.9 million tons is still expected by 2060. This will pose a significant challenge to carbon commitments.

(2) If timely joint emission reductions are implemented in the construction and upstream industries, the carbon emissions from the construction industry will trend downward. In the optimal scenario SDSC, the cumulative emission reduction potential over the next 40 years can reach 366.1 million tons. Compared with the UDBS scenario, the carbon emissions from the construction industry can be reduced by 75% in 2060, but there will still be 3.7 million tons of CO_2 that need to be compensated through carbon trading or carbon removal.

(3) Decomposition analysis shows that the decarbonization potential of the construction industry mainly comes from carbon emission reduction in the supply-side material production process and demand-side control of new building area. These two factors will contribute 43.2% and 40.7% of the cumulative carbon emission reductions. Reducing material demand intensity contributes to 14.7% of decarbonization in the construction industry.

(4) Extending the lifespan of buildings, controlling per capita building area, and avoiding unnecessary construction are crucial in reducing emissions from the demand side. On the supply side, carbon reduction in materials is the key to decarbonizing the construction industry. Therefore, it is necessary to focus on how to reasonably reduce the demand for high-carbon materials such as steel, aluminum, and cement, as well as reducing their embodied carbon.

Reference

Agency, I. E. (2021). *An energy sector roadmap to carbon neutrality in China*. OECD Publishing.

AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability—IPCC. (2022). https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/

Azari, R., & Abbasabadi, N. (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings*, *168*, 225–235. https://doi.org/10.1016/j.enbuild.2018.03.003

Building Construction Handbook-5th edition. (2012). China Architecture and Building Press.

CABR. (2019a). *Green Building Evaluation Standard*. China Construction Industry Press.

CABR. (2019b). *Standard for building carbon emission calculation*. China Construction Industry Press.

Cai, W., Wan, L., Jiang, Y., Wang, C., & Lin, L. (2015). Short-Lived Buildings in China: Impacts on Water, Energy, and Carbon Emissions. *Environmental Science & Technology*, *49*(24), 13921–13928. https://doi.org/10.1021/acs.est.5b02333

Cao, X., Li, X., Zhu, Y., & Zhang, Z. (2015). A comparative study of environmental performance between prefabricated and traditional residential buildings in China. *Journal of Cleaner Production*, *109*, 131–143. https://doi.org/10.1016/j.jclepro.2015.04.120

China MIIT. (2022). *Building materials industry carbon peak implementation plan*.

China MIIT. (2023). *Typical Experience and Practice Cases of Energy Efficiency "Leader" Enterprises in Key Energy-using Industries in 2022: Building Materials Industry*.

China NBS. (1995). *China Urban and Rural Construction Statistical Yearbook 1995*. China National Bureau of Statistics.

China NBS. (2001). *Fifth National Population Census Bulletin*. China National Bureau of Statistics.

China NBS. (2012). *China Urban and Rural Construction Statistical Yearbook 2012*. China National Bureau of Statistics.

China NBS. (2021). *Seventh National Population Census Bulletin*. China National Bureau of Statistics.

CISA. (2021). *The Yearbook of Iron and Steel Industry of China*. China Iron and Steel Association.

CNMIA. (2021). *The yearbook of nonferrous metals industry of China*. China Nonferrous Metals Industry Association.

Dai, Y. D., Kang, Y. B., & Xiong, X. P. (2017). Energy Development and Carbon Emission Scenarios Towards 2050 Energy Transition and Low Carbon Development Roadmap for China. *China Environmental Science Press: Beijing, China*.

Dixit, M. K., Culp, C. H., & Fernández-Solís, J. L. (2013). System boundary for embodied energy in buildings: A conceptual model for definition. *Renewable and Sustainable Energy Reviews*, *21*, 153–164. https://doi.org/10.1016/j.rser.2012.12.037

Fu, C. (2020). Upgrading and application of steels for building structures and its influence on energy conservation and emission reduction. *Steel Rolling*, *3*, 65–70.

Han, L. (2010). Aluminium Formwork and Its Application in High-Rise Construction of Shenton Way Project in Singapore. *Journal of Qingdao Technological University*, *31*(6), 24–30.

Hangzhou BPNR. (2001). *Master Plan of Hangzhou (1996-2010)*. Hangzhou Municipal Bureau of Planning and Natural Resources.

Hangzhou Daily. (2019, August 6). *Announcement of Progress in the Action Plan for Renovation of Old Residential Areas, Old Factory Districts, Urban Villages, and Demolition of Illegal Buildings in Hangzhou City*.

Hangzhou Daily. (2022, December 12). *The Hangzhou city started 282 new assembly building projects this year with a construction area of 26.95 million square meters*.

Hangzhou Daily. (2023, February). *"Chain" green development "assembly" to build the future*.

Hangzhou DRC. (2021). *Hangzhou's 14th Five-Year Plan for Population Development*. Hangzhou Development and Reform Commission.

Hangzhou GPNCI. (2019). *Promotion of steel structure assembly type housing pilot work program*. Hangzhou Leading Group for Promoting New Construction Industrialization.

Hangzhou HSB. (2022). *Hangzhou Housing Security and Real Estate Development "14th Five-Year Plan."* Housing Security Bureau of Hangzhou.

Hangzhou HSREA. (2022). *Notice on further promoting the stable and healthy development of the real estate market*. Hangzhou Housing Security and Real Estate Administration.

Hangzhou MBS. (1987). *Hangzhou Statistical Yearbook 1987*. Hangzhou Municipal Bureau of Statistics.

Hangzhou MBS. (2022). *Hangzhou Statistical Yearbook 2022*. Hangzhou Municipal Bureau of Statistics.

Hangzhou Municipal Government. (2019). *Work Plan for the Pilot Project of Prefabricated Steel Structure Residential Buildings in Hangzhou*.

Hangzhou URCC. (2022). *Hangzhou Green Building Special Planning Revision (2022-2030)*. Hangzhou Urban and Rural Construction Committee.

Hong, L., Zhou, N., Feng, W., Khanna, N., Fridley, D., Zhao, Y., & Sandholt, K. (2016). Building stock dynamics and its impacts on materials and energy demand in China. *Energy Policy*, *94*, 47–55. https://doi.org/10.1016/j.enpol.2016.03.024

Huang, C., Han, J., & Chen, W.-Q. (2017). Changing patterns and determinants of infrastructures' material stocks in Chinese cities. *Resources, Conservation and Recycling*, *123*, 47–53. https://doi.org/10.1016/j.resconrec.2016.06.014

ICCSD. (2021). *Understanding Carbon Neutralization: China's 2020-2050 Low Carbon Development Action Roadmap*. CITIC Press Group.

Kumanayake, R., Luo, H., & Paulusz, N. (2018). Assessment of material related embodied carbon of an office building in Sri Lanka. *Energy and Buildings*, *166*, 250–257. https://doi.org/10.1016/j.enbuild.2018.01.065

Li, D., Huang, G., Zhang, G., & Wang, J. (2020). Driving factors of total carbon emissions from the construction industry in Jiangsu Province, China. *Journal of Cleaner Production*, *276*, 123179. https://doi.org/10.1016/j.jclepro.2020.123179

Li, J., Xie, canyang, Cai, W., & Wang, can. (2022). Low Carbon Development Pathway of China's Iron and Steel Industry under the Vision of Carbon Neutrality—Consensus and Uncertainty. *Chinese Journal of Environmental Management*, *14*(1), 48–53.

Li, X., Xie, W., Xu, L., Li, L., Jim, C. Y., & Wei, T. (2022). Holistic life-cycle accounting of carbon emissions of prefabricated buildings using LCA and BIM. *Energy and Buildings*, *266*, 112136. https://doi.org/10.1016/j.enbuild.2022.112136

Lin, B., & Liu, H. (2015). CO2 mitigation potential in China's building construction industry: A comparison of energy performance. *BUILDING AND ENVIRONMENT*, *94*, 239–251. https://doi.org/10.1016/j.buildenv.2015.08.013

Lin, H., Takasu, K., Suyama, H., Koyamada, H., & Liu, S. (2022). A study on properties, static and dynamic elastic modulus of recycled concrete under the influence of modified fly ash. *Construction and Building Materials*, *347*, 128585. https://doi.org/10.1016/j.conbuildmat.2022.128585

Live in Hangzhou. (2015, September 29). *Hangzhou housing 60 years evolution history*. http://zzhz.zjol.com.cn/system/2015/09/29/020855289.shtml

Lou, N., Zhang, L., & Ren, M. (2011). *Evaluation and Selection Technology of Green Building Structure System*. China Architecture & Building Press.

Lu, X. (2010). *Project Management*.

Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Nygaard Rasmussen, F., Houlihan Wiberg, A., & Potting, J. (2018). Design and construction strategies for reducing embodied impacts from buildings – Case study analysis. *Energy and Buildings*, *166*, 35–47. https://doi.org/10.1016/j.enbuild.2018.01.033

MEE. (2022). *Implementation Plan for Synergy in Pollution Reduction, Carbon Reduction, and Efficiency*. Ministry of Ecology and Environment of the PRC.

MOHURD. (2019). *Uniform standard for design of civil buildings*.

MOHURD. (2020). *China Urban-Rural Construction Statistical Yearbook 2019*. China Planning Press Beijing, China.

MOHURD. (2022a). *China Urban-Rural Construction Statistical Yearbook 2021*. China Planning Press Beijing, China.

MOHURD. (2022b). *"14th Five-Year Plan" for the development of the construction industry*.

NDRC. (2007). *National Comprehensive Work Plan for Energy Conservation and Emission Reduction*. National Development and Reform Commission.

NDRC. (2021). *Notice on improving the ladder tariff policy of electrolytic aluminum industry*.

Ogawa, Y., & Gao, W. (2006). Research on Recycle Process and Energy Consumption about Recycle od Construction Waste. *Journal of Environmental Engineering*, *71*(604), 93–100. https://doi.org/10.3130/aije.71.93_2

UNEP. (2017). *Global Status Report 2017*. United Nations Environment Programme.

Wang, H., Zhang, Y., Gao, W., & Kuroki, S. (2020). Life Cycle Environmental and Cost Performance of Prefabricated Buildings. *Sustainability*, *12*(7), Article 7. https://doi.org/10.3390/su12072609

Wang, W. (2022, March). Review on unit energy consumption of Steel in China in 2021. *China Metallurgical News*.

Xi, J. (2022). Correctly understand and grasp the major theoretical and practical issues of China's development. *Qiushi*, *4*(10), r9.

Yu, H., Yang, H., Zhang, H., & Zeng, J. (2017). Research of Carbon Emission of Cement in Lifecycle. *Sichuan Building Materials*, *01*(43), 1–3.

Zhang, Y., Hu, S., Guo, F., Mastrucci, A., Zhang, S., Yang, Z., & Yan, D. (2022). Assessing the potential of decarbonizing China's building construction by 2060 and synergy with industry sector. *Journal of Cleaner Production*, *359*, 132086. https://doi.org/10.1016/j.jclepro.2022.132086

Zhang, Y., & Yu, B. (2017). Research and application on HRB600 in china. *China Building Materials Science and Technology*, *5*, 97–100.

Zhang, Z., & Wang, B. (2016). Research on the life-cycle CO2 emission of China's construction sector. In *ENERGY AND BUILDINGS* (Vol. 112, pp. 244–255). ELSEVIER SCIENCE SA. https://doi.org/10.1016/j.enbuild.2015.12.026

Zhao, Q., Gao, W., Su, Y., & Wang, T. (2023). Carbon emissions trajectory and driving force from the construction industry with a city-scale: A case study of Hangzhou, China. *Sustainable Cities and Society*, *88*, 104283. https://doi.org/10.1016/j.scs.2022.104283

Zhejiang DRC. (2021). *Energy conservation and energy resources to optimize the allocation of 14th Five-Year Plan in Zhejiang*. Zhejiang Provincial Development and Reform Commission.

Zhejiang MOHURD. (2021). *"14th Five-Year Plan" for the development of the construction industry in Zhejiang*.

Zhejiang PBS. (1986). *Zhejiang Statistical Yearbook 1985*. Zhejiang provincial Bureau of Statistics.

Zhejiang PBS. (1991). *Zhejiang Statistical Yearbook 1990*. Zhejiang provincial Bureau of Statistics.

Zhejiang PBS. (2000). *Zhejiang Statistical Yearbook 1999*. Zhejiang provincial Bureau of Statistics.

Zhejiang PBS. (2022). *Zhejiang Statistical Yearbook 2021*. Zhejiang provincial Bureau of Statistics.

Zhong, Z., Zhang, X., & Yang, X. (2021). BENEFIT EVALUATION OF ENERGY-SAVING AND EMISSION REDUCTION IN CONSTRUCTION INDUSTRY BASED ON ROUGH SET THEORY. In *ECOLOGICAL CHEMISTRY AND ENGINEERING S-CHEMIA I INZYNIERIA EKOLOGICZNA S* (Vol. 28, Issues 1, SI, pp. 61–73). SCIENDO. https://doi.org/10.2478/eces-2021-0006

Zhou, N., Price, L., Yande, D., Creyts, J., Khanna, N., Fridley, D., Lu, H., Feng, W., Liu, X., Hasanbeigi, A., Tian, Z., Yang, H., Bai, Q., Zhu, Y., Xiong, H., Zhang, J., Chrisman, K., Agenbroad, J., Ke, Y., … Franconi, E. (2019). A roadmap for China to peak carbon dioxide emissions and achieve a 20% share of non-fossil fuels in primary energy by 2030. *Applied Energy*, *239*, 793–819. https://doi.org/10.1016/j.apenergy.2019.01.154

Zhou, W., O'Neill, E., Moncaster, A., Reiner, D. M., & Guthrie, P. (2020). Forecasting urban residential stock turnover dynamics using system dynamics and Bayesian model averaging. *Applied Energy*, *275*, 115388. https://doi.org/10.1016/j.apenergy.2020.115388

Zhu, C., Li, X., Zhu, W., & Gong, W. (2022). Embodied carbon emissions and mitigation potential in China's building sector: An outlook to 2060. *Energy Policy*, *170*, 113222. https://doi.org/10.1016/j.enpol.2022.113222

Chapter 6

SYNERGISTIC DECARBONIZATION POTENTIAL OF THE CONSTRUCTION AND WASTE RECYCLING SECTORS

CHAPTER 6: SYNERGISTIC DECARBONIZATION POTENTIAL OF THE CONSTRUCTION AND WASTE RECYCLING SECTORS

Contents

6.1 Contents

Japan has made a legislative commitment to achieve carbon neutrality by 2050. The construction industry in Japan shares 30% of the carbon emissions and is the key sector for achieving carbon neutrality. Less attention has been paid to the carbon emissions of building demolition, especially the recycling of Construction and Demolition (C&D) Waste. This study clarifies the flow of C&D Waste and accounts for the carbon emission of C&D Waste disposal by Life Cycle Assessment and IPCC method. The contribution of C&D Waste recycling to carbon emission reduction under three scenarios (Baseline scenario, Large area scenario, Long lifespan scenario) is predicted by modeling the building stock flow. The results show that in Kitakyushu, a decarbonization pioneer region, the disposal of C&D Waste will generate 35,896 tons of CO_2 in 2019, and the recycled products could reduce emissions by 7,845 tons for the construction industry. Disposing of concrete and steel is the major source of carbon emissions of 94.1%, recycling of steel is the biggest driver of emissions reduction. Kitakyushu will soon face rapid growth in C&D Waste, contributing to a 1.9-6.8% carbon reduction in the construction industry. From a material cycle perspective, a reasonable building stock and an extended building lifespan are more conducive to achieving carbon neutrality.

6.2. Introduction

Global warming is one of the biggest challenges facing our society and profoundly impacts the sustainable development of global ecology. Increasing greenhouse gas emissions are believed to be a major contributor to global warming. To limit global warming to 1.5 degrees Celsius before 2050, countries signed the Paris Agreement in 2015 (*Paris Agreement*, 2015). Since then, countries have proposed carbon neutrality targets and routes. As the fifth largest carbon emitter, Japan has set the goal of achieving carbon neutrality by 2050 through legislation.

The construction industry is an energy-intensive industry, accounting for 39% of global emissions (*Tracking Buildings 2020*, 2020), and is essential to achieving carbon neutrality. At present, the carbon emission of architectural design, construction and operation has become a research hotspot. In contrast, the demolition stage at the end of a building's life and the emission reduction potential of recycling Construction and Demolition (C&D) Waste have received less attention(Coelho & de Brito, 2012). 11% of the carbon emissions of the construction industry come from the manufacturing of construction materials (UNEP, 2021), which means that construction waste has a great potential to reduce carbon emissions.

As a developed country, Japan has active construction activities, with a huge amount of construction, demolition, and renovation, resulting in considerable C&D Waste. In 2019, Japan produced 79.71 million tons of C&D Waste, accounting for 20.7% of the total industrial waste

(Ministry of Environment, 2022b). C&D waste usually refers to the solid waste generated by construction industry activities, composed of various inert and non-inert materials waste(Menegaki & Damigos, 2018). In 2002, C&D Waste accounted for 60% of the total waste dumped illegally. Non-inert material waste will pollute the environment, while inert material waste will cause resource loss. The Japanese government has introduced the Construction Recycling Law to strengthen the supervision of C&D waste and promote reuse and has been tightening the regulations in recent years (Construction Recycling Law, 2000). In 2021, the resource recycling industry was listed as one of the 14 key areas of the green growth strategy. (*Green Growth Strategy*, 2021). At the same time, circular building theory (Wuyts et al., 2019) and urban mining (Wuyts et al., 2020) strategies are increasingly being mentioned. Obtaining building materials from demolished buildings is increasingly recognized as an essential way to reduce carbon emissions (X. Li et al., 2022).

Many Japanese cities have also developed plans and guidelines to encourage proper disposal and recycling of construction waste. Kitakyushu city in Japan launched a basic plan to promote a recycling society in 2011. The program created a pioneering approach to waste management in Kitakyushu, introduced many recycling enterprises and promoted the development of Kitakyushu's resource recycling industry . In recent years, Kitakyushu city has added the concept of "low-carbon" and "natural symbiosis" to the plan in addition to the existing concept of "recycling"(*Kitakyushu City Basic Plan for Establishing a Recycling-Oriented Society (The Second Issue)*, 2022). The Japanese government has selected Kitakyushu as a city for the Environment Future City (*Kitakyushu Environmental Future City Plan*, 2012), a city for the SDGS Future City (Planning Bureau of Kitakyushu, 2018) and a decarbonization pioneer area (*Overview of Kitakyushu Decarbonization Pioneer Area*, 2022), so Kitakyushu is well represented. As one of the cities designated by the government ordinance of Japan, Kitakyushu has a well-developed statistical system and a reliable data source. A study of Kitakyushu will allow accurate estimation of carbon emission reductions and precise modeling of projections that will help determine the sustainability of regional development, and the research results can guide other regions.

This study aims to quantify the carbon reduction contribution of recycled C&D Waste. It will clarify the disposal process and flow of C&D Waste in Kitakyushu and account for the carbon emission of C&D Waste recycling and disposal by the whole Life Cycle Assessment (LCA) method. Then, the carbon emissions of recycled and new materials are compared, and the building stock and flow are modeled to assess the contribution of present and future recycled C&D Waste to carbon reduction in the construction industry in Kitakyushu.

6.3. Review

In the past, research on C&D Waste recycling has focused on waste management(Yu et al., 2022), economic benefits(Zheng et al., 2017), and environmental assessment(Wang et al., 2022), less research has focused on the carbon reduction contribution of C&D Waste recycling.

The need for more basic data on building demolition areas, waste generation and disposal processes is one of the reasons limiting the study of carbon emissions from waste recycling. Wang et al. developed a framework to assess the carbon emissions of C&D Waste(Wang et al., 2018), and Ivanica et al. established a project database to determine the environmental impact of waste(Ivanica et al., 2022). These single building-based studies have the advantage of accurate data, but the results may not be generalizable(Coelho & de Brito, 2012). To avoid the limitations of case studies, Cha conducted a national scale study on carbon emissions from demolition waste in South Korea based on statistical data(Cha et al., 2020), while Peng et al. collected a large amount of data to study the carbon saving potential of C&D Waste in China's Greater Bay Area(Peng et al., 2021). There are few studies on the city scale(Zhao et al., 2023), but cities have become the basic unit of carbon neutral assessment(L. Li & Yang, 2020), indicating that it is of great significance to carry out C&D Waste carbon reduction assessment on a city scale.

Different building structure types affect the type of waste, influencing the carbon reduction contribution. Cha et al. suggested that wood structures have a higher recycling potential than other structures(Cha et al., 2020), and Li et al. found that assembled concrete buildings have significantly fewer carbon emissions from waste disposal and recycling than other buildings(X. Li et al., 2022). Several studies have selected single waste for in-depth study. Colangelo et al. studied waste concrete and concluded that recycled aggregates have a positive environmental impact(Colangelo et al., 2021). Gorman et al. studied metal wastes represented by steel and concluded that increased metal recycling would benefit carbon reduction(Gorman et al., 2022). The study must distinguish building structure types to estimate C&D Waste output and carbon reduction contribution more accurately.

The definition of accounting boundaries is the basis of carbon emission studies. The whole life cycle of waste can be divided into four parts: waste generation, transportation, intermediate disposal and final disposal (Cha et al., 2020; Wang et al., 2018, 2021). Some studies examine specific stages, Ivanica et al. consider excavator operations as the primary source of carbon emissions in the demolition stage (Ivanica et al., 2022), and Coelho considers larger capacity intermediate disposal facilities to be more beneficial for carbon reduction (Coelho & de Brito, 2013). In some studies, carbon emissions from the intermediate treatment stage are not accounted for and the carbon reduction potential is used to assess the environmental impact of recycled materials (Liu et al., 2022; Peng et al., 2021), which ignores the down-cycling of construction materials(Wuyts et al., 2019). To comprehensively assess the carbon reduction contribution of C&D Waste recycling, this study sets the whole life cycle carbon emissions of C&D Waste as the boundary.

6.4. Method and models

The LCA method has been widely used in environmental impact assessment(Wang et al., 2018). As shown in Fig.6-1, the LCA will be applied to the disposal process of C&D Waste to evaluate the environmental impact of C&D Waste generation to landfill or recycled. In the context of climate warming, CO_2 emissions from energy consumption will be used as an indicator to evaluate the environmental impact. The research scope includes carbon emissions from on site disposal, intermediate disposal, final disposal and transportation.

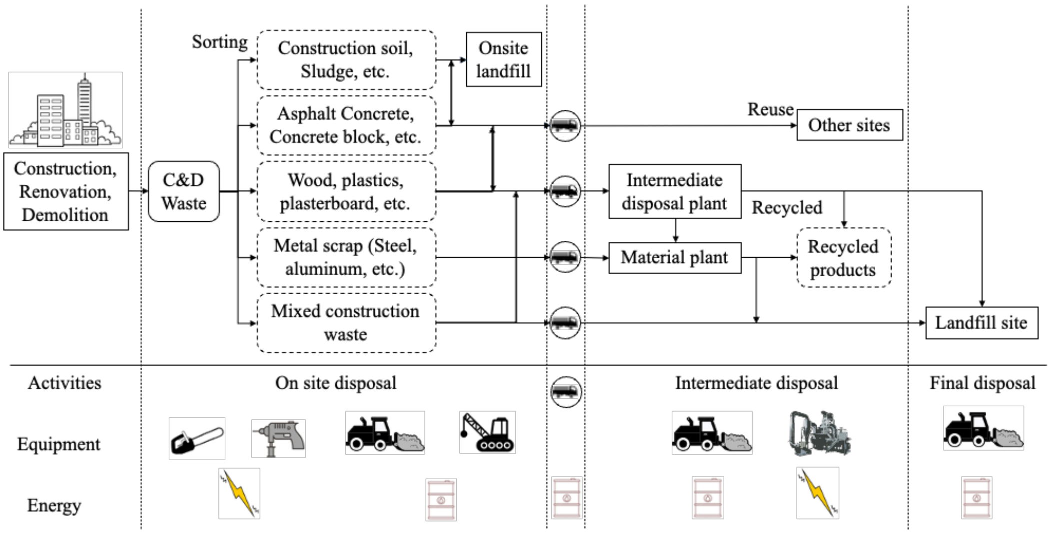


Fig.6-1 C&D Waste lifecycle and carbon emission boundary
(MLIT, 2018) (IWCD of Kitakyushu, 2019) (Ogawa, 2006)

6.4.1 Research scope

This paper explores the carbon reduction of the city scale construction industry from the perspective of C&D Waste recycling, where carbon emissions from energy consumption during the generation, flow, and disposal of C&D Waste in Kitakyushu are accounted for. The year 2019 with complete data was chosen as the current situation for analysis, while the years 2020-2100 were also chosen for projections for different scenarios.

In the estimated carbon emissions from C&D Waste generation, only emissions from building demolition are accounted for. The reason is that the product of the construction and renovation is the building, C&D waste is generated incidentally. The transportation process counts the carbon emissions of C&D Waste leaving the site, including the destinations of intermediate disposal plants, material plants, and landfill sites. The intermediate treatment process mainly counts the carbon emissions from material waste treatment, meaning that construction soil and sludge are not measured.

Based on the definition in Japan's Construction Recycling Law (Construction Recycling Law, 2000) and data from the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT of Japan), construction soil (CS), asphalt concrete (As), concrete blocks (Co), sludge, construction wood (wood A), logging wood (wood B), Waste plastic (WPl), wastepaper (WPa), metal scraps, Waste plasterboard (WPb) and mixed construction waste (MC) are considered as the C&D Waste in this study.

6.4.2 C&D Waste Life Cycle & Estimation

The yield per area method is often used to estimate the output of C&D waste (Wang et al., 2021). The coefficient is different for building types and C&D waste generation stages, so it needs to be calculated separately. Based on MLIT data (MLIT, 2018), this paper divides buildings into wood and non-wood buildings according to the main building materials. The waste generation stage is divided into the demolition and construction & renovation stages.

The C&D waste generation is equal to the sum of the waste generation in the two stages of wood buildings and non-wood buildings, as shown in Formula (6-1).

$$W_{C\&D}=W_{C,wood}+W_{C,non-w}+W_{D,wood}+W_{D,non-w} \tag{6-1}$$

Where $W_{C\&D}$ means the total of C&D Waste generation (tons), $W_{C,wood}$ and $W_{C,non\text{-}w}$ means waste generation of wood buildings and non-wood buildings during the construction & renovation stage (tons), $W_{D,wood}$ and $W_{D,non\text{-}w}$ means waste generation of wood buildings and non-wood buildings during demolition stage (tons).

The C&D Waste generation calculation formula of wood buildings in the demolition stage is as formula (2). $W_{C,wood}$, $W_{C,non\text{-}w}$, and $W_{D,non\text{-}w}$ can also be calculated using the same method. The waste generation coefficient is shown in Table 6-1.

$$W_{D,wood}=\sum_1^n A_{D,wood}\cdot WI_{D,wood}^{i} \tag{6-2}$$

Where $A_{D,wood}$ means demolition area of wooden buildings (m^2), $WI_{D,wood}^{i}$ means generation intensity of waste i (tons/m^2).

Table 6-1 C&D Waste generation factors (tons/m^2)

C&D waste	Construction & renovation		Demolition	
	Wood building	Non-wood building	Wood building	Non-wood building
CS	0.1075	0.2742	0.0225	0.0767
As	0.0101	0.0067	0.0370	0.0451
Co	0.0194	0.0272	0.4484	1.1704
Sludge	0.0017	0.0005	0.0057	0.0068
MC	0.0014	0.0036	0.0115	0.0061
Wood A	0.0041	0.0029	0.1477	0.0274
Wood B	0.0017	0.0005	0.0057	0.0068
WPl	0.0009	0.0015	0.0072	0.0053
WPa	0.0006	0.0005	0.0013	0.0002
Metal scraps	0.0010	0.0028	0.0157	0.0160
WPb	0.0010	0.0048	0.0076	0.0082

As shown in Fig.6-2, in the demolition stage, most of the C&D waste will be transported out of the site (flow ③), and some of the waste will be disposed of or stored in the site (flow ②), such as the construction soil will be used for leveling the site. Depending on the type of waste, the transportation stage will be transported to treatment plants (flow ⑤), and waste that is difficult to recycle will be transported to a landfill or thermal power plant for final disposal (flow ④). After crushing, screening and other treatments to process C&D Waste into recycled construction materials (flow ⑨), the intermediate treatment process is accompanied by the largest waste loss (flow ⑥ and ⑧). Details of C&D waste flow are shown in Table 6-2.

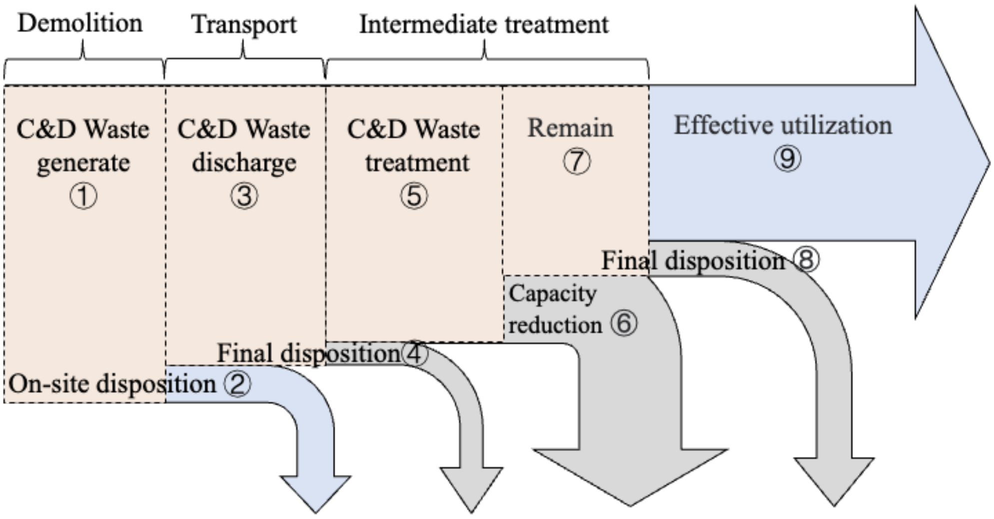


Fig.6-2 Kitakyushu C&D Waste flow

Table 6-2 C&D Waste flow

C&D waste	On-site disposal	Transport	Reuse	Intermediate treatment	Recycle	Capacity reduction	Landfill	Burn
CS	0.169	0.831	0.772	-	-	-	0.059	0.000
As	0.029	0.971	0.008	0.948	0.948	0.000	0.016	0.000
Co	0.054	0.946	0.003	0.940	0.940	0.000	0.003	0.000
Sludge	0.020	0.980	0.001	0.959	0.914	0.037	0.027	0.000
MC	0.000	1.000	0.000	0.760	0.603	0.009	0.348	0.041
Wood A	0.058	0.942	0.005	0.912	0.910	0.001	0.018	0.008
Wood B	0.042	0.958	0.053	0.875	0.874	0.002	0.005	0.024
WPl	0.000	1.000	0.000	0.995	0.534	0.204	0.263	0.000
WPa	0.138	0.862	0.000	0.862	0.609	0.160	0.094	0.000
Metal scraps	0.000	1.000	0.009	0.991	0.991	0.000	0.000	0.000
WPb	0.000	1.000	0.000	1.000	0.875	0.000	0.125	0.000

Note: C&D waste generation is 1.000

Source: Kitakyushu Industrial Waste Countermeasures Division (IWCD of Kitakyushu, 2019) and the Ministry of Land, Infrastructure, Transport and Tourism(MLIT, 2018).

6.4.3 Estimation of carbon emissions from C&D Waste disposal

The carbon emission assessment is based on the IPCC method (IPCC, 2006). The carbon emission of C&D waste recycling is added up by the building demolition process, transportation process, intermediate treatment and landfill as shown in the formula (6-3).

$$CE_{waste}=CE_d+CE_t+CE_i+CE_l \tag{6-3}$$

Where CE_d, CE_t, CE_i and CE_j mean carbon emission of building demolition, transportation, intermediate treatment and landfill.

Carbon emissions in the demolition process are determined by the type and energy consumption used by the demolition operators. Ogawa surveyed 11 demolition companies in Kitakyushu and found that energy consumption is linearly and positively correlated with the amount of waste generation (Ogawa, 2006). The energy consumed by demolition companies includes gasoline, kerosene, diesel, natural gas, and electricity, with diesel fuel accounting for the highest percentage of energy used to drive large demolition machines, gasoline used for staff commuting, and kerosene used to generate electricity to run small demolition equipment.

Carbon emissions in the demolition process can be calculated by the formula (6-4). Based on the proportion of energy used and its carbon emission factor, formula (6-5) can be obtained to calculate the carbon emission.

$$E_d=Q\cdot W_D \tag{6-4}$$

$$CE_d=\sum_{1}^{n} E_d\cdot P_q\cdot EF_q\cdot 10^{-6} \tag{6-5}$$

Where E_d means total energy consumption (MJ), Q means energy consumption intensity, W_D means waste generated during the demolition stage (tons), P_q means the share of energy q (%), EF_q means energy q carbon emission intensity (t CO_2/TJ).

Transportation carbon emissions come from fossil energy consumption by freight vehicles, which is expressed in formula (6-6). The transportation distances for C&D Waste are shown in Table S3. In this paper, the truck load is set to 10 tons, the average load per transport is 80%, and the energy consumption intensity is 0.0467 L/km·tons (Ministry of Environment, 2022a).

$$CE_t=\sum_{1}^{n} W_T\cdot L\cdot F_T\cdot CF_d \tag{6-6}$$

Where W_T means the transport weight of waste (tons), L means the transport distance of each transport (km), F_T means the intensity of energy consumption (L/km·tons), CF_d means diesel carbon emission intensity (tons CO_2/L).

Intermediate treatment is the process of cleaning, crushing, grinding, and separating C&D Waste, and the energy consumed by the equipment operation is the main source of carbon emissions. Table 6-3 shows the information on the treatment capacity and energy consumption of equipment, the data were obtained from a survey of 15 intermediate treatment companies in Kitakyushu. These companies use electricity-driven equipment to dispose of construction waste. The electricity carbon emission data comes from Kyushu Electric Power, which has an electricity carbon emission factor of 0.370 kgCO_2/kWh in 2019 (Kyushu Electric Group, 2020).

Metal waste is mainly steel, and the electric furnace method is often used to recycle waste steel (Ogawa & Gao, 2006). This study refers to the input-output method to calculate the carbon emission factor of the electric furnace steel smelting industry, which is 690 kgCO_2/ton.

Table 6-3 Carbon emission coefficient of C&D Waste intermediate treatment

	Wood	Plasterboard	Other waste
Total machine power (KW)	170	37.1	375.85
Annual running time of machinery (h)	1404	770	2142
Annual treatment weight (tons)	10763.1	893.6	20836.52
Power consumption per unit weight (MJ/ton)	79.8	115.1	139.1
Carbon emissions per unit weight (kgCO2/ton)	8.2	11.8	14.3

The carbon emission in the intermediate treatment can be calculated by the formula (6-7).

$$CE_i = \sum_1^n W_I^i \cdot EF_I^i \qquad (6\text{-}7)$$

Where W_I^i means the weight of intermediate treatment waste i (tons), EF_I^i means the carbon emission coefficient of waste i intermediate treatment (kg/tons).

The carbon emissions from landfill can be calculated by the formula (6-8).

$$CE_l = \sum_1^n W_L \cdot F_L \cdot WE_L \cdot CF_d \qquad (6\text{-}8)$$

Where W_L means the landfill weight of waste (tons), WE_L means the work efficiency of landfill (h/t), F_L means the intensity of energy consumption (L/h).

6.4.4 Estimation of the carbon reduction of recycling C&D Waste

This study defines the difference between new product manufacturing carbon emissions and carbon emissions from recycled products as the carbon reduction from recycled C&D Waste. This value is used to evaluate the carbon reduction effects of recycling C&D Waste in Kitakyushu. It can be expressed by the formula (6-9).

$$CE_{re} = CE_{new} - CE_{waste} \qquad (6\text{-}9)$$

IPCC and input-output methods are used to calculate the carbon emissions of new materials production. The input-output table provides data on economic activity and CO_2 emissions by sector, which combined with data on the production of construction materials (Ministry of ETI, 2021), can be used to calculate the carbon emissions of new materials, as shown in the formula (6-10).

$$CE_a = M_a \cdot CE^m / M^m \tag{6-10}$$

Where, CE_a means carbon emissions from new material a, M_a means weight of material a, CE^m means total carbon emission in sector m which product material a, M^m means the total weight of products in sector m.

C&D Waste will enter different intermediate treatment processes, and the same waste may correspond to various recycled materials or recycled building components. Table 6-4 summarizes the main C&D wastes and their re-resourced products under the existing technology in Kitakyushu and finds the closest new product in the Statistical Yearbook to compare the carbon saving effect(Nansai et al., 2020).

Table 6-4 Products of main C&D Wastes

C&D waste	Re-resource way	Recycling products	New products
Asphalt concrete	Recycle	Aggregate and asphalt	Gravel and asphalt
Concrete block	Recycle	Aggregate	Gravel
Sludge	Reuse & recycle	Backfill soil	-
Wood	Reuse	Beams or columns	Sawed timber
	Recycle	Wood chips	Wood chips
Waste plastics	Recycle	Plastic pellets	Plastic pellets
	Regenerate	Styrene monomer	Thermoplastic Resins
Wastepaper	Recycle	Paper pulp	Paper pulp
Metal scrap	Recycle	Crude steel	Crude steel
	Reuse	-	Building metal product
Waste plasterboard	Recycle	Gypsum powder	Gypsum

Re-resource of waste is often further subdivided into reuse, recycle and regenerate in Japan (Ogawa, 2006). The difference between the three is mainly the process of treatment and the state of the product after treatment. Reuse is a process in which dismantled materials are treated in a simple manner and then used directly as use without changing their shape and characteristics. Recycle refers to the process of collecting, separating, and reprocessing demolition materials as constituent construction materials. Regenerate refers to the process of collecting, separating and completely decomposing demolished materials as raw materials.

Waste concrete blocks are crushed and used as aggregates for concrete. About 33.3% of the asphalt concrete recycling process will be recycled in the form of aggregates and the rest will be recycled as asphalt composite. It is assumed that the ratio of asphalt to other stones in the asphalt composite is 3.8:100. Waste wood is usually crushed into wood chips. Compressed and crushed wastepaper can be recycled into pulp by mixing with water, waste plasterboard can be recycled into gypsum powder by sorting and grinding, and metal fragments can be melted to produce crude steel.

Plastics can be divided into thermoplastics and thermosets, which can be processed differently depending on their nature. Thermoplastic plastics can be molten and reprocessed after crushing, while thermosetting plastics need to be chemically dissolved and reprocessed or crushed as auxiliary materials. In this paper, the re-resource method of plastics in C&D waste is defined as recycle, the intermediate treatment process is the grinding of plastic waste into granules. The reason is the high proportion of thermoplastics, common PVC pipes, Styrofoam both belong to thermoplastics. And thermosetting plastics also have crushed for road auxiliary material recycling path. Construction soils and sludge are treated and used as backfill and are not considered.

Comparing emission reductions may not measure the contribution of recycling C&D Waste to the carbon neutrality of the construction industry, the reason being that more construction activities generate more waste and recycling more waste results in more carbon reductions. Introducing the concept of carbon emission reduction contribution to measure the environmental benefits generated by C&D Waste recycling, as shown in formula (6-11).

$$RC = CE_{re}/CE_{Con} \tag{6-11}$$

Where, RC means carbon emission reduction contribution (%), CE_{con} means carbon emissions from the construction industry. To ensure the uniformity of carbon emission accounting boundary, direct and indirect carbon emissions related to wood and non-wood building construction are defined as carbon emissions from the construction industry in this paper.

6.4.5 Building flow estimation and scene setting

The generation of C&D Waste is closely related to the building flow, a collective term for new building construction and demolition (Tang et al., 2019). Since building flows are influenced by the building stock and the building flows over the years interact with each other (Du et al., 2019), this paper introduces a system dynamics model to forecast future building flows. The dynamic change of the building stock system depends on the two flow processes of new construction and demolition. The system dynamics theory can well describe the transfer and change of stock and flow, which has obvious advantages (Ma et al., 2022).

This paper takes the system's residential and public buildings in Kitakyushu City as the boundary. The simulation period is from 1965 to 2100, and the initial value of the model is set in 1965. Fig.6-3 shows the dynamic stock model of residential buildings, and public buildings are modeled similarly.

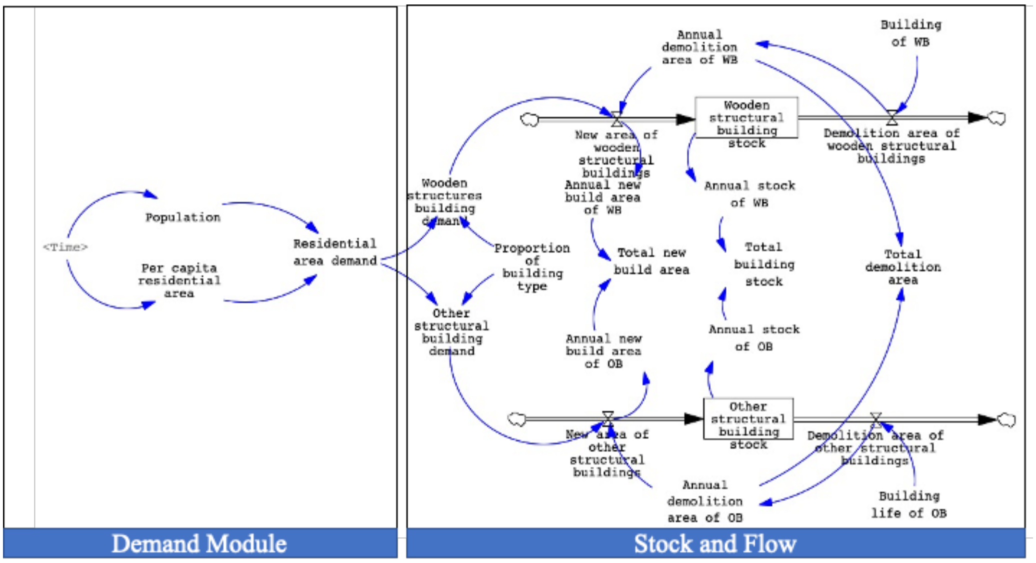


Fig.6-3 The stock-flow diagram of residential building in Kitakyushu

The model can be distinguished into two modules. Module 1 is the building demand module. This module includes two important parameters, the demand for residential space per capita (A) and the population (P), which are the main drivers of the residential building stock (S). The area of residential demand can be determined by these two parameters, such as formula (6-12). Based on the forecasts from the National Institute of Population and Social Security Research of Japan (NIPSSR) and historical data, this paper creates a forecast curve to predict the future population (Fig.6-4).

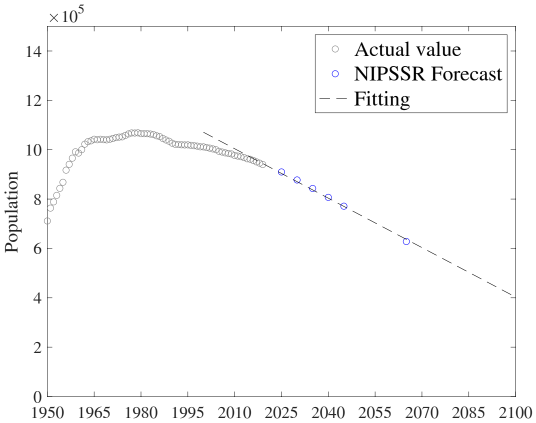


Fig.6-4 Population data and forecast of Kitakyushu

The module 2 is the flow-stock module, which simulates the dynamic change of new building area - stock area - demolition area. The annual new area (A_C) in the model is equal to the sum of the new residential area demand and the demolition area (A_D), shown in formula (6-13). It is generally accepted that building life is normally distributed, and Prof. Yukio Komatsu's study proves that this view also applies to Japan (Komatsu, 2020). Based on the normal distribution curve and the construction time of the building, the annual demolition flow can be estimated, such as the formula (6-14) and (6-15).

Since wood-frame buildings differ greatly from non-wood buildings in terms of building materials, construction waste composition, and building life expectancy, separate predictions are needed for both, and separate flow-stock subsystems have been established for the two building structures.

$$S(t) = P(t) * A(t) \tag{6-11}$$

$$A_C(t) = S(t) - S(t-1) + A_D(t) \tag{6-12}$$

$$A_D(t) = \sum_{t0}^{t'} L(t,t') * A_C(t') \tag{6-13}$$

$$L(t,t') = \frac{1}{\sqrt{2\pi\sigma}} * e^{\frac{-(t-t'-\mu)^2}{2\sigma^2}} \tag{6-14}$$

Where, t denotes the time series 1965-2100; t_0 denotes the initial year 1965; t' denotes the target year; L (t, t') denotes building life distribution; μ denotes building life; σ denotes standard deviation of normal distribution.

The model's key parameters are the residential area per capita, the public building area per capita, and the building life per capita. Three different scenarios are set up by changing these parameters, such as shown in Table 6-5. The baseline scenario sets the development trend in Kitakyushu to remain unchanged, with per capita residential area reaching 50 m^2, such as Fig.6-5. And per capita public building area reaching 27 m^2 at the level of developed European countries (Zhang et al., 2022). The life span of wood-frame buildings in Japan is 60 years, and non-wood-frame buildings, mainly reinforced concrete buildings, is 55 years (Komatsu, 2020).

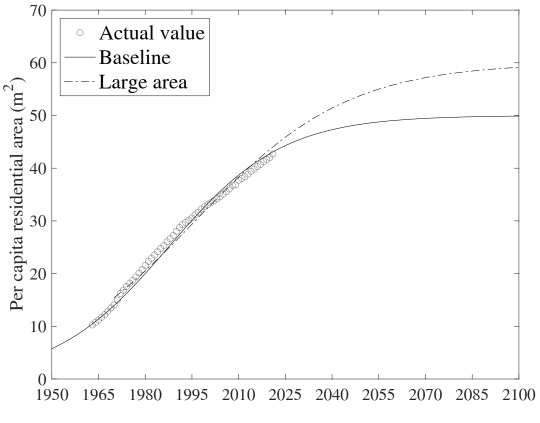


Fig.6-5 Historical and projections of per capita floor area

Table 6-5 Parameters of different scenarios

Scenarios designed		Baseline	Large area	Long lifespan
Per capita area (m^2)	Residential building	50	60	50
	Public building	27	30	27
Lifespan (year)	Wood building	60	60	60
	Non-wood building	55	55	70

Based on the baseline scenario, the large area scenario and the long-life scenario are also developed in this paper. In the long-life scenario, the paper sets the life span of new steel composite buildings after 2020 to 70 years, referring to the advances in construction technology that have extended the life span of steel composite buildings. The large area scenario refers to the dual effect of the further increase in the pursuit of comfortable living and the demographic decay of the citizens, the per capita residential and public building area exceeds that of the United States and Canada (Zhang et al., 2022), reaching 60 m^2 and 30 m^2 respectively, such as Fig.6-6.

As shown in Fig.6-6, comparing the dynamics of the building stock and the statistical values of the actual calendar year building stock, it is found that the simulated values are in high agreement with the statistical values, so the model can be considered stable and reliable.

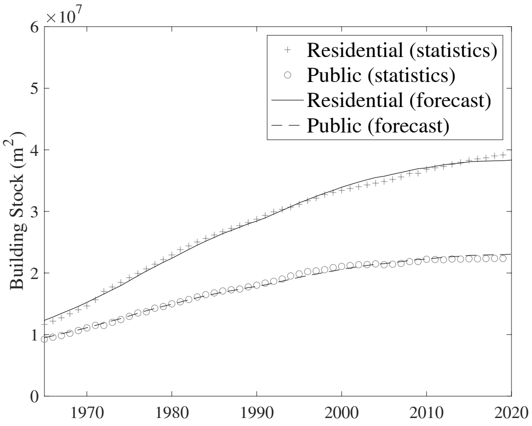


Fig.6-6. Model validation

6.4.6 Data source

Many statistics and survey data are collected to describe the generation, flow and impact of C&D waste, as shown in Table 6-6. The area of new construction, renovation, and demolition of buildings were obtained from the Kitakyushu Statistical Yearbook. C&D waste generation and transportation distance were obtained from the MLIT of Japan. Waste flow and disposal were obtained from the annual report of the Industrial Waste Survey Division of Kitakyushu, and some missing data were completed using the MLIT data. In addition, 11 construction deconstruction companies and 15 waste treatment plants were surveyed to obtain basic information.

Table 6-6 Data sources

Calculation index	Data	Time frame	Sources
S	Building stock	1965-2019	(Kitakyushu Statistics Bureau, 2020)
AC	New building area	1965-2019	(Kitakyushu Statistics Bureau, 2020)
WI	Generation intensity of waste	2018	(MLIT, 2018)
WD, WT, WI, WL	C&D Waste flow	2018, 2019	(IWCD of Kitakyushu, 2019)
EFq	Energy q carbon emission intensity	2020	(Agency for Natural Resources and Energy, 2020)
L	Transport distance	2018	(MLIT, 2018)
FT	Intensity of transportation energy consumption		(Ministry of the Environment, 2017)
EF_I^i	Carbon emission coefficient of waste i intermediate treatment	-	Intermediate processing plant survey
WEL	work efficiency of landfill	-	(Wang et al., 2018)
FL	Intensity of landfill energy consumption	-	(Central Japan railway company, 2014)
CEm	Carbon emission in sector m	2015	Environmental Impact Intensity Table (Ministry of ETI, 2021)
Mm	Weight of products in sector m	2015	Table of domestic production by sector (Ministry of ETI, 2021)
P	Population of Kitakyushu	1965-2100	(Kitakyushu Statistics Bureau, 2020) (NIPSSR, 2018)

6.5. Result

6.5.1 C&D waste generation and flow

According to the Kitakyushu Statistical Yearbook, 948,407 m^2 of buildings were newly built or renovated in 2019, including 292,870 m^2 of wood and 655,537 m^2 of non-wood buildings. The demolished building area is 804,762 m^2, containing 319,220 m^2 of wood and 485,542 m^2 of non-wood buildings.

Fig.6-7 shows the estimated generation of C&D waste in Kitakyushu. In 2019, 1.26 million tons of C&D waste were generated. The new construction or renovation of the building generated 0.36 million tons of waste, mainly construction soil and sludge totaling 87.6%, and the rest was construction material waste, about 44.8 kilotons. This indicates that the waste generated during these two processes mainly comes from site grading and excavation of underground space. The demolition process generated 0.90 million tons of waste, of which construction material waste accounted for 92.1% or about 0.84 million tons. The waste generated by the demolition process is mainly the materials installed in the building.

As one of the most important materials in modern buildings, concrete blocks make up the largest proportion of C&R waste, about 0.73 million tons. Construction soil is the second largest waste, generating 0.38 million tons. There is a huge stock of wooden buildings in Japan, and construction activities are frequent. As the primary material for wood building, wood A is a relatively large waste.

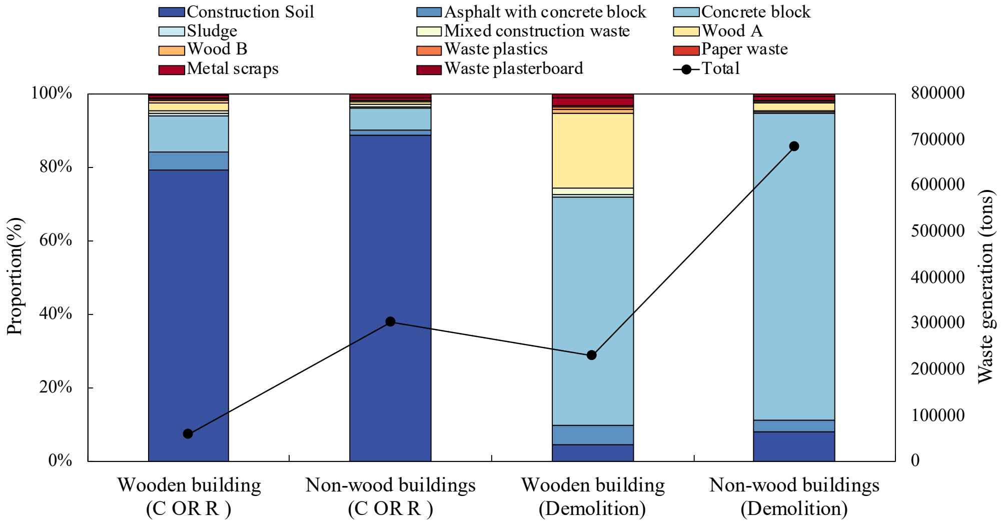
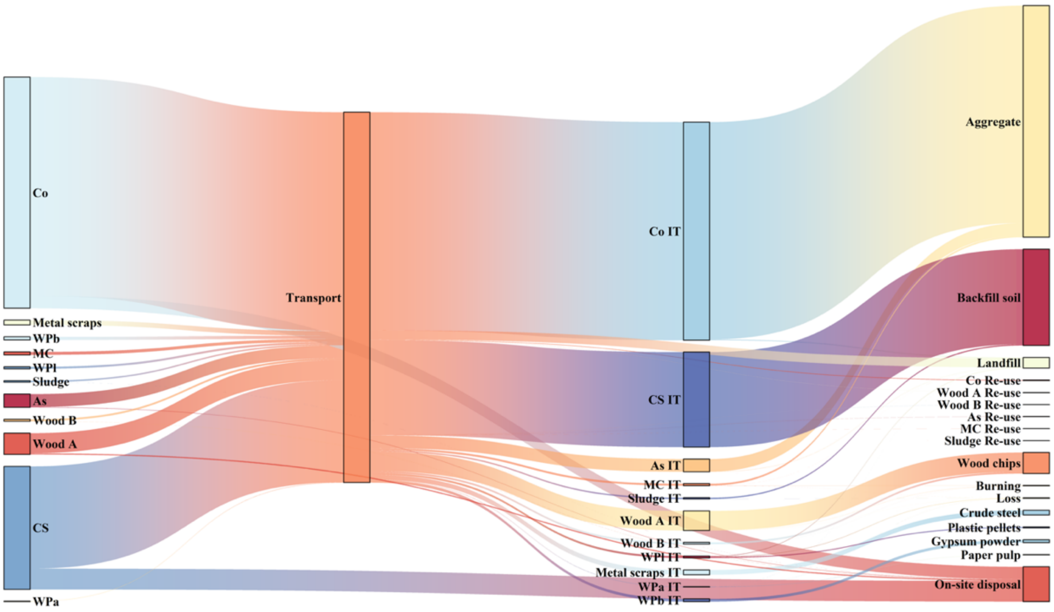


Fig.6-7 C&D Waste generation 2019

As Fig.6-8 shows, after C&R waste is generated, about 0.11 million tons of waste will be disposed of on site, which is dominated by inert materials such as construction soil and concrete blocks. 1.15 million tons of waste will be transported out of the construction site, including

0.82 million tons of construction material waste. 3.0 kilotons of construction materials will be reused directly and about 1.0 kilotons of waste will be incinerated. 10.5 kilotons of construction material waste will be disposed of in landfills, mainly mixed construction waste and concrete blocks that are difficult to separate. A small portion of wood cannot be re-resourced and is disposed of directly in landfills. Approximately 0.82 million tons of construction material waste was transported to an intermediate treatment plant for recycling disposal with a loss of 1,794 tons, and the rest was recycled.



Note: IT is the abbreviation for intermediate treatment

Fig.6-8 C&D Waste flow in 2019

6.5.2 Carbon emissions of C&D Waste disposal

According to formula (6-3) to (6-8) and C&D Waste flow, the carbon emissions of C&D Waste disposal in Kitakyushu in 2019 were calculated. As shown in Fig.6-9, the disposal of C&D Waste emits 37,425 tons of CO_2. Intermediate treatment and building demolition are the primary sources of carbon emissions, while landfill & onsite disposition emit 40.6 tons of CO_2.

A total of 11,960.1 tons of CO_2 was emitted from the demolition of buildings, of which 3015.2 tons were emitted from the demolition of wooden buildings and 8944.9 tons. Carbon emissions mainly came from removing concrete from the building, with carbon emissions amounting to 77.9% of the total carbon emissions in demolition. The removal of wood A is an important source of carbon emissions from dismantling wood buildings, accounting for 20.4% of the carbon emissions from the removal of wooden buildings.

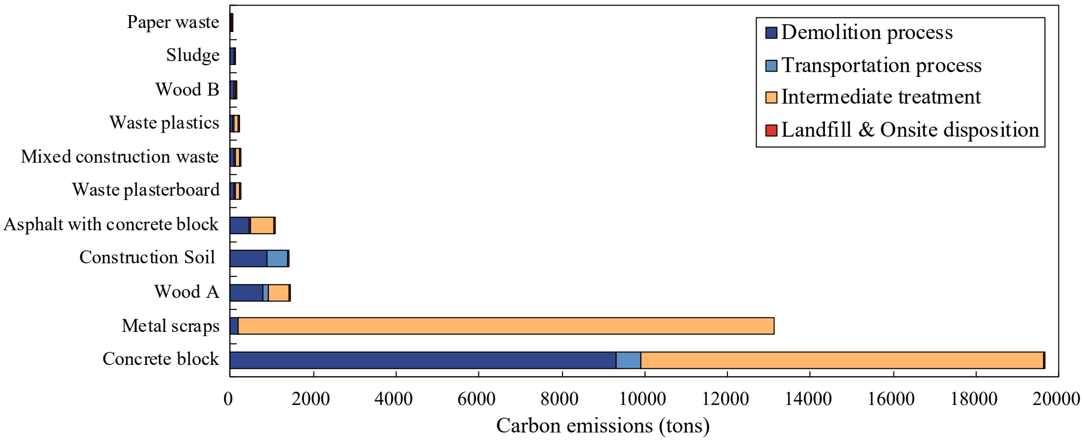


Fig.6-9 Carbon emissions of C&D Waste disposal

In transporting waste, the trucks consume diesel fuel and emit 1402.1 tons of CO_2. Concrete blocks, construction soil and wood A, the primary sources of carbon emissions from transportation, account for 43.3%, 35.3% and 9.4% of total, respectively. Kitakyushu has a well-developed recycling industry and C&D waste is transported over similar distances, as shown in Table 6-7. Therefore, transportation carbon emissions are mainly influenced by the amount of waste output.

Table 6-7 C&D Waste transportation distance (km)

C&D Waste	New construction or renovation		Demolition	
	Wood building	Non-wood building	Wood building	Non-wood building
CS	13.9	13.0	13.7	10.6
As	15.6	6.6	11.4	8.6
Co	13.9	6.5	6.5	7.6
Sludge	22.4	13.0	18.2	18.0
MC	23.7	22.6	23.6	18.2
Wood A	17.9	19.6	18.3	14.4
Wood B	10.0	16.5	6.1	14.3
WPl	18.3	21.3	21.8	28.7
WPa	24.6	21.0	23.1	33.5
Metal scraps	11.3	17.2	12.3	18.2
WPb	120.0	23.7	22.9	19.0

Source: Ministry of Land, Infrastructure, Transport and Tourism

The recycling and utilization of construction material waste are mainly considered. The waste with the largest carbon emission in the intermediate treatment process is metal scraps, 12,919.1 tons of CO_2. Although metal scraps' waste weight in the intermediate treatment is only

14,771 tons, the carbon emission is large because of the energy consumed to melt steel by the electric furnace method. Next is concrete block. Because of the vast output of concrete block waste, its intermediate treatment also emits a lot of CO_2. 680,039 tons of concrete waste enters the intermediate treatment process and emits 9,724.6 tons CO_2. The above two together account for 94.1% of carbon emissions in the intermediate treatment process, which is the main source of carbon emissions in the intermediate treatment stage.

6.5.3 Carbon saving capacity of C&D Waste

The carbon emission factors of the new production are calculated based on the IPCC method and input-output model, such as Table 6-8. As shown in Figure 6, the carbon emissions of new and recycled materials are compared. Kitakyushu saved a total of 0.819 million tons of new construction materials through re-resourcing in 2019, of which the majority was recycled, with a low percentage of reused waste of 3010 tons. The orange color on the left side of Fig. 6-10 shows the carbon emission of manufacturing new materials. It will generate a total of 45274.3 tons of carbon emissions. The green color on the right side shows the carbon emissions from recycling materials, totaling 35,896 tons of CO_2. The blue color means the difference between the two is 7849.9 tons of CO_2. This indicates that the construction industry in Kitakyushu decarbonized 7849.9 tons by recycling and reusing C&D Waste. Kitakyushu has achieved carbon balance in the building demolition stage through C&D waste recycling, which positively impacts the environment.

Table 6-8 The carbon emission factors of the new production

	Product output (tons)	CE intensity (tonsCO_2/million JPY)	Output value (million JPY)	CE factor (tons CO_2/tons)
Gravel	212254000	6.5	284865	0.009
Wood chips	5745000	3.0	102158	0.053
Paper pulp	8701044	10.7	580881	0.712
Thermoplastic Resins	7966499	8.8	1380325	1.524
Gypsum	5113734	6.5	179208	0.228
Asphalt	3267793	5.9	114981	0.208
Building metal product	5213447	7.7	1287237	1.903
Sawed timber	4615500	2.1	553673	0.252
WRB	50420981	2.1	8882183	0.368
NWRB	29035458	3.4	7378934	0.859
WPB	4177020	2.3	769328	0.432
NWPB	50717119	3.1	12245596	0.748

Note: CE means carbon emission, WRB means wooden residential buildings, NWRB means non-wooden residential buildings, WPB means wooden public buildings, NWRB means non-wooden public buildings.

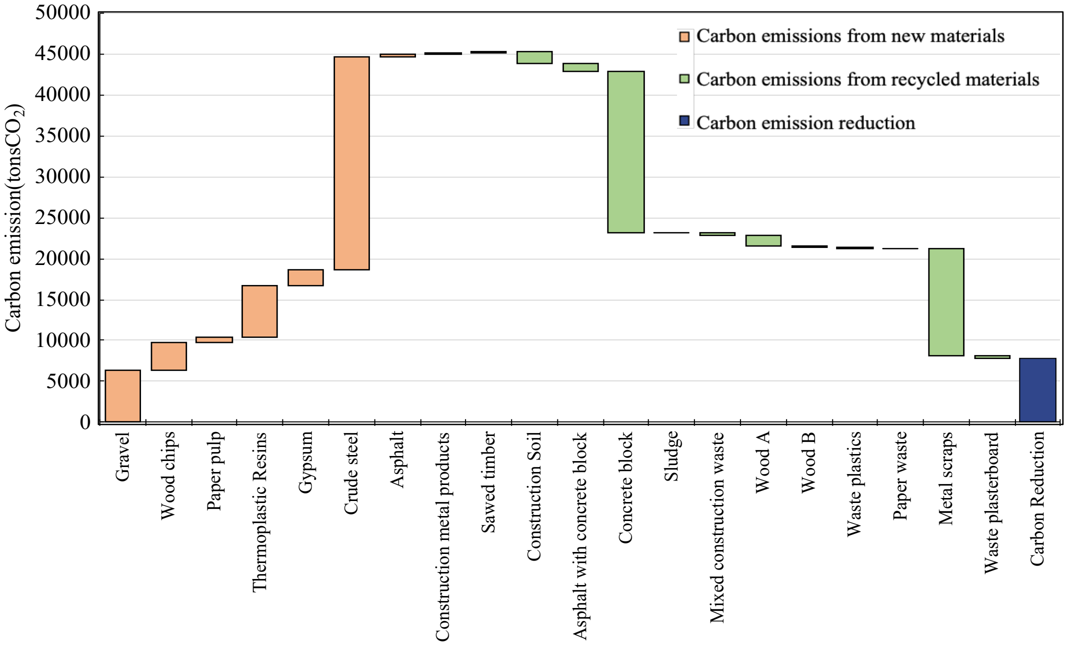


Fig. 6-10 Comparison of carbon emissions of new and recycled materials

6.5.4 Future scenarios and C&D waste production forecasting

As shown in Fig.6-11, the projected results of building flows and stock in Kitakyushu under different scenarios are shown. Statistical data are used in the figure until 2020, and forecast data are used after 2020.

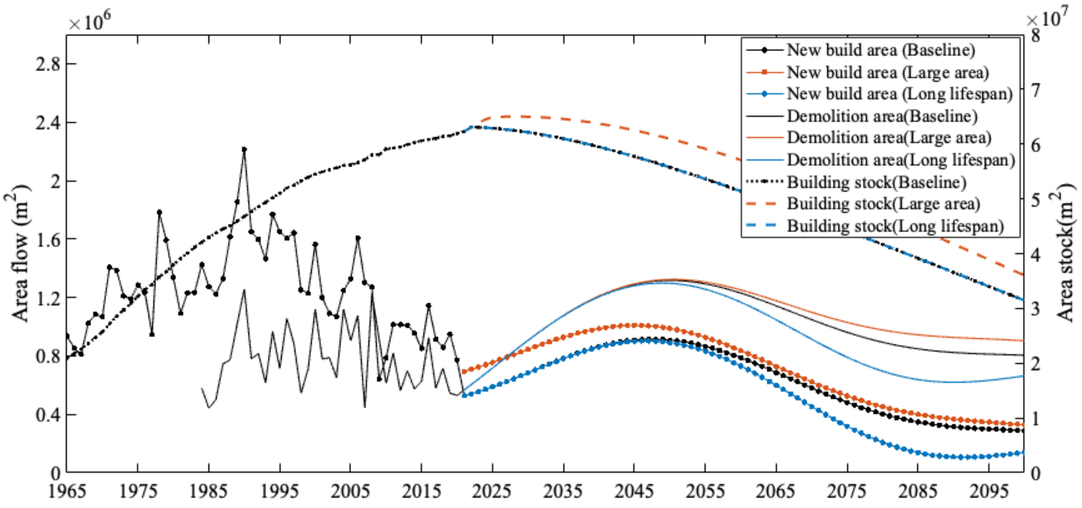


Fig.6-11 Building flow and stock under different scenarios in Kitakyushu

In the baseline scenario, as the population of Kitakyushu continues to decrease, the building stock will reach saturation in 2023, at 63.1 million m^2. This is 3.8 times the building stock of 16.61 million m^2 in 1960, when the population was similar, indicating that the material living standards of Kitakyushu residents have been greatly improved. Forecasts indicate that building demolition flows will peak in 2050 at 1.32 million m^2, indicating that buildings constructed during Japan's rapid economic development will reach the end of their life cycle by the middle of the century.

In the large area scenario, the peak of the building stock is pushed back as per capita floor area increases and will reach saturation in 2028 at 65 million m^2. The new build area flow will peak in 2045 at about 1.01 million m^2. Compared to the baseline scenario, the large area scenario will maintain a higher level of new build area flows, with a maximum difference of 0.17 million m^2. It will then gradually decrease until it stabilizes at about 0.4 million m^2. The difference between the demolition area and the baseline scenario will become apparent after 2050.

In the long lifespan scenario, the new area flow and demolition area flow curves fluctuate significantly compared to the other scenarios, which can be interpreted as buildings getting longer use and presenting less demolition and construction, indicating that the increase in building life reduces building construction and demolition. The new build and demolition area flow are reduced to a minimum of 0.1 million m^2 and 0.62 million m^2.

Kitakyushu will face the pressure of rapid growth in building demolition areas in the next 30 years. All three scenarios indicate that the peak in demolition area will occur around 2050, as a large number of buildings built during Japan's rapid economic growth from 1960 to 1990 are reaching the end of their life cycle. At the same time, the large number of demolished buildings means that new buildings will be needed to meet public demand, and both new construction and demolition of buildings will generate large amounts of C&D waste, which will have a huge potential for carbon reduction.

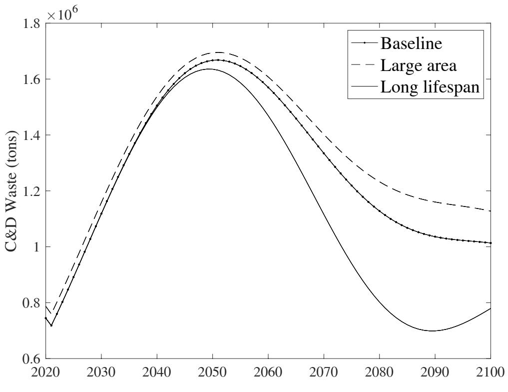


Fig.6-12 C&D waste production forecast

Both new construction and demolition of buildings generate large amounts of C&D waste. As shown in Figure 6-12, The peaks of waste production in all three scenarios occur around

2050, at 1.67 million tons in the base scenario, 1.70 million tons in the large area scenario, and 1.63 million tons in the long lifespan scenario, with the quantities of the three closes to each other. After 2050, waste in the base and large area scenarios shows a decreasing trend and finally stabilizes at 1 million tons and 1.1 million tons. The long lifespan scenario declines rapidly, reaching a low of 700,000 tons in 2090 before trending upward again, with waste production rebounding to 780,000 tons in 2100. Reinforced concrete buildings with an extended building life of 70 years are the main driver of the renewed rise in waste production.

The prediction results show that the smaller the building area per capita, the smaller the peak of C&D waste and the smaller the impact on the environment. Building life also affects the change of C&D waste. Extending the building life can reduce the peak of waste, slow down the output of waste and reduce the environmental pressure. In general, Kitakyushu will inevitably face a situation of rapid growth in construction waste. City managers should make full use of Kitakyushu's resource recycling industry and be well prepared to expand treatment to cope with the coming impact and dispose of waste properly.

6.5.5 Carbon emission reduction from C&D Waste

The carbon emission reduction after recycling such waste and utilization is estimated, as shown in Fig.6-13. The change patterns of carbon saving potential and carbon emissions from waste disposal under the three scenarios are similar. It will increase first and then decrease, and the turning point will be around 2050. This is related to the change of the new area and the demolished area of the building. In the baseline scenario, the peak carbon saving potential is 69,681.3 tons in 2051, 70,568.7 tons in 2050 and 68,816.5 tons in 2049 in the large area scenario and the long lifespan scenario respectively.

Carbon reduction is the difference between carbon saving potential and carbon emissions from waste disposal. The trend of emission reductions is similar for the three scenarios, with an increasing trend until 2045. The large area scenario has slightly greater emission reductions than the other two scenarios, with 12,740.5 tons in 2045, about 300 tons more than the other two scenarios. This small difference comes from the waste generated by new construction. After 2045, the carbon emission reduction tends to decrease with the reduction of new construction and demolition. After 2060, the difference between the three scenarios gradually starts to appear. In 2100, the emission reduction of the large area scenario is 5737.4 tons, which is significantly higher than that of the base scenario 4872.1 tons and the longevity scenario 4480.0 tons.

The line in Fig.8 shows the carbon reduction contributions for the three scenarios. Under the baseline scenario, Kitakyushu can reduce carbon emissions by recycling C&D Waste by about 2.2% for the construction industry in the next 80 years. The emission reduction contribution increases gradually over time. The carbon reduction contribution of recycled C&D Waste is 2.1% in the large area scenario, which also shows an increasing trend. Carbon emission reduction is worse than the baseline scenario most of the time, with a maximum difference of 0.4%, and exceeds the baseline scenario after 2084. The long lifespan scenario has the highest carbon reduction contribution from recycling C&D Waste at 3.3% and is consistently higher than the baseline scenario, with a maximum value of 6.8% in 2091. This indicates that from the perspective of reusing construction waste, extending the building life also contributes to carbon neutrality.

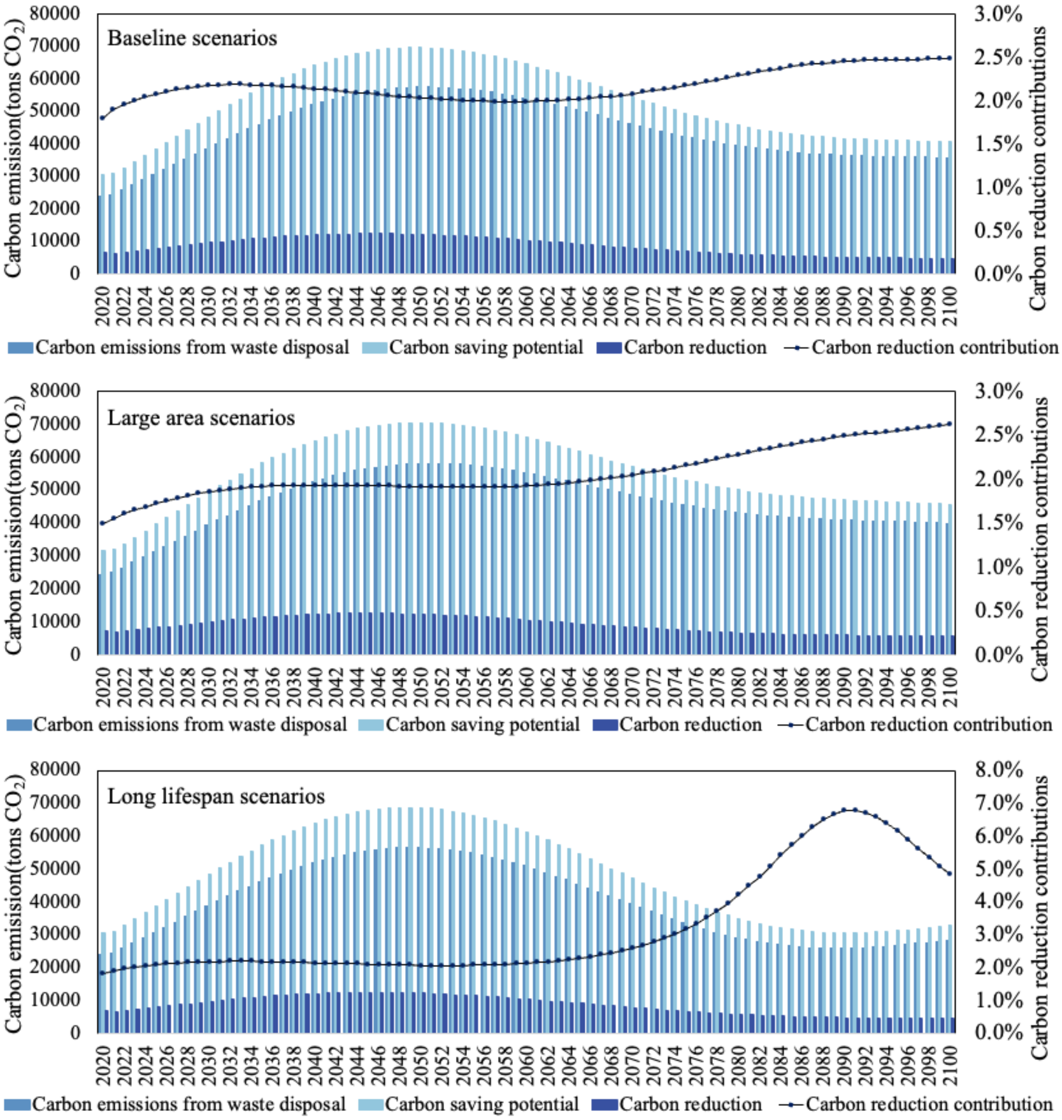


Fig.6-13 Carbon emission reduction forecast

6.6. Discussion

6.6.1 Carbon emissions from C&D Waste

This paper uses the weight of C&D Waste to estimate carbon emissions from demolition, which is different from the usual estimation method using carbon emissions per unit area. Therefore, the carbon emission factor per unit area of the demolition process is calculated, which is 14.8 $kgCO_2/m^2$, a value higher than that of Ivanica's study (10.3 $kgCO_2/m^2$) (Ivanica et al., 2022). This may be related to the different system boundaries. In most studies, carbon emissions are usually calculated by calculating the diesel consumption of large machinery to demolish buildings(Geng et al., 2022), without considering the carbon emissions of activities such as site grading, small machinery to cut metal, and worker transportation.

After differentiating by building structure, the carbon emission factor for wooden building demolition in this study is 9.4 $kgCO_2/m^2$, which is close to Ivanica's study (CASE2: 9.1 $kgCO_2/m^2$, CASE3: 8.3 $kgCO_2/m^2$). The carbon emission factor of 18.4 $kgCO_2/m^2$ for the demolition of non-wood buildings is significantly higher than that of Ivanica's study (CASE4: 10.6 $kgCO_2/m^2$) and Wang et al.'s study (8.7 $kgCO_2/m^2$) (Wang et al., 2018). This confirms the system boundary inference. The demolition of wooden buildings is less difficult and shorter than non-wood buildings, implying less carbon emissions not accounted for in other studies. The carbon emission factors are closer to those of other studies. This paper's carbon emission calculation of the demolition process is considered credible.

As shown in Table 6-9, the carbon emission factors for each waste transportation were calculated. The maximum carbon emission factor for transporting waste gypsum and plastic waste is 3.9 $kgCO_2$/ton, and the smallest is 1.2 $kgCO_2$/ton for concrete blocks. The average carbon emission factor for construction waste transportation in Kitakyushu is 1.6 $kgCO_2$/ton, which is smaller than in other studies.

Table 6-9 Carbon emission coefficient of waste transportation

C&D waste	Coefficient (kg/tons)	C&D waste	Coefficient (kg/tons)
CS	2.05	Wood A	2.79
As	1.54	Wood B	1.84
Co	1.18	WPl	3.89
Sludge	2.82	WPa	3.78
MC	3.45	Metal scraps	2.54
Wood A	2.79	WPb	3.91

In Wang's study(Wang et al., 2021) the carbon emission factor for transportation of C&D Waste in the Greater Bay Area of China was 4.7 $kgCO_2$/ton (2,617 kilotons waste, 12.26 kilotons CO_2). The reason for the difference is the transportation distance. Wang believes that the average transportation distance of waste in the Greater Bay Area is 44 km to 81 km, the transportation distance of major C&D waste in Kitakyushu is less than 20 km. This indicates that the resource recycling industry in Kitakyushu is well developed, supported by the policy of encouraging recycling companies to move in, which shortens the transportation distance of C&D waste and contributes to carbon emission reduction.

Fewer studies have considered carbon emissions from intermediate treatment processes. In this study, data for this process were obtained through interviews and carbon emission factors were calculated accordingly. The carbon emission factor of intermediate treated concrete blocks in this study (14.3 kg/tons) is close to Cha's study (13.8 kg/tons). In contrast, the carbon emission factor of recycled wood differs significantly (8.2 and 13.6 kg/tons)(Cha et al., 2020). This difference may be the result of different recycled products. Recycled products from concrete blocks are usually considered aggregates and therefore have close carbon emission factors in different studies. The recycled product of wood is not unique. Wood chips are identified as the recycled product of waste wood in this study, while in Cha's study the wood recycling product may be more complex wood chip products, such as wood composite board. Wood composite boards undergo more manufacturing processes and emit more CO_2, resulting in a difference in carbon emission factors.

6.6.2 Comparison of recycled materials and new materials

The difference between the carbon emission factor of the new product manufacturing and the recycled product reflects the carbon reduction capability of the C&D waste recycling efforts. The difference between the two is compared as shown in Table 6-10. Carbon from recycled materials is reflected in three key processes. In line with previous studies(Wang et al., 2018), the transportation stage has the smallest share of carbon emissions coefficient, averaging 7.8%. Similar to Dahlbo's study(Dahlbo et al., 2015), the carbon emissions in the intermediate treatment stage are higher than those in the demolition stage. Especially for metal, the share of carbon emissions from intermediate treatment is as high as 98.5%, similar to 97.1% in the study of Dahlbo. Therefore, the intermediate treatment stage should not be neglected in evaluating the environmental benefits of waste recycling.

Some C&D waste such as scrap metal, waste plastic, wastepaper, and waste plasterboard have smaller carbon emission coefficients than the corresponding new materials, indicating that recycling these materials benefits carbon emission reduction. Wang's research on decoration waste(Wang et al., 2021) and Gorman's research on metal waste supports this view(Gorman et al., 2022).

The coefficients for inert waste such as concrete blocks and asphalt concrete are larger than those for new materials and have a negative impact on carbon reduction. It shows that recycling techniques for materials such as concrete and asphalt need to be improved. This view is supported by Wang(Wang et al., 2018), who believes on-site recycling and disposal of these wastes is the solution. Some studies have concluded that recycled concrete blocks will benefit the environment(Peng et al., 2021). The reasons for the inconsistency of views are twofold. On the one hand, the reports of the energy consumed for the production of recycled aggregates vary greatly for different researchers(Wang et al., 2022). On the other hand, some studies use carbon reduction potential as a measure of the environmental benefits of recycling waste(Liu et al., 2022). These studies idealized that concrete block waste is still used as concrete materials after recycling treatment, ignoring the downcycling of the waste(Tanikawa & Hashimoto, 2009)

As the city with the highest building vacancy rate in Japan, how to dispose of abandoned buildings is an urgent issue for the government to overcome. By analyzing the carbon reduction capacity of using recycled materials, it was demonstrated that in Kitakyushu, the carbon emissions from building demolition and waste disposal reached and exceeded the carbon balance with the reduction in carbon emissions due to the use of recycled materials. This indicates that building demolition will not put carbon emission pressure on the construction industry. This provides a solid basis for implementing the construction material urban mining (Wuyts et al., 2020). It also proves that Kitakyushu's idea of recycling resources can be replicated to help other regions reduce carbon emissions.

Table 6-10 Carbon emission coefficient of recycled products and new products

C&D waste to recycled products	Coefficient ($tonsCO_2/tons$)				New products	Coefficient (tons CO_2/tons)
	Demolition	Transportation	Intermediate treatment	Total		
Asphalt concrete	0.011	0.001	0.014	0.027	2.5% Asphalt & 97.5% Gravel	0.014
Concrete blocks	0.014	0.001	0.014	0.029	Gravel	0.009
Mixed construction waste	0.015	0.004	0.018	0.038	Gravel	0.009
Wood A	0.013	0.002	0.008	0.024	Wood chips	0.053
Wood B	0.012	0.002	0.007	0.021	Wood chips	0.053
Waste plastic	0.019	0.006	0.027	0.052	Thermoplastic Resins	1.524
Wastepaper	0.009	0.004	0.020	0.034	Paper pulp	0.712
Metal scraps	0.011	0.002	0.875	0.888	Crude steel	1.764
Waste plasterboard	0.010	0.003	0.013	0.027	Gypsum	0.228

6.6.3 Comparison of recycled materials and new materials

Scenario analysis is a common way to assess environmental benefits. Based on the building stock-flow model, this study developed three scenarios to predict the carbon reduction benefits of Kitakyushu under different construction development patterns. In contrast to other cities, Kitakyushu has well-developed waste disposal regulations, a well-developed recycling industry, and a high waste recycling rate (MLIT, 2018), so the common scenario-building model based on waste disposal methods(Coelho & de Brito, 2013), recycling rate (Dahlbo et al., 2015; Liu et al., 2022; Wang et al., 2021) was not used. Scenarios were built based on rapid population decay and high building vacancy rates.

With all three scenarios showing a rapid growth in demolition areas over the next 30 years, Kitakyushu will inevitably face rapid growth in construction waste. City managers should fully use Kitakyushu's resource recycling industry and be prepared to expand disposal to cope with the coming impact, properly dispose of waste, and contribute to carbon reduction in the construction industry.

Similar to Zhang's study (Zhang et al., 2022), floor area per capita and building lifespan significantly influence the construction industry. The building stock in the large area scenario is higher than in the other scenarios, which means more new construction and demolition activities, generating more C&D Waste. Although more waste can lead to more carbon emission reduction, its emission reduction contribution is smaller than in other scenarios. Therefore, a reasonable amount of floor area per capita is essential to achieve carbon neutrality in the construction sector. This conclusion is consistent with Hu's study on residential buildings (Hu et al., 2010), and this study extends the findings. The higher carbon emission reduction contribution of the long-life scenario stems from the fact that longer-lived buildings effectively delay building demolition and new construction activities, which is supported by Peng (Peng et al., 2021), and this study distinguishes building life by building structure, which makes the study more accurate.

Under the high recycling rate in Kitakyushu, C&D Waste recycling would contribute up to 6.8% of carbon reduction to the construction industry, but this is a special case of long lifespan. There is no increase in carbon emission reduction at this point, and fewer construction activities drive the high carbon emission reduction contribution. Carbon reduction through recycled waste is influenced by the amount of recycled waste, while the activities of the construction industry also influence the contribution to carbon reduction. Long lifespan buildings can contribute to the carbon neutrality of the construction industry by delaying and dispersing construction activities, Zhang confirms this view that sustainable building stock dynamics can make a significant contribution to climate change (Zhang et al., 2022).

In other two scenarios, the carbon emission reduction contribution will be between 1.9% and 2.5% most of the time. The study by Li shows that the building demolition and recycling stage can provide about 4% carbon reduction contribution(X. Li et al., 2022), and that more careful demolition work(Christensen et al., 2022) and higher recycling technology(Wang et al., 2021) will further increase the carbon reduction contribution. This indicates the potential for improving carbon emission reduction from construction waste recycling in Kitakyushu.

6.7. Summary

Using the LCA method, this study assesses the generation and environmental impact of C&D waste from construction activities in Kitakyushu, Japan. The disposal process and flow of C&D waste are also sorted out. Based on comparing carbon emissions from recycled and new materials, a prediction model is developed to analyze the emission reduction contribution of C&D Waste recycling. The main points of carbon reduction are also proposed. The research proves that Kitakyushu's developed resource recycling industry contributes to the carbon emission reduction in the construction industry, the synergistic decarbonization of the construction industry and the waste recycling industry is an effective path to carbon reduction. which can provide reference for other regions. The results reveal some critical findings.

(1) In 2019, C&D Waste production in Kitakyushu was about 1.26 million tons, of which construction material waste accounts for the majority, and the recycling rate of significant waste has exceeded 95%. C&D waste has been freed from illegal dumping, and the focus should be on recycling waste more efficiently and profitably.

(2) The LCA study shows that recycling and disposal of C&D Waste in 2019 generated 35,896 tons of CO_2, which is 7,849.9 tons less than the carbon emissions of equivalent new material. This indicates that the demolition of Kitakyushu buildings will not impact the environment. This can provide a new idea and basis for vacant building disposal and recycling building theory.

(3) Concrete and metals are the primary sources of carbon emissions in the recycling process due to their large volume and high energy consumption in the recycling process, respectively. The overly simple recycling scheme makes the recycling process of concrete blocks detrimental to carbon reduction. The development of lower carbon concrete recycling technologies and a more rational program for reusing concrete waste will be an essential part of the sustainable development of the construction industry in Kitakyushu.

(4) The scenario analysis found that the city of Kitakyushu is about to face the pressure of rapid growth of C&D Waste. This is also an opportunity for carbon reduction and will provide a 1.9-6.8% carbon reduction contribution to the carbon neutrality of the construction industry. Increasing the building life can smooth out the building flow, which is more conducive to achieving carbon neutrality in the construction industry.

Finally, the limitations of this paper are as follows. The intermediate treatment of C&D Waste is very complex. Although detailed research has been conducted in this study, some processes have been simplified, and the carbon emissions may need to be considered. In the future, the process of waste disposal needs to be explored in more detail to make carbon emissions estimates more accurate.

Reference

Agency for Natural Resources and Energy. (2020). Standard calorific value and carbon emission factor (Comprehensive Energy Statistics). https://www.enecho.meti.go.jp/statistics/total_energy/carbon.html

Central Japan railway company. (2014). Central Shinkansen environmental impact assessment.

Cha, G.-W., Moon, H. J., Kim, Y.-C., Hong, W.-H., Jeon, G.-Y., Yoon, Y. R., Hwang, C., & Hwang, J.-H. (2020). Evaluating recycling potential of demolition waste considering building structure types: A study in South Korea. Journal of Cleaner Production, 256, 120385. https://doi.org/10.1016/j.jclepro.2020.120385

Christensen, T. B., Johansen, M. R., Buchard, M. V., & Glarborg, C. N. (2022). Closing the material loops for construction and demolition waste: The circular economy on the island Bornholm, Denmark. Resources, Conservation & Recycling Advances, 15, 200104. https://doi.org/10.1016/j.rcradv.2022.200104

Coelho, A., & de Brito, J. (2012). Influence of construction and demolition waste management on the environmental impact of buildings. Waste Management, 32(3), 532–541. https://doi.org/10.1016/j.wasman.2011.11.011

Coelho, A., & de Brito, J. (2013). Environmental analysis of a construction and demolition waste recycling plant in Portugal – Part II: Environmental sensitivity analysis. Waste Management, 33(1), 147–161. https://doi.org/10.1016/j.wasman.2012.09.004

Colangelo, F., Petrillo, A., & Farina, I. (2021). Comparative environmental evaluation of recycled aggregates from construction and demolition wastes in Italy. Science of The Total Environment, 798, 149250. https://doi.org/10.1016/j.scitotenv.2021.149250

Dahlbo, H., Bachér, J., Lähtinen, K., Jouttijärvi, T., Suoheimo, P., Mattila, T., Sironen, S., Myllymaa, T., & Saramäki, K. (2015). Construction and demolition waste management – a holistic evaluation of environmental performance. Journal of Cleaner Production, 107, 333–341. https://doi.org/10.1016/j.jclepro.2015.02.073

Du, Q., Shao, L., Zhou, J., Huang, N., Bao, T., & Hao, C. (2019). Dynamics and scenarios of carbon emissions in China’s construction industry. Sustainable Cities and Society, 48, 101556. https://doi.org/10.1016/j.scs.2019.101556

Kitakyushu City Basic Plan for Establishing a Recycling-Oriented Society, Environmental Council of Kitakyushu (2011) (testimony of Environmental Council of Kitakyushu).

Overview of Kitakyushu decarbonization pioneer area, Environmental Council of Kitakyushu (2022) (testimony of Environmental Council of Kitakyushu).

Geng, J., Wang, J., Huang, J., Zhou, D., Bai, J., Wang, J., Zhang, H., Duan, H., & Zhang, W. (2022). Quantification of the carbon emission of urban residential buildings: The case of the Greater Bay Area cities in China. Environmental Impact Assessment Review, 95, 106775. https://doi.org/10.1016/j.eiar.2022.106775

Gorman, M. R., Dzombak, D. A., & Frischmann, C. (2022). Potential global GHG emissions reduction from increased adoption of metals recycling. Resources, Conservation and Recycling, 184, 106424. https://doi.org/10.1016/j.resconrec.2022.106424

Green Growth Strategy, Ministry of Economy, Trade and Industry (METI) (2021).

Hu, M., Pauliuk, S., Wang, T., Huppes, G., van der Voet, E., & Müller, D. B. (2010). Iron and steel in Chinese residential buildings: A dynamic analysis. Resources, Conservation and Recycling, 54(9), 591–600. https://doi.org/10.1016/j.resconrec.2009.10.016

IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, IGES.

Ivanica, R., Risse, M., Weber-Blaschke, G., & Richter, K. (2022). Development of a life cycle inventory database and life cycle impact assessment of the building demolition stage: A case study in Germany. Journal of Cleaner Production, 338, 130631. https://doi.org/10.1016/j.jclepro.2022.130631

IWCD of Kitakyushu. (2019). Industrial waste production and disposal in Kitakyushu City. IWCD of Kitakyushu.

Kitakyushu City Basic Plan for Establishing a Recycling-Oriented Society (The second issue), Municipal Government of Kitakyushu (2022).

Kitakyushu Statistics Bureau. (2020). Statistical Yearbook of Kitakyushu.

Komatsu, Y. (2020). Lifetimes and Values of Buildings. Journal of Architecture and Building Science, 135(1744), 3–6.

Kyushu Electric Group. (2020). Kyushu Electric Group Environmental Data Collection. Kyushu Electric Group.

Li, L., & Yang, J. (2020). A new method of energy-related carbon dioxide emissions estimation at the provincial-level: A case study of Shandong Province, China. Science of The Total Environment, 700, 134384. https://doi.org/10.1016/j.scitotenv.2019.134384

Li, X., Xie, W., Xu, L., Li, L., Jim, C. Y., & Wei, T. (2022). Holistic life-cycle accounting of carbon emissions of prefabricated buildings using LCA and BIM. Energy and Buildings, 266, 112136. https://doi.org/10.1016/j.enbuild.2022.112136

Liu, H., Guo, R., Tian, J., Sun, H., Wang, Y., Li, H., & Yao, L. (2022). Quantifying the Carbon Reduction Potential of Recycling Construction Waste Based on Life Cycle Assessment: A Case of Jiangsu Province. International Journal of Environmental Research and Public Health, 19(19), 12628. https://doi.org/10.3390/ijerph191912628

Ma, W., Yuan, H., & Hao, J. L. (2022). A bibliometric visual analysis of the system dynamics approach for construction and demolition waste management. Cleaner Waste Systems, 1, 100004. https://doi.org/10.1016/j.clwas.2022.100004

Menegaki, M., & Damigos, D. (2018). A review on current situation and challenges of construction and demolition waste management. Current Opinion in Green and Sustainable Chemistry, 13, 8–15. https://doi.org/10.1016/j.cogsc.2018.02.010

Construction Recycling Law, (2000). https://www.env.go.jp/recycle/build/gaiyo.html

Ministry of Environment. (2022a). Greenhouse Gas Emissions Report. Ministry of Environment.

Ministry of Environment. (2022b). Status of industrial waste discharge and disposal. Ministry of Environment, Japan.

Ministry of ETI. (2021). Extended input-output table. Ministry of ETI.

Ministry of the Environment. (2017). Guidelines for Calculation of Total Greenhouse Gas Emissions Ver. 1.0. Ministry of the Environment.

MLIT. (2018). Survey of construction by-products. MLIT.

Nansai, K., Fry, J., Malik, A., Takayanagi, W., & Kondo, N. (2020). Carbon footprint of Japanese health care services from 2011 to 2015. Resources, Conservation and Recycling, 152, 104525. https://doi.org/10.1016/j.resconrec.2019.104525

NIPSSR. (2018). Estimated population of Japan by region. NIPSSR.

Ogawa, Y. (2006). Study on the process of recycling construction waste and calculation of energy consumption. the University of Kitakyushu.

Ogawa, Y., & Gao, W. (2006). Research on Recycle Process and Energy Consumption about Recycle od Construction Waste. Journal of Environmental Engineering, 71(604), 93–100. https://doi.org/10.3130/aije.71.93_2

Paris Agreement, UNITED NATIONS (2015).

Peng, Z., Lu, W., & Webster, C. J. (2021). Quantifying the embodied carbon saving potential of recycling construction and demolition waste in the Greater Bay Area, China: Status quo and future scenarios. Science of The Total Environment, 792, 148427. https://doi.org/10.1016/j.scitotenv.2021.148427

Kitakyushu environmental future city plan, Planning bureau of Kitakyushu (2012) (testimony of Planning bureau of Kitakyushu).

Planning bureau of Kitakyushu. (2018). Kitakyushu SDGs Future City. Planning bureau of Kitakyushu.

Tang, S., Zhang, L., Hao, Y., Liu, Q., Liu, Y., & Han, J. (2019). Dynamic modeling of stock and flow in an urban residential building system: A case study of Beijing. Acta Ecologica Sinica, 39(4), 1240–1247. https://doi.org/10.5846/stxb201809131977

Tanikawa, H., & Hashimoto, S. (2009). Urban stock over time: Spatial material stock analysis using 4d-GIS. Building Research & Information, 37(5–6), 483–502. https://doi.org/10.1080/09613210903169394

Tracking Buildings 2020. (2020). IEA2021. https://www.iea.org/reports/tracking-buildings-2021

UNEP. (2021). Emissions Gap Report 2021. UNEP.

Wang, J., Teng, Y., Chen, Z., Bai, J., Niu, Y., & Duan, H. (2021). Assessment of carbon emissions of building interior decoration and renovation waste disposal in the fast-growing Greater Bay Area, China. Science of The Total Environment, 798, 149158. https://doi.org/10.1016/j.scitotenv.2021.149158

Wang, J., Wei, J., Liu, Z., Huang, C., & Du, X. (2022). Life cycle assessment of building demolition waste based on building information modeling. Resources, Conservation and Recycling, 178, 106095. https://doi.org/10.1016/j.resconrec.2021.106095

Wang, J., Wu, H., Duan, H., Zillante, G., Zuo, J., & Yuan, H. (2018). Combining life cycle assessment and Building Information Modelling to account for carbon emission of building demolition waste: A case study. Journal of Cleaner Production, 172, 3154–3166. https://doi.org/10.1016/j.jclepro.2017.11.087

Wuyts, W., Miatto, A., Sedlitzky, R., & Tanikawa, H. (2019). Extending or ending the life of residential buildings in Japan: A social circular economy approach to the problem of short-lived constructions. Journal of Cleaner Production, 231, 660–670. https://doi.org/10.1016/j.jclepro.2019.05.258

Wuyts, W., Sedlitzky, R., Morita, M., & Tanikawa, H. (2020). Understanding and Managing Vacant Houses in Support of a Material Stock-Type Society—The Case of Kitakyushu, Japan. Sustainability, 12(13), 5363. https://doi.org/10.3390/su12135363

Yu, S., Awasthi, A. K., Ma, W., Wen, M., Di Sarno, L., Wen, C., & Hao, J. L. (2022). In support of circular economy to evaluate the effects of policies of construction and demolition waste management in three key cities in Yangtze River Delta. Sustainable Chemistry and Pharmacy, 26, 100625. https://doi.org/10.1016/j.scp.2022.100625

Zhang, Y., Hu, S., Guo, F., Mastrucci, A., Zhang, S., Yang, Z., & Yan, D. (2022). Assessing the potential of decarbonizing China’s building construction by 2060 and synergy with industry sector. Journal of Cleaner Production, 359, 132086. https://doi.org/10.1016/j.jclepro.2022.132086

Zhao, Q., Gao, W., Su, Y., & Wang, T. (2023). Carbon emissions trajectory and driving force from the construction industry with a city-scale: A case study of Hangzhou, China. Sustainable Cities and Society, 88, 104283. https://doi.org/10.1016/j.scs.2022.104283

Zheng, L., Wu, H., Zhang, H., Duan, H., Wang, J., Jiang, W., Dong, B., Liu, G., Zuo, J., & Song, Q. (2017). Characterizing the generation and flows of construction and demolition waste in China. Construction and Building Materials, 136, 405–413. https://doi.org/10.1016/j.conbuildmat.2017.01.055

Chapter 7

CONCLUSION AND PROSPECT

CHAPTER 7: CONCLUSION AND PROSPECT

Contents

7.1 Conclusion

Global warming and climate crisis have become major challenges facing the world. As the relationship between carbon emissions and climate change is continuously explored, governments around the world have recognized the importance of curbing carbon emissions to control global warming and have set carbon neutrality targets. The construction industry is a significant source of carbon emissions and an important avenue for achieving carbon neutrality goals. Carbon Emissions from the Construction Industry (CECI) mainly come from the production of building materials, energy consumption during construction, and energy consumption during the building operation. To achieve decarbonization of the construction industry, low-carbon and environmentally friendly building materials are usually used, and measures such as designing more energy-efficient and environmentally friendly building structures and equipment and improving the energy utilization efficiency of buildings are taken.

This study focuses on the materialization and demolition processes of buildings, exploring the carbon emission trajectory and key driving factors of the construction industry at the city scale. Based on this, the study selects typical cities at different stages of development, Hangzhou in China and Kitakyushu in Japan, to discuss the potential for decarbonization of the construction industry and carbon neutrality from the perspectives of synergistic decarbonization with upstream sectors and synergistic carbon reduction with downstream waste recycling sectors, and to provide corresponding policy recommendations.

The main works and results can be summarized as follows:

Chapter 1, RESEARCH BACKGROUND AND PURPOSE OF THE STUDY, introduces the current state of global climate change, explores the relationship between carbon emissions and global warming, and provides an overview of the overall carbon emissions and building-related carbon emissions of various countries. The purpose is to emphasize the importance of CECI for achieving carbon neutrality. By combing through the sources of CECI, it highlights the need for active support from upstream and downstream departments for carbon reduction in the construction industry. Finally, the climate actions and carbon neutrality goals of various countries are summarized to emphasize the strong practical significance of researching carbon emissions in the construction industry.

Chapter 2, LITERATURE REVIEW OF CARBON EMISSIONS FROM CONSTRUCTION INDUSTRY, is mainly to sort out the research status of CECI. Firstly, the method of bibliometric analysis is used to analyze the development trend and hot issues of research on CECI based on 282 articles included in SCIE and SSCI in Web of Science from 1992 to 2022. The analysis summarizes the value and information of important literature and scholars. The research on CECI is in its infancy, with energy efficiency, sustainable development, green buildings, and policy evaluation being the current research hotspots. Then, these articles were manually reviewed, mainly reviewing the accounting scale, object, boundary, and method. It was found that the calculation of CECI at the city scale is still a problem, and most studies have not distinguished between different types of buildings, requiring more detailed research on rural housing, education, and office buildings. In addition, the carbon emissions accounting of building demolition or the processing and recycling of C&D waste is a challenge that needs to be addressed. Finally, based on the research in this paper, this chapter proposes the possibility of future development in the research of CECI.

Chapter 3, RESEARCH OBJECTS AND CARBON ACCOUNTING & ANALYSIS METHODS, is about research objects and methodological. First, some basic information about the two research objects, Hangzhou in China, and Kitakyushu in Japan, is introduced. These two cities have comparability due to their similar city status, while the different stages of urban development make it possible to analyze the impact of carbon emissions factors more comprehensively. Secondly, the carbon emission accounting methods and carbon emission boundary definitions used in this paper are introduced. The carbon emission factor method (IPCC method) is the basis of this paper. The input-output method is applied in Chapter 4 for top-down carbon emission accounting, while the life cycle assessment and carbon emission intensity method are applied in Chapters 5 and 6 for bottom-up carbon emission accounting. In addition, methods such as system dynamics and scenario analysis are introduced for establishing prediction models and predicting carbon emissions.

Chapter 4, CARBON EMISSION ACCOUNTING AND DRIVING FORCE ANALYSIS OF CONSTRUCTION INDUSTRY WITHIN A CITY SCALE. The city scale CECI has not been thoroughly studied, and the assessment and development of policies in the context of carbon neutrality present challenges. Therefore, this chapter selects and simplifies the China city-level MRIO Table (2012) and establishes a nested multi-regional input-output model (MRIO model) with a focus on China, Zhejiang, and Hangzhou. Based on this model and the carbon emission factor method, a framework for carbon emission accounting at the city scale is established, and the CECI of Hangzhou from 2005 to 2019 is quantitatively evaluated. The analysis tracks the sources of direct CECI and examines the trajectory of indirect CECI. Finally, the LMDI method is used to decompose the carbon emission increment into contributions from different factors, aiming to identify the factors influencing CECI changes and CECI reduction pathways. Additionally, the carbon intensity method is applied to calculate the CECI of Kitakyushu and decompose the carbon emission reduction. By comparing the influencing factors of CECI between Hangzhou and Kitakyushu, the effects of various factors on CECI in different stages of urban development are validated. The research results indicate that the construction industry in Hangzhou and Kitakyushu has reached its carbon peak, and construction scale and energy efficiency are the main factors influencing carbon emissions.

Chapter 5, SYNERGISTIC DECARBONIZATION POTENTIAL OF THE CONSTRUCTION AND UPSTREAM SECTORS. The factors that may affect the future carbon emissions of the construction industry, such as population growth, per capita floor area demand, material CI, and material demand intensity, are divided into two types: development mode and policy control, with three development paths for each type, resulting in nine scenarios. Then, using a system dynamics model, a building stock flow model is constructed to estimate building demand and new construction area under different scenarios. This allows for the calculation of material requirements, and a process-based life cycle assessment method is employed to calculate Materialization Stage Carbon Emissions (MSCE) in the construction industry. Finally, the LMDI method is used to decompose the carbon emission differences among different scenarios, identify the core influence factors of MSCE, and explore the possibility of decarbonization of the construction industry. The results show the potential for collaborative emissions reduction between the upstream sector and the construction sector is huge, but Hangzhou’s construction sector will still need help from other industries to become carbon neutral by 2060.

Chapter 6, SYNERGISTIC DECARBONIZATION POTENTIAL OF THE CONSTRUCTION AND WASTE RECYCLING SECTOR. This chapter first clarifies the flow, disposal methods, and recycling methods of the 11 types of C&D waste in Kitakyushu. Through an analysis of the disposal and recycling processes for each type of C&D waste, a bottom-up accounting of the full life cycle carbon emissions of C&D waste is conducted using a life cycle assessment method and carbon emission coefficient method. Then, by comparing the carbon emission intensity of recycled materials with that of new materials, the carbon emission reduction contribution of Kitakyushu’s waste recycling industry to the construction industry in 2019 is calculated. Finally, using a system dynamics method, the building stock and flow in Kitakyushu are modeled to predict the generation of C&D waste and its potential carbon emission reduction contributions under three scenarios (baseline, large-scale, and long lifespan scenarios). The research results show that recycling demolition waste can contribute to a 1.9-6.8% reduction in CECI, while material recycling and “urban mining” can be one of the methods used by Kitakyushu to deal with vacant building.

Chapter 7, CONCLUSION AND PROSPECT have been presented.

In summary, this study conducted a detailed assessment of carbon emissions from the construction industry within a city scale. Its aim was to identify key factors influencing CECI and explore pathways for carbon reduction. By implementing different carbon reduction strategies in two typical cities at different stages of development, the study investigated the Synergistic decarbonization potential between the construction industry and upstream material supply sectors or downstream waste recycling sectors. It also explored the possibilities of decarbonizing the construction industry.

In the city-scale carbon emissions accounting, the carbon emissions from the construction industry in both Hangzhou and Kitakyushu have reached their peaks, with carbon neutrality being a shared goal for these cities’ construction sectors. In Hangzhou, although the total emissions from the construction industry peaked in 2014, they remain significant, and the main contribution to emission reduction comes from the upstream sector. Hangzhou exhibits a significant spillover effect in carbon emissions, with a substantial amount of CO_2 being emitted outside Hangzhou through the upstream sector. The indirect CECI of Hangzhou mainly originates from industries such as building materials, energy, and transportation. The increase in construction area is the most significant factor influencing the growth of the CECI in Hangzhou, while energy intensity plays a crucial role in restraining carbon emissions. The energy consumption structure and efficiency of the upstream sector positively contribute to reducing carbon emissions, highlighting the need for greater support from upstream industries for emission reduction in Hangzhou’s construction industry. In Kitakyushu, the CECI are relatively stable. The reduction in newly constructed building area and the decrease in energy intensity are the main driving factors for carbon emission reduction, while the intensity of output value hinders carbon reduction. By comparing the driving factors of carbon emission changes between the two cities, the study reveals the primary drivers of carbon emission changes in the urban construction industry, which are equally applicable to cities at different stages of development.

Regarding the synergistic decarbonization potential between the construction industry and its upstream sectors, this study found that without any emission reduction measures, the CECI from the materialization stage in Hangzhou will continue to increase. It is projected to reach 27.6 million tons by 2027 and a massive scale of 14.9 million tons is still expected by 2060, posing a significant challenge to carbon commitments. However, if timely joint emission reductions are implemented in the construction industry and its upstream sectors, the CECI will trend downward. In the optimal scenario, the cumulative emission reduction potential over the next 40 years can reach 366.1 million tons. Nevertheless, even in 2060, the target of carbon neutrality cannot be achieved, and 3.7 million tons of CO_2 need to be compensated through carbon trading or carbon removal. The collaborative decarbonization potential mainly comes from carbon emission reduction in the supply-side material production process and demand-side control of new building area. These two factors contribute 43.2% and 40.7% of the cumulative carbon emission reductions, respectively. Extending the lifespan of buildings, controlling per capita building area, and avoiding unnecessary construction are crucial in reducing emissions from the demand side. On the supply side, carbon reduction in materials is the key to decarbonizing the construction industry. It is necessary to focus on how to reasonably reduce the demand for high-carbon materials such as steel, aluminum, and cement, as well as reducing their embodied carbon.

Regarding the synergistic decarbonization potential between the construction industry and waste recycling sector, this study found that as one of the most developed regions in the recycling industry, Kitakyushu has achieved a recycling rate of over 95% for major C&D waste. In 2019, the total production of C&D waste was approximately 1.26 million tons, with building material waste being the majority. The recycling and disposal of these waste generated 35,896 tons of CO_2, which is 7,849.9 tons less than the carbon emissions from equivalent new materials. This indicates that the demolition of buildings in Kitakyushu does not have a negative impact on the environment, providing new insights and evidence for the disposal of vacant buildings and the theory of building recycling. Concrete and metals are the primary sources of carbon emissions in the recycling process due to their large volume and high energy consumption. It is necessary to develop low-carbon concrete recycling technologies and more rational plans for reusing concrete waste. Scenario analysis reveals that Kitakyushu is about to face the pressure of rapid growth in C&D waste. It is also an opportunity for carbon reduction and will contribute 1.9-6.8% to the carbon neutrality target of the construction industry.

Decarbonizing the construction industry has become a major challenge we currently face. Achieving carbon neutrality in the construction industry still needs to be supported through carbon trading and carbon removal. With the tightening of carbon emission policies, the construction sector will soon be included in the carbon emission control system along with other high-energy-consuming and carbon-intensive industries. Unlike other industries, the carbon emissions in the construction industry mainly stem from the upstream material production. This study takes an innovative approach by linking decarbonization efforts in the construction industry with its upstream and downstream sectors. From the perspective of collaborative decarbonization, it provides new insights and solutions for decarbonizing the construction industry. It is hoped that this research can serve as a reference for the formulation and implementation of relevant policies.

7.2 Prospect

With the popularization of decarbonization concepts and the deepening of carbon emission research, we can hope to improve global warming and climate change issues. In the construction industry, taking proactive emission reduction measures is a necessary approach to achieve carbon neutrality goals. These measures include reducing new building area, improving energy efficiency, optimizing the supply chain, and reducing the demand for high-carbon materials. The government plays a crucial role in promoting decarbonization transformation in the construction industry by strengthening policy support, promoting technological innovation, and fostering industry collaboration.

Research on CECI is an emerging field that is still in its early stages but holds vast prospects and potential. However, there are also limitations. Currently, research on CECI mainly relies on carbon emission factor or carbon intensity methods, which may result in inaccurate carbon accounting when using the same coefficients. With further development in carbon measurement and monitoring technologies, the construction industry can accurately and efficiently measure and monitor both direct and material-related carbon emissions.

Furthermore, the carbon emissions during the demolition phase and the disposal of C&D waste are often overlooked. Although this study estimated the carbon emissions of C&D waste in Kitakyushu, the waste disposal process is complex, and there may be simplifications in the research. It is believed that with increased attention from researchers on the demolition phase, this process will be studied in more detail and carbon accounting will be more accurate.

Lastly, the carbon footprint of the building retrofit process also deserves more attention. Currently, there are debates regarding the building materials required for retrofitting and the lifespan of retrofitted buildings. In this study, the influence of retrofitting on building flow was not considered in the building stock flow prediction model for Hangzhou City in Chapter 5. However, in the study on Kitakyushu City in Chapter 6, retrofitting was included due to detailed data. In the future, carbon emissions from building retrofits will be one of the key areas for breakthroughs in this research.