Building Energy Research Center of Tsinghua University

Decarbonize Urban Heating System

China Building Energy and Emission Yearbook 2023

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Building Energy Research Center of
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Preface

Since the introduction of the dual-carbon strategy by the central government in 2020, the main task for achieving carbon neutrality has been to transform the current carbon-based energy structure into a zero-carbon energy structure. The urban energy supply system is responsible for the conversion of primary energy to end-use forms, the transmission and distribution from the supply side to the demand side, as well as the reception and transformation at the end-users. The carbon neutrality of the urban energy supply system is key to achieving comprehensive carbon neutrality goals. Therefore, this report comprehensively discusses the issues related to the urban energy supply system, exploring how to meet the current needs of urban development, comprehensively achieve future carbon neutrality goals, and gradually transition from the existing system to a new system while ensuring social development, resident livelihoods, and economic growth.

After more than three years of continuous research by the research teams of Fu Lin, Xia Jianjun, and Jiang Yi from the Building Energy Research Center of Tsinghua University, preliminary ideas have been formulated regarding the structure, characteristics, and operation modes of the urban energy supply system under the carbon neutrality vision in China. Additionally, initial clarification has been made on how to ensure the current energy demands for buildings and industries, as well as the growing needs, and how to transform the existing system step by step, eventually transitioning to a new energy supply system that meets the requirements of carbon neutrality. This book provides a comprehensive account of the research results mentioned above, describing the current status of heat demand in buildings and non-process industries and predicting future demand. It also introduces the challenges faced by the urban energy supply system in achieving carbon neutrality and elucidates the low-carbon heating model primarily based on low-grade waste heat. Consequently, under the carbon neutrality vision, the dense urban areas with high-density heat demand can be provided by utilizing abandoned wind and solar power, nuclear power, power plant waste heat, and industrial waste heat. As for low-density heat demand, heat can be obtained directly from the surrounding environment, including air, soil, and surface water, using electric heat pumps. Due to time and space constraints, the introduction of key technologies and typical engineering cases on low-carbon heat use cannot be included in this book, but this part has been presented in the Chinese version, and readers can refer to this book for further understanding if they are interested.

A zero-carbon urban energy supply system is a revolution in the energy system and requires a firm sense of innovation, a high level of social responsibility, and a scientific and pragmatic spirit to advance step by step. Only through incremental progress and implementation of individual components can we ultimately comprehensively build a new zero-carbon urban energy supply system and achieve our carbon neutrality goals.

Beijing, China Yi Jiang

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The report was finally compiled by Ziyi Yang.

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Building Energy Research Center of Tsinghua University

The Building Energy Research Center (BERC) of Tsinghua University was founded in 2005 by Prof. Yi Jiang and his colleagues. The mission of BERC is to devote to the development of energy-efficient and environmentally responsible buildings in China in accordance with national and international energy and environmental targets, including building research and innovation. The principal research activities within BERC include

- Assessment of the current building status in China and the provision of strategic outlooks on buildings' energy consumption and efficiency.
- Occupant behavior and building simulation research.
- Research and development (R&D) of innovative high-efficiency building technology and systems.
- Energy efficiency application research on subsectors, including space heating in Northern China; rural residential buildings and urban residential buildings; and public and commercial buildings.

Since 2007, BERC has been publishing the annual report on China Building Energy Efficiency (in Chinese) to provide data references, and technical and policy suggestions for policy makers and engineers in the field of building energy conservation.

BERC is also involved in international exchange and cooperation, including on-going collaboration with the International Energy Agency. Since 2016, BERC has started to publish the English version of this report for international audiences conducting building energy research.

Previous English reports and data could be download from
https://cloud.tsinghua.edu.cn/d/aac3b0127a244f9985c5/.

Executive Summary

Building Construction and Building Embodied Energy Use and Emissions in China Have Shown a Visible Post-Pandemic Recovery

In 2021, China reached a population of 1413 million, with the urbanization rate rising from 37.7% in 2001 to 64.7% in 2021. Rapid urbanization drives the continuous development of the building construction. There is a slowdown in civil building construction in 2020 due to the impact of COVID-19, but a visible recovery in 2021. In 2021, the total building stock in China reached 67.8 billion m^2, including 30.5 billion m^2 of urban residential buildings, 22.6 billion m^2 of rural residential buildings, and 14.7 billion m^2 of public and commercial (P&C) buildings. The floor area for northern urban heating is 16.2 billion m^2.

The embodied energy use and embodied CO_2 emissions of China's civil buildings have been decreasing since 2016. In 2021, the embodied energy use of civil buildings in China was 0.52 Gtce, and embodied carbon emissions of civil building construction was 1.6 $GtCO_2$. Adequate planning and speed of construction of the entire building stock, a shift from new construction to maintenance and renovation of existing buildings, low-carbon building materials, and construction methods are important issues for the low-carbon transition of China's building sector.

Energy Use and Carbon Emission Intensity of Building Operation in China Continues to Grow Steadily, But Remains Lower Compared to Developed Countries

In 2021, the total commercial energy consumption of building operation in China was 1.11 Gtce, and the total carbon emissions during building operation were 2.2 Gt CO_2. Following the post-pandemic recovery, the electricity consumption of buildings rose greatly from 2020 to 2021. The electricity consumption of building operation exceeded 2.2 PWh in 2021, leading to a corresponding increase in the indirect carbon emission from electricity use to 1.24 $GtCO_2$. On the other hand, the indirect carbon emission from heating during building operation was 430 million tons of CO_2, which showed a gradual but steady growth trend.

China's building operation energy consumption per capita and per square meter remains significantly lower than the US, Canada, Europe, Japan, and South Korea. Specifically, China's equivalent electricity consumption per capita of building operation was approximately one-fifth of that in the US and Canada, and half of that in Japan and South Korea. Similarly, the equivalent electricity consumption per square meter of building operation in China was one-third of that in Canada and half of that in the US, Europe, Japan, and South Korea. As a result, China's building carbon emissions per capita and per square meter are lower than those in most developed countries.

China's Building and Industrial Sectors Have a Significant Demand for Heat, Making Them a Focal Point for Low-Carbon Energy Systems

Currently, the total heat demand of urban heating systems is approximately 13 billion GJ, and most of this heat is provided by fossil fuels emitting approximately 1.1 billion tCO_2.

Heating in Northern Cities: The total building area for heating in northern urban areas is 16.2 billion m^2, with a total heat demand of 5.88 billion GJ. The main heating methods still rely on burning fossil fuels, account for 85.8% of the total. Industrial waste heat, geothermal energy, sewage and waste, rural biomass, and electric heating have also seen some development, but their proportion remains relatively low.

Heating in the Yangtze River Basin: In 2015, the potential heating demand of civil buildings in the 9 provinces and 2 cities of the Yangtze River Economic Belt was approximately 27.7 billion m^2. The proportion of decentralized heating is more than 99%.

Heating for Industrial: Considering the different characteristics of non-electric energy in the industrial sector, this book classifies it into two categories. The first is process industries, where fossil energy is used as fuel or raw material in the production process. These industries often have high-temperature requirements and abundant waste heat resources. The second is non-process industries, where fossil fuels are mainly used to produce steam, high-temperature hot water, and other thermal sources required for the production process. These industries often have a significant demand for medium and low-temperature heat. Non-process industries mainly rely on coal-fired and gas-fired boilers to supply hot water and steam, resulting in a large amount of carbon emissions. In 2020, non-process industries consumed approximately 8 billion GJ of heat, equivalent to about 278 million tons of standard coal, and generated approximately 710 million tons of carbon emissions.

DHW and Steam for Special Functions: In 2020, the total demand for domestic hot water in various types of buildings in China was approximately 830 million GJ.

The demand for steam in special functions such as hotels and hospitals was around 100 million GJ.

In the Future, There Will Still Be a Substantial Demand for Heat, and It Is Urgent to Seek Low-Carbon Heat Sources as Replacements

By 2050, the building heating area will increase to 21.8 billion m^2, and the heat consumption per unit area on the heat source side can be reduced to 0.25 GJ/m^2. The total heating demand will decrease to 5.4 billion GJ. The heat demand for non-process industries above 150 °C is approximately 6 billion GJ, and the heat demand for below 150 °C is approximately 7.6 billion GJ. This heat demand can be supplied by recovering various types of low-grade waste heat.

Heat demand of non-process industries above 150 °C approximately 6 billion GJ can be met by high-temperature gas-cooled reactors.

The heating demand in the Yangtze River Basin will increase to 35 billion m^2. The total heat required will be about 2.1 billion GJ. The total heat demand for domestic hot water and steam for special buildings will be 1 billion GJ per year. This heat demand can be supplied by electric heat pumps, heat pump steam generators, and electric steam generators.

The Heating Mode Primarily Based on Low-Grade Waste Heat Is Key to Achieving Carbon Neutrality in the Urban Energy Supply System

China has a significant amount of low-grade waste heat emitted by power plants, industries, data centers, etc., totaling approximately 20 billion GJ by 2050. The main sources are industrial waste heat and power plant waste heat, which has an amount of 5 billion GJ/year and 12 billion GJ/year. By utilizing existing centralized heating systems and establishing a waste heat resource sharing system to recover, transport, store, and utilize about 70% of the heat, it would be possible to fully meet the heating demands for buildings and non-process industries below 150 °C.

Building a waste heat resource sharing system requires large-scale and long-term heat storage technology to address the temporal mismatch between waste heat generation and heat demand; long-distance heat transfer technology to address the geographical mismatch between waste heat sources and heat users; and heat transformation technology based on heat pumps to address the temperature mismatch between emitted waste heat and heating demand.

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China's Building Energy Use and GHG Emissions

1.1 Basic Situation of China's Building Sector

1.1.1 Urban and Rural Demographic

In recent years, urbanization has grown rapidly in China. In 2021, China had an urban population of 914 million and a rural population of 498 million, with the urbanization rate rising from 37.7% in 2001 to 64.7%, as shown in Fig. 1.1.

Urbanization is fundamentally characterized by the massive migration of people from rural areas to cities. In China, urbanization means that the people, for the most part, migrate to superlarge cities and county-level cities. According to relevant research by Xiaojiang Li,[1] former director of the China Academy of Urban Planning and Design, from 2000 to 2010, 41% of urban population growth was contributed by megacities, superlarge cities, and large cities, and 37% came from counties and towns. Recent years have seen a significant decline in the population growth of overpopulated large cities with excessively strict entry restrictions. For instance, the number of permanent residents in Beijing and Shanghai has remained basically stable since 2016.

On the other hand, rural residents migrate to counties and small towns, which is another characteristic of urbanization in China. Currently, about one-fourth of Chinese people now lives in small towns. Until 2021, China had a total of 1,482 counties, with a total population of 139 million in built-up areas, and 19,072 designated towns, with a total population of 166 million in built-up areas. Since 2001, the residential building stock in designated towns has doubled, from 2.86 to 6.32 billion square meters.[2] Historically, the main function of such small towns with a population

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[1] Xiaojiang Li, Degao Zheng. Characteristics of the Urbanization of Population and Formation of the National Urban System.

[2] Source: *China Urban-Rural Construction Statistical Yearbook* (2006–2021), Ministry of Housing and Urban-Rural Development of the People's Republic of China.

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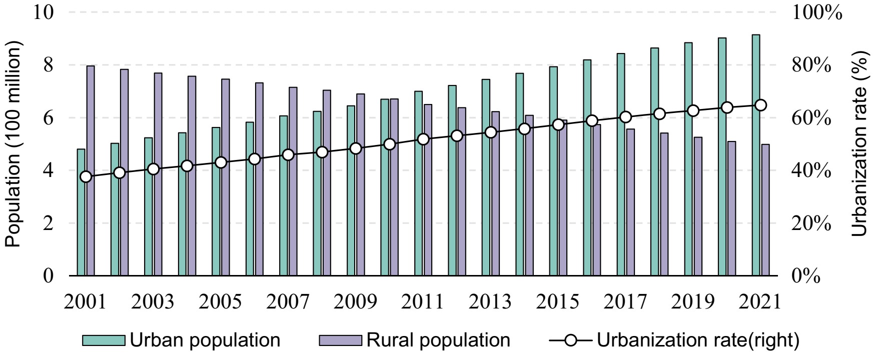


Fig. 1.1 Population growth in China by year (2001–2021)

of 10–100 thousand has been to provide surrounding rural areas with economic and trade, cultural, and medical services, and the support of their economic operation has been determined by the scale of surrounding agriculture, animal husbandry, and forestry they serve. The economic activities of these small towns have been dominated by the service sector, and it has been very difficult to arrange activities of the secondary industry there. As the proportion of urbanization rises and the agricultural population declines, the corresponding service functions of small towns also decrease accordingly. Housing vacancy occurs in these small towns when the ratio of their population to the surrounding rural population they serve is higher than a certain limit. How to plan the functions of these small towns and develop their infrastructure system represented by energy system scientifically and rationally to enable their sustainable development will be an important issue to be addressed in the new era.

1.1.2 Building Stock

Rapid urbanization drives continuous development of the construction sector, and the scale of China's construction sector has been expanding. From 2007 to 2021, thanks to the rapid growth of building construction in China, the floor space greatly expanded in urban and rural areas. Specifically, from 2007 to 2014, the newly built building stock for civil buildings grew steadily from 2 billion m^2 per annum to more than 4 billion m^2. From 2014 to 2019, the newly built building stock of civil buildings in China slowly decreased year by year, but basically remained above 4 billion m^2. In 2020, due to the impact of COVID-19, construction slowed down, and the newly built building stock of civil buildings dropped to 3.8 billion m^2. In 2021, the pandemic in China was getting better, and the newly built building stock of civil buildings rose again to 4.1 billion m^2. The total newly built building stock of urban residential buildings and public and commercial (P&C) buildings fell from about 3.6

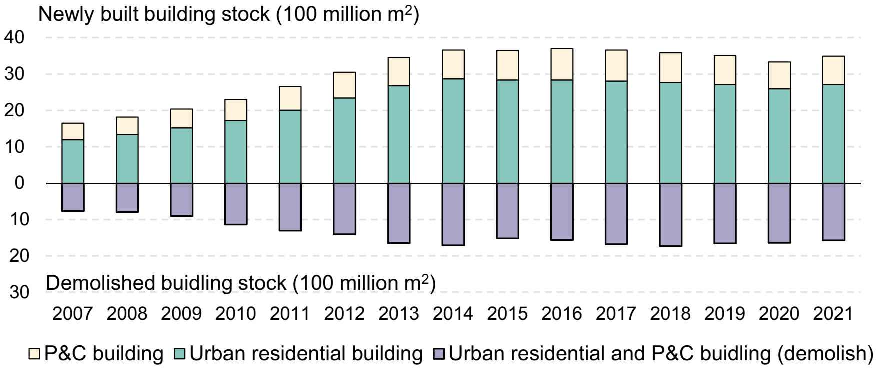


Fig. 1.2 Newly built and demolished building stock of civil buildings in China (2007–2021)

billion m^2 in 2014 to 3.34 billion m^2 in 2020 and then rose again to 3.49 billion m^2 in 2021 (Fig. 1.2). Driven by the large number of construction projects, the demolished building stock of urban residential areas and P&C buildings increased rapidly from 700 million m^2 in 2007 to a stable level of approximately 1.6 billion m^2 per year at present.

In 2021, residential buildings and non-residential buildings made up about 78 and 22% of the newly built building stock of civil buildings in China respectively. According to the difference in building functions, public and commercial (P&C) buildings can be categorized into offices, hotels, malls, hospitals, schools, and others. From 2001 to 2021, the main types completed each year were dominated by offices, malls, and schools. In 2021, the total newly built building stock of these three types accounted for about 70% of that of public and commercial (P&C) buildings, with the proportions of malls, office buildings, and schools at 29, 21, and 20% respectively. For the remaining types, hospitals and hotels had a smaller proportion of 7 and 3% respectively (Fig. 1.3).

Among the newly built building stock of civil buildings in 2021, the construction speed of urban residential buildings and P&C buildings was significantly higher than that in 2020. Among P&C buildings, the construction speed of schools and hospitals increased substantially compared to that in the previous year. The newly built building stock of school buildings increased by 13% and that of hospital buildings increased by 22% compared to those in the previous year.

Large-scale building construction activity has led to the rapid growth of China's building stock every year. In 2021, the total building stock in China was about 67.8 billion m^2, including urban residential buildings accounted for 30.5 billion m^2, rural residential buildings accounted for 22.6 billion m^2, and P&C buildings accounted for 14.7 billion m^2 (Fig. 1.4). The floor area for northern urban heating stood at 16.2 billion m^2.

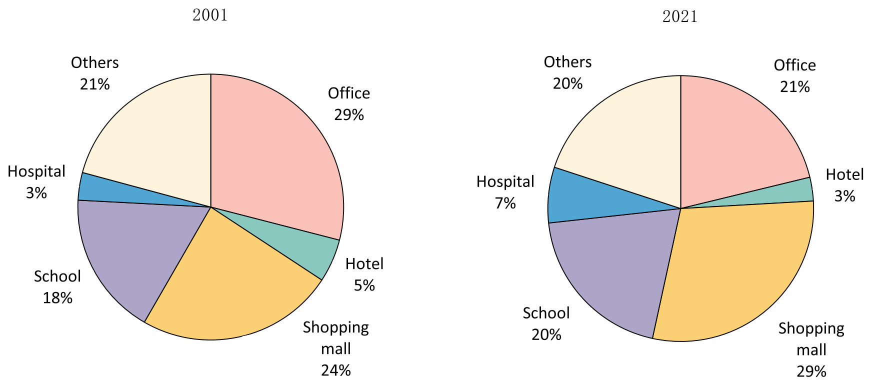


Fig. 1.3 Newly built building stock of P&C buildings according to different functions (2001, 2021)

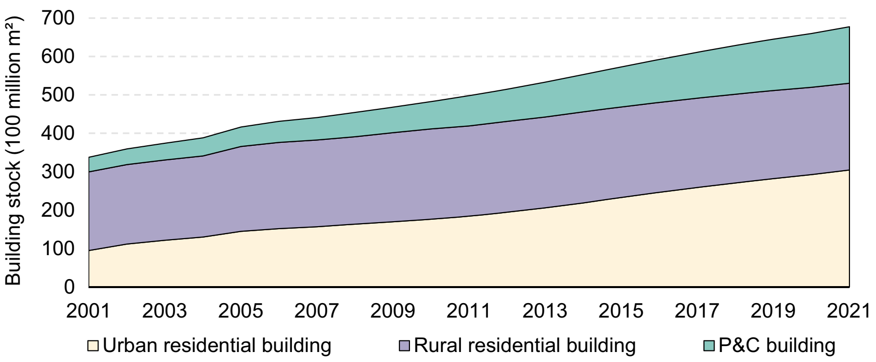


Fig. 1.4 China's existing building stock (2001–2021). *Source* Estimation results from CBEEM of the Building Energy Research Center (BERC), Tsinghua University. The newly built building stock entered in the model is the data under the statistical standards for construction enterprises as specified in the China Statistical Yearbook on Construction

1.2 Demarcation of China's Energy Consumption and GHG Emissions in the Building Sector

1.2.1 Calculation Method of Energy Consumption in the Building Sector

Energy consumption for the building sector covers different phases of buildings life cycle. In this report, the embodied energy consumption of buildings and the building operation energy consumption are analyzed respectively. The embodied energy consumption of buildings refers to the energy consumption of building material exploration, production, transportation and on-site construction and also includes the energy consumption during building demolition. In China's statistical standards, civil building construction, production building (non-civil building) construction, and infrastructure construction are included in the construction sector, so their energy consumption is collectively known as the embodied energy consumption related to the construction sector. Based on the China Building Energy and Emission Model of BERC, Tsinghua University, this book provides the analysis data of the standard for embodied energy consumption of China's construction sector and the standard for embodied energy consumption of China's civil buildings (see Sect. 1.3.2 for details).

Building operation energy consumption, which is the focus of this book, refers to the energy consumption from the operation of civil buildings, including the energy consumed by the provision of heating, ventilation, air conditioning, lighting, cooking, and domestic hot water (DHW) to occupants or users in residential buildings, office buildings, schools, malls, hotels, transportation hubs, recreational and sports facilities, and other non-industrial buildings, and energy consumed by service functions of such buildings. It is very difficult to distinguish the operational energy consumption of buildings that fully serve industrial production processes from the industrial production energy consumption, because the energy consumption in ventilation, air conditioning, and purification of factory buildings including metallurgical factory buildings and integrated circuit or pharmaceutical production factory buildings accounts for a very large proportion in the production energy consumption. However, it is very difficult to include such energy consumption in building energy consumption. Hence, this report does not discuss the buildings serving production processes and only studies civil buildings.

Based on our long-term research on the energy consumption of civil building operation in China and given the difference in heating methods in winter between northern and southern China, the difference in architectural forms and lifestyles between urban and rural areas, and the difference in personnel activities and energy use equipment between residential and P&C buildings, this report divides the building energy use in China into four categories, i.e. northern urban heating (NUH) energy use, urban residential building energy use (excluding NUH energy use), public and commercial building energy use (excluding NUH energy use), and rural residential building energy use, which are defined in detail as follows.

(1) NUH energy use

This refers to the energy consumption of heating in winter, including all forms of centralized heating and decentralized heating, in provinces, autonomous regions, and municipalities that adopt centralized heating, including all urban areas of Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Henan, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang as well as part of Sichuan. Heating is also needed in winter in Tibet, western Sichuan, and part of Guizhou, but should be considered separately as the local energy situations, issues, and characteristics are completely different from those in northern China. The reason for the separate calculation of NUH energy use is that centralized heating has been the main heating method in northern urban areas, including a large number of city-level heating networks and community-level heating networks. Different from other categories of building energy use, in which the calculation is based on the consumption of a single building or a single household, NUH energy use is largely related to the structural form and operation mode of a heating system, and the actual value of energy use is counted and calculated in a unified manner based on the heating system, so NUH energy use is taken as a separate category and treated differently from other categories of building energy use. Based on the form and scale of heat source systems, the current heating systems can be classified into centralized heating systems, which adopt such methods as large- and medium-scale coal-fired combined heat and power (CHP), large- and medium-scale gas-fired CHP, small-scale coal-fired CHP, small-scale gas-fired CHP, large coal-fired boilers, large gas-fired boilers, district coal-fired boilers, district gas-fired boilers, heat pump for centralized heating, residual heat from nuclear power and industrial residual heat, and household heating systems, which adopt such methods as household gas furnaces, household coal furnaces, air conditioners and heat pumps for decentralized heating, and direct electric heating. The main types of energy sources used include coal, gas, and electricity. This report studies the primary energy consumption, including the primary energy or electricity consumption at heat sources and the electricity consumption of equipment (fans and water pumps) serving heating systems. Such energy consumption can also be divided into the conversion loss from heat sources and heating stations, the heat loss and energy consumption of the distribution pipe networks, and the final heat gains of buildings.

(2) Urban residential building energy use (excluding NUH energy use)

This refers to the energy consumption of urban residential buildings, except for the heating energy consumption in northern China. In terms of energy end-users, it includes energy consumption of household appliances, air conditioners, lighting, cooking, and domestic hot water, as well as energy consumption of heating in winter in provinces, autonomous regions, and municipalities in the hot-summer and cold-winter (HSCW) zone. The main types of commercial energy sources used in urban residential buildings include electricity, coal, natural gas, liquefied petroleum gas (LPG), and city gas. Decentralized heating is mostly adopted in winter in the HSCW zone, and the energy consumption of the following heating methods all falls into this category: building space heating methods such as air source heat pumps and direct electric heating, and local heating methods such as fire pans, electric blankets, and electrical hand warmers.

(3) Public and commercial building energy use (excluding NUH energy use)

The public and commercial (P&C) buildings here refer to buildings where people carry out various public activities including office buildings, commercial buildings, tourism buildings, scientific research, educational, cultural, and medical buildings, communication buildings, and transportation buildings in urban and rural areas. Except for NUH energy consumption, the energy consumption of activities in buildings includes the energy consumption of air conditioning, lighting, sockets, elevators, cooking, and service facilities, as well as the energy consumption of heating of urban

P&C buildings in winter in the HSCW zone. The types of commercial energy sources used in P&C buildings include electricity, gas, fuel oil, and coal.

(4) **Rural residential building energy use**

This refers to the energy consumption of rural households, including cooking, heating, cooling, lighting, hot water, household appliances, etc. The main types of energy sources used in rural residential buildings include electricity, coal, LPG, gas, and biomass energy (straw and firewood). The consumption of biomass energy is not included in the national macrostatistics of energy. However, as an important part of rural residential building energy use, it will be listed separately in this report.

In this report, actual consumption of electricity other types of energy is counted and calculated separately whenever possible. If they have to be combined, all energy sources will be converted into primary energy sources for addition, namely, the electricity consumption will be converted into primary energy consumption calculated in standard coal based on the annual average coal consumption for power supply in China. As to the CHP method of centralized heating source for building operation, the input fuels are allocated based on the exergy values of output electricity and heat according to relevant provisions of the *Standard for Energy Consumption of Building* (GB/T 51,161-2016). In this report, the conversion coefficient for the exergy of heat is calculated based on an ambient temperature of 0 °C and a supply/return water temperature of 110 °C/50 °C, and the conversion coefficient for heat is 0.22.

1.2.2 Calculation Method of Carbon Emissions in the Building Sector

The embodied carbon emissions of buildings include the carbon emissions from the building material production, transportation, on-site construction, and demolition of civil buildings. In China's statistical standards, civil building construction, production building (non-civil building) construction, and infrastructure construction are included in the construction sector, so their carbon emissions are collectively known as the embodied carbon emissions related to the construction sector. Based on the China Building Energy and Emission Model of BERC, Tsinghua University, this report provides the analysis data of the standard for embodied carbon emissions of China's construction sector and the standard for embodied carbon emissions of China's civil buildings (see Sect. 1.4.2 for details).

Carbon emission during building operation mainly includes the carbon emission from the direct burning of fossil fuels and the indirect use of non-fossil energy during the operation of buildings, which consists of three main types:

1. **Direct carbon emission**: It refers to the direct emission of carbon dioxide in buildings by burning fossil fuels including coal, fuel oil, and gas. The carbon emission can be calculated based on the types of fuels and their different carbon emission factors.

2. **Indirect carbon emission from electricity use**: It refers to the carbon emission during the generation of electricity transmitted into buildings from the outside. The carbon emission can be calculated through the multiplication of the total external electricity used for buildings by the average carbon emission factor of electricity in the power grid, and the PV power generation and electricity consumption in buildings themselves are not counted.
3. **Indirect carbon emission from heating**: It refers to the indirect carbon emission resulting from centralized heating in northern urban areas. The centralized heating systems in northern urban areas adopt combined heat and power generation or centralized coal- and gas-fired boilers for the supply of heat. In this regard, carbon dioxide emitted by coal- and gas-fired boilers fall into the indirect carbon emission from building heating, while carbon emissions of combined heat and power generation plants are allocated according to exergy values of output electricity and heat. In this report, the conversion coefficient for the exergy of heat is calculated based on an ambient temperature of 0 °C and a supply/return water temperature of 110 °C/50 °C, and the conversion coefficient for heat is 0.22. That is to say, 22% of the output heat is treated as the equivalent electricity, which shares the total carbon dioxide emitted from power plants with the output electricity.

   In addition to carbon emissions, non-CO_2 greenhouse gas (GHG) emissions can also occur during building operation, which mainly refers to the GHG effect caused by the leakage of refrigerants from refrigeration and heat pump equipment in buildings, and is measured in carbon dioxide equivalent. This type of emission is analyzed in detail in Sect. 1.4.3. In this report, the China Building Energy and Emission Model (CBEEM) built by BERC, Tsinghua University is used to calculate and analyze all types of emissions in China's building sector (See Sect. 1.4 for details).

1.3 Energy Consumption of China's Building Sector

1.3.1 Building Operation Energy Consumption

The building energy consumption data in this chapter comes from the results of research with the China Building Energy and Emission Model (CBEEM) built by BERC, Tsinghua University, and is used to analyze the development of building energy consumption and carbon emissions in China. In 2021, the total commercial energy consumption of building operation was 1.11 gigatonnes of coal equivalent (Gtce), accounting for about 21% of the total energy consumption in China, and the commercial energy consumption and biomass energy consumption of buildings amounted to 1.2 Gtce (biomass energy consumption: about 0.09 Gtce), with details given in Table 1.1.

Table 1.1 Building operation energy consumption in China in 2021

Energy use category	Macro parameter	Electricity (10^8 kWh)	Fossil fuel (10^8 tce)	Commercial energy (10^8 tce)	Primary energy use intensity
NUH	16.2 billion m^2	770	1.89	2.12	13.1 kgce/m^2
Urban residential building (excluding NUH)	30.5 billion m^2	6051	0.96	2.78	769 kgce/household
P&C building (excluding NUH)	14.7 billion m^2	11,717	0.33	3.86	26.3 kgce/m^2
Rural residential building	22.6 billion m^2	3754	1.19	2.32	1,220 kgce/household
Total	1.41 billion people 67.8 billion m^2	22,292	4.37	11.1	

Note In the table, commercial energy consumption means the energy consumption calculated in standard coal converted from electricity, heat, and fuels, and electricity consumption specifically refers to the electricity consumption in the building energy use

From 2010 to 2021, the total energy consumption of buildings and electricity consumption increased dramatically, as shown in Fig. 1.5. The COVID-19 pandemic slowed down various social activities, and the growth in electricity consumption of buildings in 2020 was slower than that in 2019. However, as production and life returned to normal in 2021, the electricity consumption of buildings rose greatly. The electricity consumption of buildings in the whole society exceeded 2.2 PWh in 2020.

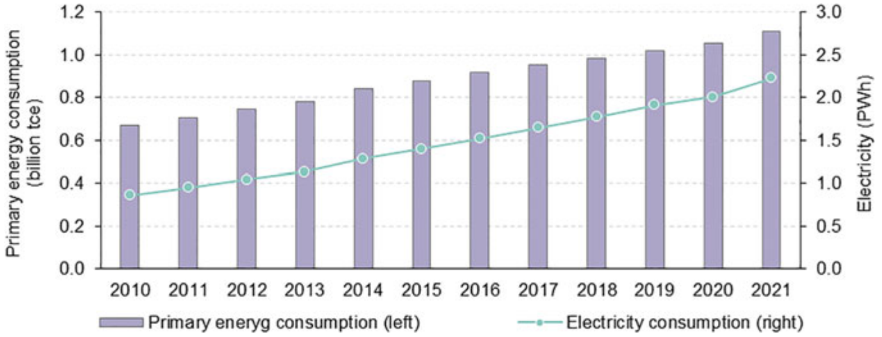


Fig. 1.5 Primary energy consumption and total electricity consumption of building operation in China (2010–2021)

The scale, intensity, and total quantity of the four categories of building energy use are represented in the four blocks in Fig. 1.6 respectively, in which the horizontal axis represents building floor area, and the vertical axis represents energy use intensity per square meter of building. The total area of the four blocks represents the total energy consumption of buildings. In terms of building floor area, urban residential buildings and rural residential buildings have the largest floor area, while the floor areas of NUH and P&C buildings account for about one-fourth and only one-fifth of the total, respectively. However, from the perspective of energy use intensity, the energy use intensity of P&C buildings and NUH is higher than that of the other two categories. Therefore, in terms of total energy use, each of the four categories accounts for about one-fourth of the total building energy consumption. In recent years, the growth in the scale and average energy use intensity of P&C buildings have made their energy consumption the largest proportion of the building energy consumption in China.

Figure 1.7 shows the changes in the total quantity and intensity of the four categories of energy use from 2010 to 2021. The total quantity and intensity in the four categories mainly exhibit the following characteristics:

- The energy use intensity in NUH was relatively large but has been decreasing with the improvement of the new energy-saving standards and the heat source efficiency

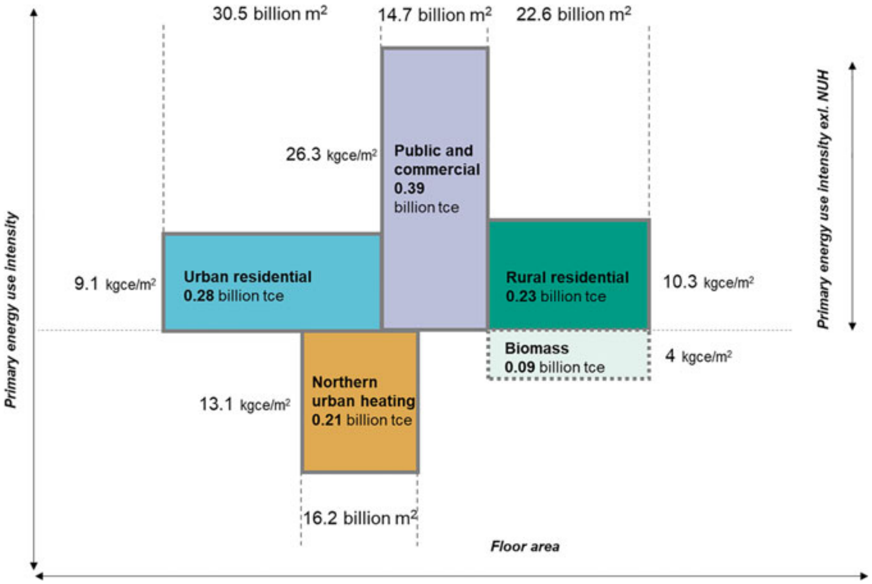


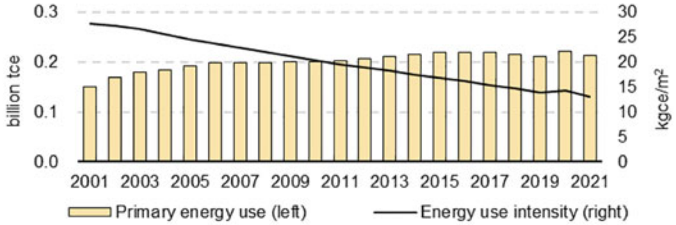
Fig. 1.6 Building operation energy consumption in China (2021). *Note* Electricity, heat, and fuels are uniformly converted into primary energy, which is measured in standard coal, and the electricity consumption is converted into primary energy consumption calculated in standard coal based on the annual average coal consumption for power supply in China. The conversion coefficient in 2021 was 302 gce/kWh

in recent years, and the total energy consumption remained stable without any further increase.

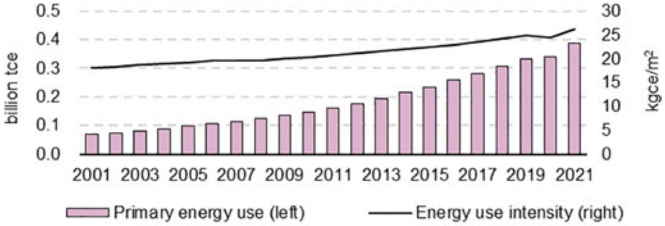
- Energy use intensity per unit area of P&C buildings continued to increase. The increasing terminal energy demand of P&C buildings (air conditioners, devices, lighting, etc.) was the major cause for the increase in building energy use intensity. In particular, some large new buildings with large-scale centralized systems have been constructed in many cities in recent years, with energy use intensity much higher than that of similar buildings. As the size of P&C buildings grows, their total energy consumption is still increasing.
- The energy use intensity per household of urban residential buildings increased because there was an increasing demand for domestic hot water, air conditioners, and household appliances. The issue of heating in winter in the HSCW zone also aroused extensive discussions. There was not too much increase in the energy consumption of lighting in residential buildings because of the adoption of energy-efficient illumination devices. The energy use intensity of cooking also remained unchanged. With the further promotion of urbanization and the growth in the size of urban residential buildings, their total energy consumption is still increasing.
- The commercial energy use intensity per household of rural residential buildings increased slowly. As the rural population and the number of households slowly decreased, commercial energy consumption in rural areas remained stable. However, as household appliances became more popular in rural areas and the policy of "switching from coal to electricity" was implemented for clean heating in northern China, electricity consumption has increased dramatically in recent years. Meanwhile, biomass energy use has dropped continuously. Hence, the total energy use of rural residential buildings has declined slowly in recent years.

(1) NUH

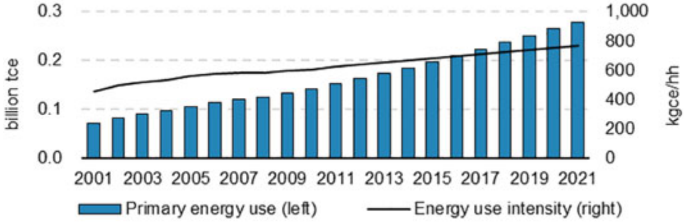
In 2021, the energy consumption of NUH was 212 million tce, making up 19% of the total energy consumption of buildings in China. From 2001 to 2021, the NUH area tripled from 5 to 16.2 billion m^2, while the total energy consumption increased, but did not double. Obviously, the increase in total energy consumption was less than the increase in building floor area, indicating that remarkable results had been achieved in energy saving. The average energy consumption per unit area of heating was 13.1 kgce/m^2 in 2021, a significant decline from 23 kgce/m^2 in 2001. Specifically, the main reasons for the decrease in energy use intensity include the improvement of building insulation, which resulted in the decrease in the heat demand of buildings, as well as the increased share of efficient heat sources, and the improvement of operation management. In recent years, the total energy consumption of NUH has been on a declining trend from the peak around 2017. Due to the COVID-19 pandemic, the heating time was extended to varying degrees in different places in the 2019–2020 heating season. According to the statistical data released in the 2022 Annual Report on Urban Heating Development in China, 75% of cities extended the heating time in the 2019–2020 heating season, so the total energy consumption in NUH went up a little in the 2019–2020 heating season.



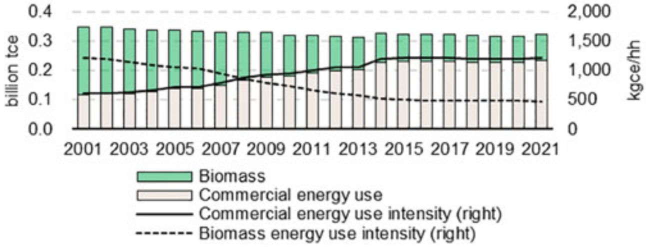
a) NUH



b) P&C building



c) Urban residential building



d) Rural residential building

Fig. 1.7 Changes in total building energy use and energy use intensity by year (2001–2021)

Gradual improvement of building envelope performance. In recent years, the Ministry of Housing and Urban–Rural Development of the People's Republic of China has adopted various methods to improve building insulation, including the establishment of building energy efficiency design codes that cover different climate zones and building types, the special examination of energy-saving work that started from 2004, and the renovation of existing residential buildings during the 13th Five-Year Plan period. During the 13th Five-Year Plan period, the energy efficiency design standard for new urban residential buildings in severe cold and cold areas in China was raised to "75% energy-saving standard", approximately 10 million square meters of ultra-low and near zero energy buildings completed construction, and 514 million square meters of existing residential buildings and 185 million square meters of P&C buildings completed the energy-saving retrofit. These methods have greatly enhanced building insulation in China and lowered the actual heating demand of buildings, especially in northern China.

Optimization of heat source structure and significant improvement of heat source efficiency. Recent years have seen a gradual increase in the share of efficient CHP to gradually replace boilers. The results of urban heating surveys in 2013, 2016, and 2020 (as shown in Fig. 1.8) revealed that the proportion of CHP in heat sources for NUH was 42, 48, and 55% respectively in the three years. Gas-fired boilers replaced coal-fired boilers. From 2013 to 2020, the proportion of coal-fired boilers dropped from 42 to 13%, while that of gas-fired boilers increased from 12 to 22%. In the meantime, all types of new heat sources kept on growing, with rising proportions of industrial residual heat, residual heat from nuclear power, ground-source heat pumps, and biomass in heating. Heating system efficiency has also been increasing notably in recent years, thus enabling the overall improvement of the efficiency of all types of centralized heating systems.

(2) Urban Residential Buildings (Excluding NUH)

Urban residential building energy consumption (excluding NUH) in 2021 was 278 million tce, accounting for one-fourth of the total commercial energy consumption in the building sector. Electricity consumption was 605.1 TWh. With the economic and social development and the improvement of living standards in China, the average annual growth rate of urban residential building energy consumption reached up to 7% from 2001 to 2021, and the terminal electricity consumption in 2021 quintupled that in 2001.

From the view of energy use, cooking, household appliances, and lighting consumed the most energy in urban residential buildings (excluding NUH) in China. Thanks to policies and projects for improving the energy efficiency of cooking, household appliances, and lighting, the terminal energy consumption of these three categories was kept under control, and the total energy consumption has undergone a slower increase in recent years. Improving energy efficiency and lowering standby energy consumption should become the optimal methods to limit the energy consumption of cooking, household appliances, and lighting. For example, the promotion of energy-saving lamps significantly improved the lighting efficiency of residential buildings. Energy efficiency standards and behaviors need to be upgraded

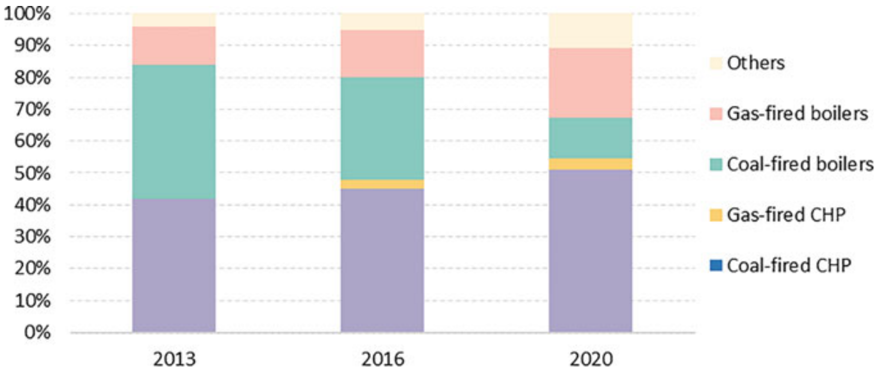


Fig. 1.8 Changes in structures of heat sources for NUH in 2013, 2016 and 2020

to lower the electricity consumption from long standby time and frequent reheating and restarting of household appliances. The production standards of such appliances as TV set-top boxes, water dispensers, and electric toilet seats need to be improved to lower the waste of energy when they are in standby mode. The methods, for example, include improving the controllability of set-top boxes, enhancing the insulation capacity of water dispensers, and adopting intelligent control of toilet seats. Policy incentives or subsidies shall not cover electric appliances such as clothes dryers, which may change the lifestyle, and we should watch for the energy spikes of these high energy consumption appliances. Even though the energy consumption of winter heating, summer cooling, and domestic hot water accounts for a smaller proportion in the HSCW zone and the energy consumption per household is at a low level, they have been growing rapidly. The annual average growth rate of heating energy consumption in the HSCW zone could be well over 50%. Therefore, saving terminal energy use for those three categories should be our priority in the next stage of energy saving for urban residential buildings. We should avoid the massive adoption of centralized systems, promote decentralized systems in residential buildings, improve the energy efficiency standards of distributed equipment, and prevent drastic energy consumption increases while improving the indoor service level. Refer to the *China Building Energy Use and Carbon Emission Yearbook 2021* for detailed discussions about the energy-saving and emission-reduction pathways for urban residential buildings in China.

(3) P&C Buildings (Excluding NUH)

In 2021, the total floor space of China's P&C buildings was approximately 14.7 billion m^2, and the total energy consumption of P&C buildings (excluding NUH) was 0.386 Gtce, making up 35% of that of the building sector. Electricity consumption stood at 1.17 PWh. The total area of P&C buildings and the proportion of large P&C buildings were all on the rise, which led to an increase in energy demand. The energy consumption per unit area of P&C buildings grew from 17 kgce/m^2 in 2001 to over 26.3 kgce/m^2 in 2021. The energy use intensity increased rapidly, and the total energy consumption surged as well.

In 2020, due to the impact of COVID-19, the operation duration and intensity of public and commercial buildings were subject to pandemic-related control measures, leading to a slight decrease in the average energy use intensity of public and commercial buildings in China. In 2021, the growth rate of energy used in the operation of public and commercial buildings picked up. Since 2001, the newly built building stock of P&C buildings amounted to almost 8 billion m^2, approximately 79% of the current stock. This means that three-fourths of P&C buildings were built after 2001. There are two reasons for this increase. First, a lot of new commercial buildings such as office buildings and commercial complexes have been constructed in recent years. Second, the scale of public service buildings such as schools, hospitals, and sports stadiums has increased due to the necessity for the gradual perfection of relevant infrastructure to promote the building of a well-off society in an all-around way and the improvement of public services. In recent years, the proportion of school and hospital buildings in the new public and commercial buildings has been increasing gradually. In 2021, there were more new hospital and school buildings than new office and hotel buildings.

While the stock of P&C buildings is growing, the number of large-scale P&C buildings is also increasing. In particular, many public and commercial buildings completed in recent years are large top-grade commercial buildings with central air-conditioning. Their electricity consumption per unit area is over 100 kWh/m^2, while the electricity consumption of smaller schools, offices, and stores built in the past is approximately 60 kWh/m^2. The average electricity consumption of public and commercial buildings will continue to increase as the proportion of such new public and commercial buildings with high energy consumption in the total number of public and commercial buildings has been on the rise. Due to the volume and form constraints of such new buildings, the energy use intensity of air conditioning, ventilation, lighting, and elevators in them is much higher than that in general public and commercial buildings. This is also an important cause of the continuous growth in the energy use intensity of public and commercial buildings in China. Refer to the *China Building Energy Use and Carbon Emission Yearbook 2022* for detailed discussions about paths toward energy saving and emission reduction for P&C buildings in China.

(4) **Rural Residential Buildings**

In 2021, the commercial energy consumption of rural residential buildings was 0.232 Gtce, accounting for 21% of the total energy consumption of buildings in China. Electricity consumption was 375.4 TWh, and the consumption of rural biomass energy (straw and firewood) was equivalent to about 0.09 Gtce. From 2001 to 2021, urbanization led to a decline of the rural population from 800 to 500 million, and the scale of rural residential buildings was maintained at approximately 23 billion m^2 and has begun to decrease slowly in recent years.

Owing to the higher availability of electricity in rural areas, higher income for rural residents, and more household appliances, the electricity consumption per household in rural areas has increased rapidly. For instance, the number of air conditioners per hundred households in rural areas increased from 16 in 2001 to 73.8 in 2020, which led to not only the growth of electricity consumption but also a longer peak power load in rural areas during summer. The implementation and promotion of "switching from coal to electricity" in northern China contributed to significant growth in winter heating electricity consumption and peak power load there. Moreover, increasing biomass energy has been replaced by commercial energy, leading to a rapid reduction of the proportion of biomass energy in household energy consumption in rural areas.

China released the *Work Plan for Implementation of the PV Poverty Alleviation Project* in 2014, which proposed the development of the photovoltaic (PV) industry in rural areas as an important means of poverty alleviation. A new energy system based on rooftop PV may be built by taking advantage of abundant renewable resources in rural areas. Such a system can realize the net power output to the power grid while meeting the energy demands of rural life, production, and transportation. It can totally cancel the use of fossil and biomass fuels while raising the living standard in rural areas. Thus, it will not only root out the environmental pollution and carbon emission problems caused by the burning of fossil and biomass fuels but also make the production and output of zero-carbon energy another important economic activity in rural areas. Besides, this can make an important contribution to the sustainable development of China's energy system and become an important part of the rural revitalization strategy.

In recent years, with the thorough implementation of haze control measures and clean heating in eastern China, governments at all levels and relevant enterprises have made huge investments to increase the power supply capacity, lay gas pipe networks and change original small household coal-fired furnaces into low-pollution forms in rural areas, which leads to a substantial increase in electricity and gas consumption. The change in rural energy structure will lead to a fundamental transformation of rural energy use patterns, thus facilitating the modernization of rural areas. This opportunity should be leveraged and scientific planning should be made to revolutionize rural energy supply and consumption and establish a new energy system with renewable energy sources as the mainstay for rural residents, which will play an important role in the current energy revolution of China.

1.3.2 Embodied Energy Consumption of Building Sector

China's continuous advancement of urbanization in the last two decades has also enabled the embodied energy consumption of civil buildings to become an important part of the total energy consumption of the whole society. A large quantity of building materials is needed, the production process of which lead to great energy consumption and carbon emissions. This is one of the key reasons for the continuing growth of energy consumption and carbon emissions in China.

According to the estimation from the BERC, embodied energy use of civil buildings in China amounted to 0.52 gigatonnes of coal equivalent (Gtce), accounting

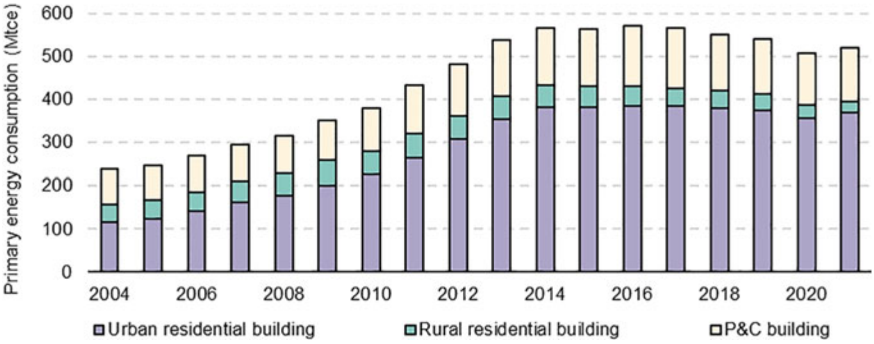


Fig. 1.9 Embodied energy use of China's civil buildings (2004–2021). *Source* Estimation by BERC, Tsinghua University. This figure only covers civil building construction[3]

for 10% of China's total energy consumption. The embodied energy use of civil buildings in China grew from 0.24 Gtce in 2004 to 0.52 Gtce in 2021, as shown in Fig. 1.9. Due to the slow decrease in the newly built building stock of civil buildings in recent years, its embodied energy use has also dropped gradually since 2016. The newly built building stock of civil buildings declined markedly in 2020 due to the impact of COVID-19 and rebounded in 2021 with the stabilization of the pandemic. As a result, the embodied energy of civil buildings fell considerably in 2020 from that in the previous year and rose again in 2021. In 2021, the embodied energy of urban residential, rural residential, and P&C buildings accounted for 71, 5, and 24%, respectively.

In fact, the construction sector consists of not only civil buildings but also buildings for production purposes and infrastructures such as motorways, railways, and dams. The embodied energy use of the construction sector mainly includes all types of energy use related to the construction of buildings and infrastructures. According to the calculation of BERC, Tsinghua University, the total embodied energy use of China's construction sector in 2021 was 1.37 Gtce, accounting for up to 26% of the primary energy consumption of the whole society. From 2004 to 2021, embodied energy use in China's construction sector grew from approximately 0.4–1.37 Gtce, as shown in Fig. 1.10. Embodied energy from building materials is the mainstay of the total embodied energy use of buildings, in which iron and steel and cement production consumes more than 80%.

The construction demands of rapid urbanization in China have not only driven the growth of energy consumption directly but also determined China's industrial structure which is dominated by traditional heavy and chemical industries including steel and cement. This is also a key reason for the high energy consumption per unit of industrial value added in China.

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[3] The newly built building stock data is based on the data under "the statistical standards for construction enterprises as specified in the *China Statistical Yearbook on Construction*".

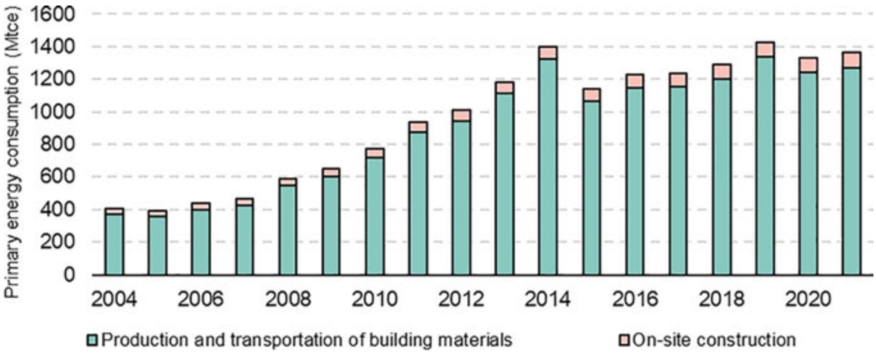

Fig. 1.10 Embodied energy consumption of China's construction sector (2004–2021). *Source* Estimation by BERC, Tsinghua University. The construction sector involves the construction of civil buildings, production buildings, and infrastructures[4]

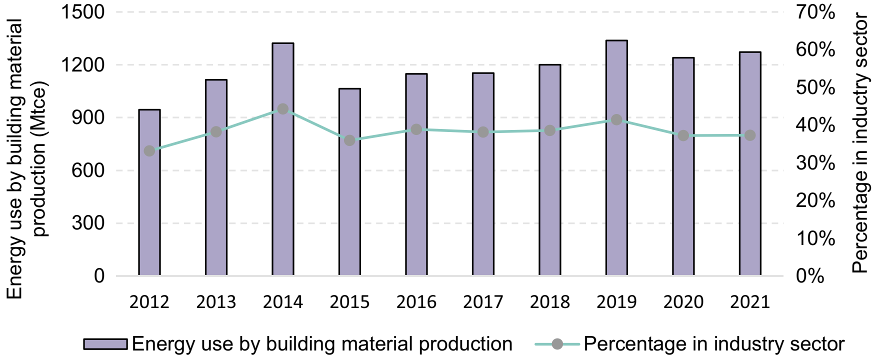

Fig. 1.11 Energy consumption for building material production[5]

There was 1.27 Gtce of industrial energy used for producing building materials in 2021. Between 2013 and 2021, building materials accounted for approximately 40% of the total industrial energy consumption, as shown in Fig. 1.11. The fast pace of urbanization in China drove the demand for building materials, which was the key reason why the higher percentage of total energy consumption was represented by iron and steel, building materials, and other traditional heavy industries.

As urbanization and infrastructure development have achieved initial progress in China, the transformation of the construction mode is ongoing. In 2020, the per capita floor area for urban residential buildings was 33 m^2 in China, which was close to that of some developed countries in Asia, such as Japan and South Korea, but still far

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[4] Data about the consumption of building materials is from the *China Statistical Yearbook on Construction*.

[5] Materials for the construction sector here mainly include steel, cement, aluminum, glass and architectural ceramics.

lower than that of the US. The reason was that during China's urbanization, the main type of building in the urban communities was apartments instead of single houses, such as that of the US. From the perspective of urban form, the utilization ratio of P&C buildings was high in China because of the high-density large city mode of development, so it is unnecessary to follow the per capita P&C building scale in Europe and America. In the future, there will be no more rapid growth of iron and steel, building materials, and other high energy consumption industries, so long as there is less demolition, and the building life cycle can be properly maintained. Therefore, for the next round of urbanization, the demolition of buildings that have not reached the end of life shall be abolished. Technologies to extend the building life cycle shall be invented. Buildings and infrastructures should be properly repaired, and the building life cycle should be extended to facilitate industrial transformation and total energy control.

1.3.3 GHG Emissions of China's Building Sector

1.3.3.1 Carbon Dioxide Emissions from Building Operation

The carbon dioxide emissions from building operation are affected by the growth in total energy demand of buildings, the improvement of building energy efficiency, and the adjustment of building fuel types and energy supply structure. Electricity, coal, and gas were the major energy sources for building operation. Electricity accounted for 70% of the total energy use in urban residential buildings and P&C buildings, in which CO_2 was indirectly emitted. The adoption of CHP in NUH could also lead to indirect CO_2 emissions. The percentage of coal and gas consumption was higher than that of electricity consumption for NUH and rural residential buildings. The percentage of coal and gas consumption was about 90% for NUH and the percentage of fossil energy consumption was about 50% for rural residential buildings, which led to massive direct carbon dioxide emissions. In another aspect, as the percentage of zero-carbon electricity has increased in China, the average emission factors have declined tremendously, at 558 gCO_2/kWh in 2021. Besides, the share of electricity consumption in building operation energy consumption gradually increased as well. These two trends have promoted the low-carbon development of building operation energy consumption.

According to the analysis results from CBEEM, in 2021, the total carbon emissions during building operation in China were 2.2 billion tonnes of carbon dioxide (Gt CO_2), equivalent to 1.6 t per capita carbon emissions and 32 kg/m^2 of average carbon emissions per unit area. In the total carbon emissions, the proportions of direct carbon emissions (0.51 Gt CO_2), indirect carbon emissions from electricity use (1.24 Gt CO_2), and indirect carbon emissions from heating (0.43 Gt CO_2) were 23, 57, and 20%, respectively, as shown in Fig. 1.12.

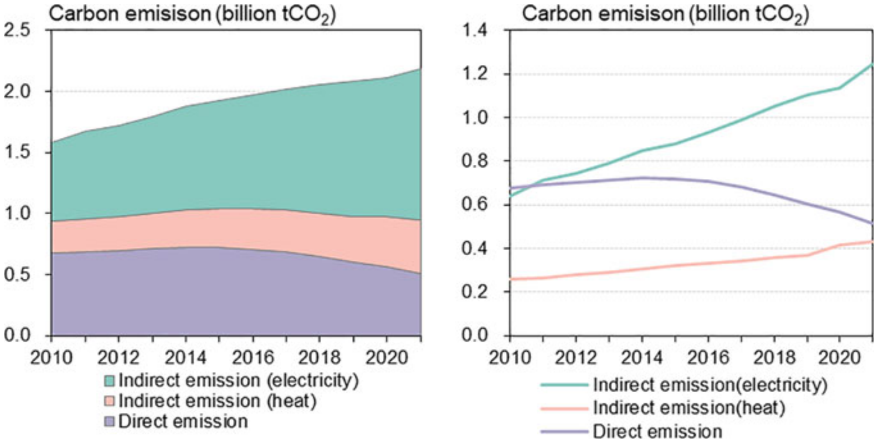

Fig. 1.12 Carbon dioxide emissions from building operation (2021)

(1) Direct Carbon Emission

In 2021, the direct carbon emissions of buildings were 510 million tons of CO_2, including about 230 million tons of CO_2 directly emitted from urban and rural cooking, about 150 million tons of CO_2 emitted from household gas- and coal-fired heating boilers,[6] and 130 million tons of CO_2 directly emitted from natural gas consumption for hot water, steam boilers, absorption refrigeration, and other purposes. Emissions from rural areas accounted for more than half of the direct carbon emissions.

In recent years, with the vigorous promotion of "switching from coal to electricity", "switching from coal to gas" and clean heating in rural areas, the direct carbon emissions in the building sector of China have been declining slowly from the peak around 2015. Direct carbon emissions of the building sector will continue to decrease and no longer reach a new peak as long as electrification is continuously promoted in new buildings.

To reduce direct carbon emissions of the building sector to zero, the key lies in the point-in-time and intensity of promoting "electrification". It is expected that direct carbon emissions of buildings will be reduced to zero during 2040–2045. Analyses indicate that electrification will not increase the operation cost in 80% of all cases and that the initial investment in equipment will be returned in about 5 years through the reduction of operating cost. Therefore, the major obstacle to promoting electrification in buildings is not economic cost but the change in the concept of energy use and cooking culture. Increasing the publicity of "zero carbon emissions of buildings by electrification" among the public and promoting "switching from gas to electricity"

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[6] Refers to gas- and coal-fired heating boilers installed in urban and rural residential buildings as well as coal- and gas-fired boilers installed in public and commercial buildings. Such fuels are burned directly in buildings, so the resulting carbon emissions fall into the category of direct carbon emissions from buildings.

in new and existing buildings are the most important approaches to realizing zero direct carbon emissions from building operation.

(2) Indirect Carbon Emission from Electricity Use

In 2021, the electricity consumption by building operation in China was 2.2 PWh, and the indirect carbon emission from electricity use was 1.24 billion tons of CO_2. At present, the per capita electricity consumption of the building sector in China is one-sixth of that in the US and Canada and about one-third of that in France and Japan, while the electricity consumption per unit area of buildings in China is one-third of that in the US and Canada. The difference in lifestyle and building operation is one of the main reasons for the difference in electricity use intensity between China and developed countries.

In recent years, the carbon emission increase caused by the growth in electricity consumption of buildings has exceeded the carbon emission decrease resulting from the reduction of the carbon emission factor of electricity. The indirect carbon emissions from electricity consumption of buildings will keep increasing before peaking. China should maintain a green and economical lifestyle and building operation mode to avoid any surge in energy use of buildings that once occurred after rapid economic growth in the history of the US, Japan, and other developed countries. When the building floor area in China reaches 75 billion m^2 in 2060, the electricity consumption of buildings should be 3.8 PWh, which will meet the demand of the Chinese people for a good life and energy consumption of buildings. On this basis, the new type of electric power system adopting "photovoltaic, energy storage, direct current and flexibility (PEDF)" technologies should be promoted. When the reduction in indirect carbon emissions from building electricity use caused by the increase of "green electricity" in practical electricity consumption through flexible electricity use is greater than the growth in indirect carbon emissions from building electricity use caused by the growth in the total scale and electricity use intensity of buildings each year, the indirect carbon emissions from the electricity use of buildings in China can peak. Upon overall popularization of the "PEDF" power distribution mode and flexible means of electricity use, the zero-carbon goal for electricity consumption of buildings can be achieved earlier than that for the national power system.

(3) Indirect Carbon Emission from Heating

In 2021, the building floor area of NUH in China was 16.2 billion m^2, and the indirect carbon emission from heating during building operation was 430 million tons of CO_2. Recent years have seen continuous growth in the centralized heating area and heating demand in northern China but a continuous decrease in energy consumption and carbon emissions per square meter of heat supply. The total indirect carbon emissions from NUH showed a trend of slow growth. The indirect carbon emissions from heating during building operation can peak by around 2025 through further strengthening the renovation of existing buildings, fully exploiting low-grade residual heat resources, and phasing out scattered coal-fired boilers. Afterward, with the gradual completion of the zero-emission transformation of the remaining thermal power (to be replaced with CCUS and biomass fuel) by the electric power sector, the indirect carbon emissions from building heating can be reduced to zero in sync with the decarbonization process of the power system.

To this end, it is necessary to continue improving the envelope performance of new buildings and the renovation of existing buildings in a strict manner, so that the average heating demand of buildings in northern China can decrease from 0.37 GJ/m^2 at present to below 0.25 GJ/m^2. During 2020–2035, the return water temperature should be lowered through the terminal renovation of centralized heating systems, thus effectively recovering the residual heat of thermal power plants and the industrial low-grade residual heat. The increasing building heating demand will be met by tapping into the potential heating capacity of existing heat sources. CHP transformation will be carried out for the coastal nuclear power in northern China to supply heat to areas within 200 km from the normal of coastal northern China. From 2035, in coordination with the schedule of the thermal power shutdown of the electric power system, seasonal heat storage projects will be implemented simultaneously to solve the problem of reduced heat source power resulting from the shutdown of thermal power plants. Until 2045, the annual residual heat of nuclear power, the annual residual heat of peak shaving thermal power, the residual heat of wind and solar curtailments at the centralized wind and solar PV power bases, as well as the heat emitted annually from the industrial low-grade residual heat will have been collected through seasonal heat storage projects. In this way, the indirect carbon emissions from building heating can be reduced to zero, while zero-carbon emission of the power system is realized.

In view of the four categories, the scale, intensity, and total quantity of carbon emissions from them are represented in the block diagram in Fig. 1.13 respectively, in which the horizontal axis stands for the building floor area and the vertical axis for carbon intensity per square meter for the four categories. The total area of the four blocks represents the total carbon emissions. The growth in the total carbon emissions from the four categories is shown in Fig. 1.14. It can be seen that the characteristics of carbon emissions from the four categories are not the same as those of their energy consumption. As public and commercial buildings have the highest energy use intensity, their carbon intensity per unit area is also at the peak. In 2021, their carbon intensity was 48.9 kg CO_2/m^2, and their total carbon emissions were still on the rise as their total energy consumption and energy use intensity were growing steadily. For NUH, its carbon intensity was only second to that of public and commercial buildings due to the consumption of a lot of coal. In 2021, the carbon intensity was 29.7 kg CO_2/m^2, and the carbon emissions peaked and remained stable at approximately 0.5 Gt CO_2 due to the increasing heat demand, the improvement of heat supply efficiency, and the consistent speed in the transformation of energy structure. Although there is little difference in primary energy use intensity per square meter between rural and urban residential buildings, the carbon intensity per square meter of rural residential buildings is higher than that of urban residential buildings due to a low level of electrification and a high proportion of coal fuel. The carbon intensity per unit area of rural residential buildings was 21.7 kg CO_2/m^2. Due to the implementation of "switching from coal to electricity" and "switching from coal to gas" in rural areas, the total carbon emissions of rural residential buildings have

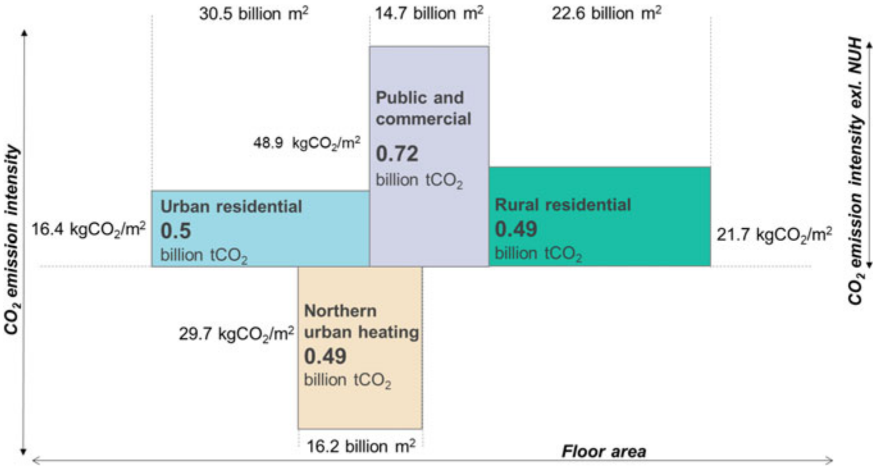

Fig. 1.13 Carbon dioxide emissions from building operation in China (2021)

peaked and then declined annually in recent years. The carbon intensity per unit area of urban residential buildings was 16.4 kg CO_2/m^2 and was increasing slowly with the growth in electricity consumption.

1.3.4 Embodied CO_2 Emission of Building Sector

As urbanization continues, the embodied energy use of civil buildings in China also increases rapidly. The construction of buildings and infrastructures not only consumes a colossal amount of energy but also leads to a lot of carbon dioxide emissions. In addition to carbon dioxide emissions resulting from energy consumption, emissions in the cement production process[7] are also an important part.

In 2021, the total carbon emissions from civil building construction in China were about 1.6 Gt CO_2, mainly including carbon emissions from energy use for the manufacturing and transportation of building materials (77%), the industrial process emissions of cement (20%) and energy use during construction (3%), as shown in Fig. 1.15. Although such carbon emissions are included in the industry and transportation sectors, they are driven by the demand of the building sector. Hence, the building sector shall also be responsible for such carbon emissions and reduce its demand to contribute to emission reduction. With the end of the large-scale construction period in China, the scale of newly built building stock has been decreasing each year. The carbon emissions from civil building construction peaked in 2016 and have been declining slowly year by year in recent years. The scale of

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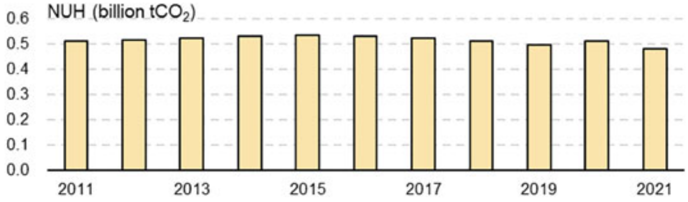
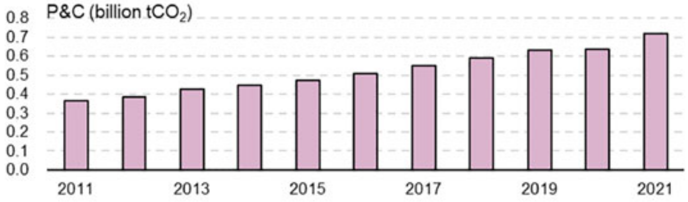
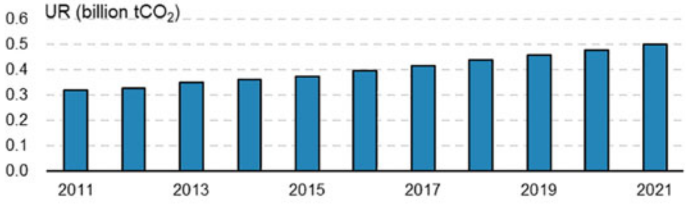
[7] Refers to carbon emissions from chemical reactions (excluding combustion) for cement production.



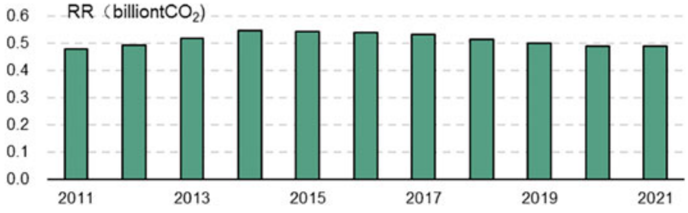
a) NUH



b) P&C building



c) Urban residential building



d) Rural residential building

Fig. 1.14 Carbon emissions of building energy use (2011–2021)

newly built building stock declined markedly in 2020 due to the impact of COVID-19 and rebounded in 2021 as the pandemic in China was getting better. As a result, the embodied carbon emissions of civil buildings fell heavily in 2020 and rose again in 2021.

In fact, as China is still in the urbanization stage, various infrastructures need to be constructed in addition to civil buildings. In 2021, the total carbon emissions from

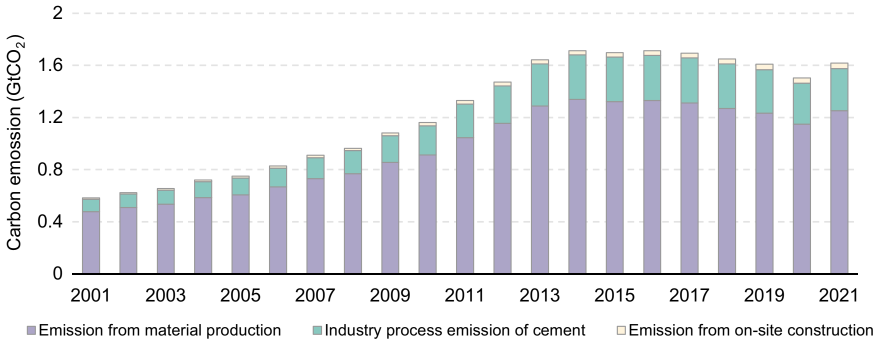


Fig. 1.15 Embodied carbon emissions of civil buildings in China (2004–2021). *Source* Estimation by BERC, Tsinghua University. Civil building construction is included only

construction in the construction sector were about 4.1 Gt CO_2, nearly half of China's total carbon emissions, as shown in Fig. 1.16. Carbon emissions from civil building construction were about 40% of the total carbon emissions from construction in China's construction sector.

To realize zero carbon emissions from building construction as early as possible, the total number and scale of buildings should be controlled reasonably first to minimize excessive construction and avoid large-scale demolition and construction. At present, the total building stock and per capita floor area in China have met the demands of urban and rural residence, production, and living. By 2060, the production and living demands of the future urban and rural populations in China can be met with 40 m^2 of per capita residential floor area, 15.5 m^2 of per capita P&C building stock, and 75 billion m^2 of total floor area. To realize zero-carbon emissions from building construction in China, the construction speed, total quantity, and scale of buildings need to be planned rationally.

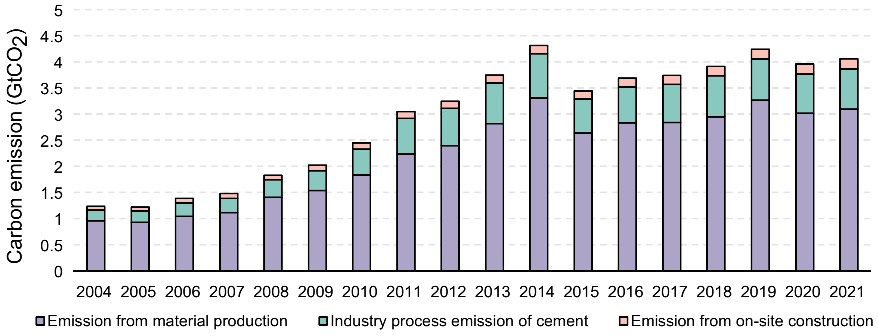


Fig. 1.16 Embodied carbon emissions of the construction sector in China (2004–2021). *Source* Estimation by BERC, Tsinghua University. The construction sector involves the construction of civil buildings, production buildings, and infrastructures

In the meantime, China's construction sector will shift from the large-scale construction of new buildings to the maintenance and functional improvement of existing ones. The construction of houses in China has shifted from increasing the supply of houses to meet immediate needs to demolishing old ones and building new ones to improve building performance and functionality. The "Mass-Demolition-for-Mass-Construction" pattern has become the main mode of the construction sector. Based on the objective of total number planning for civil buildings in the future and in view of the reasonable construction speed, the gradual transformation from "Mass-Demolition-for-Mass-Construction" to "replacing demolition with fine repair" will enable the stabilization of China's construction sector and the gradual reduction of carbon emissions from civil building construction to 0.2 Gt CO_2. Zero emissions from building construction are expected to be realized in 2050 through further application of new building materials and new structural systems and technologies.

Chapter 2
Comparison of Energy Consumption and Carbon Emissions from Building Operation Between China and Other Countries

2.1 Energy Consumption and GHG Emissions in the Global Building Sector

2.1.1 Energy Consumption by Global Building Operation

According to the International Energy Agency's (IEA) calculation of global energy use and emissions of the building sector (as shown in the figure below), in 2021, the embodied energy consumption during the global building construction stage (including building and infrastructure construction) and the building operation energy consumption accounted for 37% of the total global energy consumption, in which the embodied energy consumption during building and infrastructure construction accounted for 7% and the energy consumed during the operation stage accounted for 30%. In 2021, the total global CO_2 emissions (including energy-related and industrial process emissions) were 36.3 Gt CO_2, in which the embodied CO_2 emissions from construction (including building and infrastructure construction) in the construction sector accounted for 12% and the CO_2 emissions from building operation accounted for 28% (Fig. 2.1).

According to BERC's calculation of China's building energy use and emissions, in 2021, China's embodied energy use and operational energy use in the building sector accounted for 31% of the total social energy use,[1] which was close to the global level. However, China's building embodied energy use was 10% of the total social energy use, higher than 7% of the global level. If coupled with the embodied energy use for production building and infrastructure construction, China's building embodied energy use will be up to 26% of the total social energy use. The building

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[1] The primary energy consumption method is adopted for conversion. The heat consumption and electricity consumption of buildings are converted by the coefficient of coal consumption for thermal power supply into primary energy consumption, which is then added together with the consumption of other energy types at terminals.

Building Energy Research Center of Tsinghua University,
Decarbonize Urban Heating System, https://doi.org/10.1007/978-981-99-7875-5_2

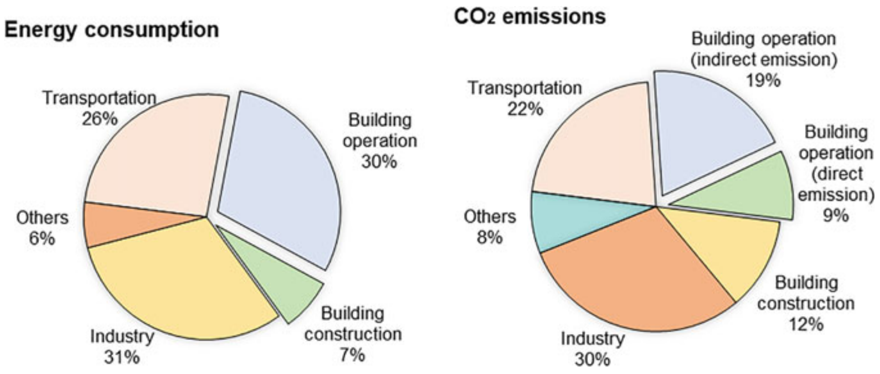

Fig. 2.1 Energy use and CO_2 emissions in the global building sector (2021). *Source* 2022 Global Status Report for Buildings and Construction, International Energy Agency. The construction sector involves civil building construction, production building construction, and infrastructure construction. This figure uses the terminal energy consumption data provided by IEA, which is obtained through the direct addition of heat consumption for heating, electricity consumption of buildings, and terminal use of various energy types. The electricity consumption is converted to primary energy using a calorific value equivalent method. This conversion method is different from that used in the comparison of building energy consumption among countries in the ensuing part of this research, so it should be treated differently in data comparison

operation energy use accounted for 21% of the total and was still lower than the global average. In the future, the share of China's building sector energy use will continue to increase with economic and social development and the improvement of living standards.

In terms of CO_2 emissions, in 2021, China's total social carbon emissions (including energy-related and industrial process emissions) were about 11.5 Gt CO_2, in which the embodied CO_2 emissions from building construction and the CO_2 emissions from building operation accounted for approximately 33%, including 14% from building construction and 19% from building operation (Fig. 2.2). If the energy-related CO_2 emissions were considered only, the CO_2 emissions from energy consumption of the whole society in China could be about 10.3 Gt CO_2 in 2021, including about 22% from building operation.

As China's urbanization is still ongoing, the major share of energy consumption and emission has come from building and infrastructure construction. The share of embodied energy consumption from building construction in China is higher than the global average and also higher than that of member countries of the Organization for Economic Co-operation and Development (OECD) that have already been urbanized. However, compared with those in OECD member countries, the building operation energy consumption and carbon emissions in China are at a lower level. As urbanization becomes slower in China, the proportions of building operation energy consumption and related emissions in the social total will further increase. China

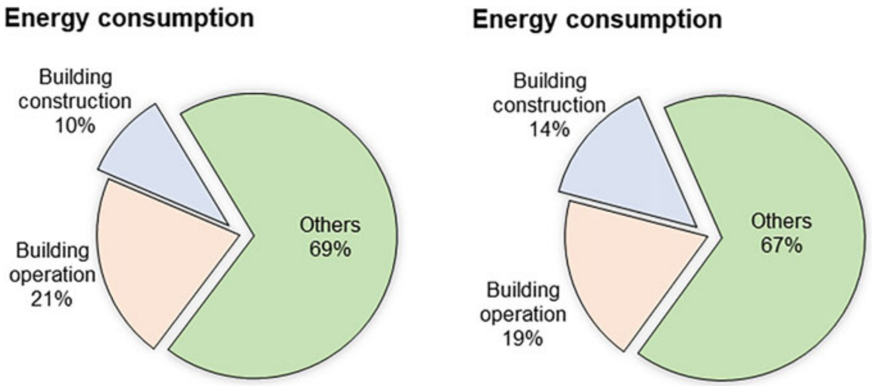

Fig. 2.2 China's building energy use and CO_2 emissions (2021). *Source*: Estimation with CBEEM of BERC, Tsinghua University. The construction sector involves the construction of civil buildings, production buildings, and infrastructures. The diagram on the right illustrates the structure of China's total social carbon emissions (including energy-related and industrial process emissions)

will gradually shift the focus of its building energy efficiency and low-carbon work from the low-carbon development of new buildings to the low-carbon operation of existing ones.

2.1.2 Boundaries and Comparative Study Methods of Building Energy Consumption and Emissions

Comparing building energy consumption among countries is an important means to know the building energy consumption in China, analyze its future development trend, and design the paths of building energy saving. In this section, the building operation energy consumption and carbon emission data of countries in the world are collected and analyzed through comparison. To ensure data comparability and better reflect actual energy use, the energy consumption data in this study only included commodity energy and did not include biomass energy that was not circulating.

Two types of data are collected to compare building energy consumption among countries. The first type includes population, the number of households, and the floor area of buildings. The other is building energy consumption data, which mainly includes the total consumption of electricity, heat, coal, natural gas, and other fuels during building operation. The building energy data of countries around the globe collected in this study mainly comes from two sources:

(1) Databases of international organizations and agencies: mainly including IEA, Odyssee, World Bank, and Eurostat databases;
(2) Official statistics of countries: For example, Japan's data mainly comes from the *Statistical Handbook of Japan* and the *Japan Statistical Yearbook* published

by the Statistics Bureau of Japan. The data on the US is mainly sourced from the periodic surveys conducted on representative buildings of the country and the statistics released per year by the Energy Information Administration(EIA). Canada's data mainly comes from Natural Resources Canada. The data on South Korea mainly comes from the building information statistics of the Ministry of Land, Infrastructure, and Transport and the KOSIS data. The data of India is mainly from the National Statistical Office (NSO) and the Ministry of Statistics and Programme Implementation (MoSPI).

(3) Some published research reports and literature also provide important support and reference for this study as they have studied the building energy and emissions in various countries and provided quantitative data.

(1) Calculation of Building Energy Consumption

In the analysis and comparison of building energy consumption, it is necessary to add the consumption of all types of energy in buildings together to get the total building energy consumption, on account of the different percentages of electricity, fuels, and heat used for building operation in various countries. At present, the end-use energy consumption method and the primary energy consumption method are commonly used for calculation. In the context of the low-carbon energy transition, the development trend of building energy use in various countries is to achieve full electrification. With the gradual increase in the percentage of electricity in the energy structure, it will be more meaningful to convert all categories of energy use into electricity and then add them together to get the total energy consumption of buildings. Therefore, the total energy consumption of buildings is calculated in this section through the conversion of various types of energy into electricity. To decouple the level of building energy use and the level of the energy conversion system, a unified energy conversion factor benchmark is used for the conversion between each fuel and electricity in this study. Under the principle of the energy conversion factor benchmark, the total global building energy use can be directly allocated to the global primary energy, and the energy conversion systems have positive and negative values respectively to reflect their efficiency (high or low) and energy structure (good or bad), and the sum is zero. The energy conversion factor benchmark theoretically means the global average conversion level, namely the global average of the power generation capacity of each fuel. The energy conversion factor benchmark used in this section are listed in the table below (Table 2.1):

Table 2.1 Energy conversion factor benchmark in the calculation of total energy consumption of buildings in various countries

Energy	Unit	Conversion factor benchmark
Coal	gce/kWh	300
Oil	goe/kWh	191
Natural gas	Nm^3/kWh	0.2
Heat from boiler	kWh/GJ	133
Heat from CHP	kWh/GJ	70

(2) **Calculation of Carbon Emissions from Buildings**

The data on carbon emissions from building operation of different countries in this section is sourced from IEA and the calculation results of the CBEEM model by BERC, Tsinghua University. When calculating the total carbon emissions from building operation, the direct carbon emissions, indirect carbon emissions from electricity use, and indirect carbon emissions from heating in buildings were considered. When calculating indirect carbon emissions from building electricity use, the total carbon emissions from electricity generation in each country were divided by the total electricity generation to obtain the average carbon emission factor for electricity use in each country. The carbon emission factor was used to calculate indirect carbon emissions from building electricity use. Carbon emissions from building heat use were calculated with the building heat use and the carbon emission factor per unit of heat. In the study of the building operation energy consumption in each country, various types of energy were converted into electricity by taking a unified conversion factor benchmark as the conversion coefficient. In the study of carbon emissions from building operation in each country, the real carbon emission factor instead of a unified carbon emission factor was used to calculate the real carbon emissions because carbon emissions from buildings are closely related to the energy structure and must be discussed together with the energy structure and the energy conversion system.

For carbon emissions during building operation, each country proposed a goal to reduce carbon emissions in the building sector. The technical pathways and priorities to achieve carbon neutrality in buildings differ between countries. To quantify and analyze the various problems confronted by each country in their attempt to achieve carbon neutrality in the building sector, the carbon emission factors for electricity and heat of each country were used in the calculation. Therefore, differences in the energy mix and efficiency among countries will affect the total amount and intensity of carbon emissions during building operation.

2.2 Energy Consumption and Carbon Emissions in the Building Sector of Different Countries

2.2.1 Building Operation Energy Consumption of Different Countries

Three indicators were selected to compare building energy use across countries: total amount, energy use per capita, and energy use per floor area, as illustrated in Fig. 2.3. The building energy use in this figure was calculated by adopting the electricity-equivalent method to calculate the total energy use of building operation. Energy use intensity per capita and energy use intensity per floor area are shown on the horizontal and vertical axes, respectively. The size of the bubbles represents

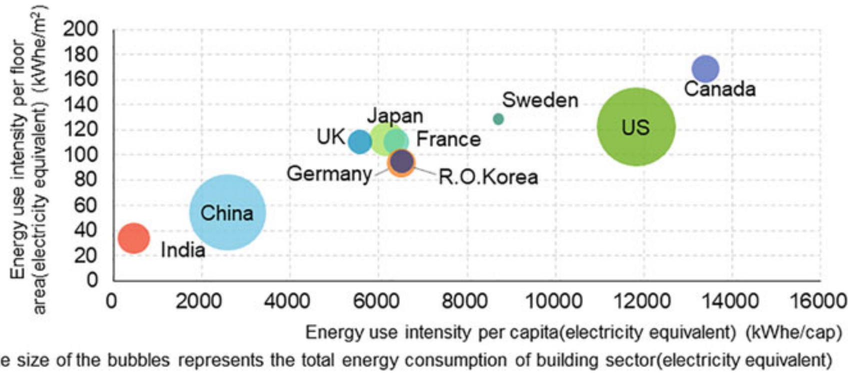

Fig. 2.3 Comparison of building operation energy consumption in different countries (electricity equivalent method). *Source* CBEEM of BERC, Tsinghua University; World Energy Balances, Energy Efficiency Indicators database (2022 edition) of IEA; WDI database of the World Bank; Satish Kumar (2019) of India.[2] Data from 2021 is adopted for China, data from 2019 for Canada, Germany, and Sweden, and data from 2020 for other countries

the total energy use for building operation in specific countries. The bubble chart demonstrates that total energy use for building operation in China was similar to that in the US, although the energy use intensity remained at a lower level. The energy consumption per capita and per floor area in China were far lower than those in the US, Canada, Europe, Japan, and South Korea. The equivalent electricity consumption per capita for building operation was about one-fifth of that in the US and Canada and about half that in Japan and South Korea. The equivalent electricity consumption per floor area for building operation was one-third of that in Canada and half that in the US, Europe, Japan, and South Korea. In the context of tackling climate change and reducing carbon emissions, most countries are carrying out energy transformations, including promoting electrification in the building sector and replacing fossil fuel-based energy with renewable electricity. China needs to develop a different route from developed countries to achieve the target for low carbon emission and energy-saving in the building sector. This would pose a significant challenge to China's low-carbon and sustainable development in the building sector. Meanwhile, many developing countries are experiencing rapid changes in building energy use. China's building energy development pathway will serve as an important reference for many countries' choices, which will further influence global building energy development.

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[2] Satish Kumar et al. (2019). Estimating India's commercial building stock to address the energy data challenge. Building Research & Information, 2019, 47, 24–37.

2.2.2 *Carbon Emissions from Building Operation in Different Countries*

Several countries have set their own goals for achieving carbon neutrality and their paths to achieving carbon neutrality in the building sector. Reducing carbon emissions in the building sector is also one of the important fields to realize carbon neutrality in the whole society. Figure 2.4 shows the total carbon emissions from building operation (bubble chart area), per capita carbon emissions (horizontal axis), and carbon emissions per unit building floor area (vertical axis) of different countries, which are converted according to the energy structures of these countries. The bubble chart of carbon emissions demonstrates that carbon emissions in the building sector are affected not only by the total energy consumption but also by the energy structures of these countries. The per capita carbon emissions and carbon emissions per unit floor area from building operation in China are lower than those in most developed countries due to China's low building operation energy consumption. However, the energy structure of France is dominated by low-carbon nuclear power; although it has higher building energy use intensity than China does, its carbon intensity is lower than that of China. This also shows that the low-carbon transition of both energy systems and building energy use structure should be achieved in addition to the improvement of energy saving and energy efficiency of buildings on the path toward carbon neutrality.

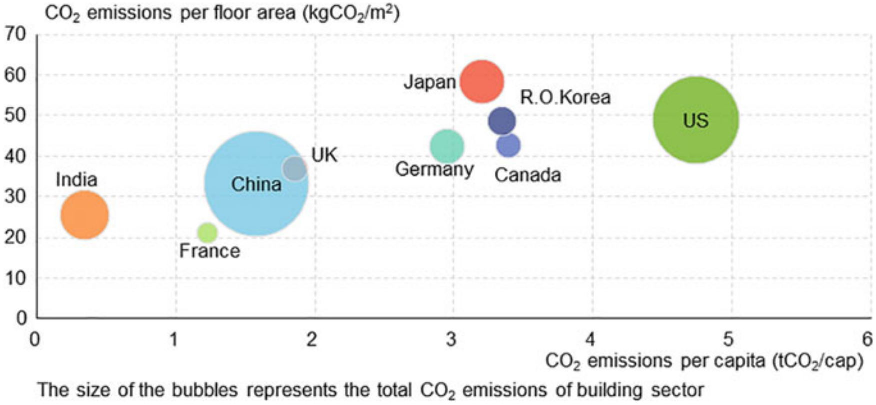

Fig. 2.4 Comparison of per capita carbon emissions of different countries (2020). *Source* Data of countries in 2020 as provided in the CO_2 Emissions from the Fuel Combustion Highlights 2021 database, IEA. Data from China are the results of 2021 as estimated with CBEEM of BERC, Tsinghua University

2.3 Comparison of Energy Consumption and Carbon Emissions from Building Space Heating Among Countries

Energy efficiency improvement and low-carbon transition of building heating are important tasks to achieve carbon neutrality in the building sector. The scenarios of space heating in China varied significantly from north to south. The northern regions mainly adopt the centralized district heating systems with a continuous heating mode, and the key to their energy efficiency improvement and low-carbon transition lies in the gradual improvement of the energy conversion efficiency of heat sources for the centralized heating system and the low-carbon transition of heat sources through the utilization of zero-carbon residual heat. In contrast, the HSCW zones adopt flexible and decentralized electric heat pumps, wall-hung gas boilers, and local electric heating as the main heating methods, and the key to their energy efficiency improvement and low-carbon transition is making decentralized heating appliances more flexible and energy-efficient. These two heating modes are distinct from each other in terms of the operation mode and energy consumption characteristics and thus should not be subject to parallel comparison. Hence, this subsection focuses on northern urban heating (NUH) in China and its comparison with space heating in several European countries with similar climatic and heating conditions. The countries selected for the comparison are Germany, the UK, England, Poland, and four Nordic countries (Sweden, Denmark, Finland, and Norway). The reasons for the differences between NUH and heating in these European countries are analyzed from such influencing factors as building heating demand, heating method, energy efficiency, and primary energy supply structures, thus making suggestions for the low-carbon development of NUH in China.

The European countries involved in this subsection may fall into the following three main categories: (1) Country in which centralized heating is mainly used for urban areas: In Sweden, Denmark, Finland, and Poland, the proportion of district heating is above 50%, and district heating is generally adopted for their urban areas (especially apartment dwellings), like the northern urban areas in China; (2) Country that mainly adopts decentralized heating with electric heating in the majority: In Norway, the heat supplied by all kinds of electric heating appliances makes up 58% of the total heat consumption of buildings; (3) Country that mainly adopts decentralized heating with fossil fuels in the majority: In Germany, the UK and France, household fossil fuel-fired boilers are used as the main heating method, and the heat supplied by electric heating appliances accounts for 4%, 6%, and 15% respectively.

The sources of data on these countries used for comparison are listed in Table 2.2. It should be noted that, although the energy consumption for heating and domestic hot water (DHW) are generally combined into one in the reports published by European statistical agencies, the energy consumption for heating is extracted separately in this subsection to facilitate the comparison with NUH under the same standard.

Table 2.2 Types and sources of data used for comparative study

Data type	Data source	
	Northern urban areas in China	European countries
Floor area, heat consumption, and primary energy consumption of building heating	China Building Energy and Emission Model (data of 2021)	Reports of the Directorate-General for Energy in the European Commission (data of 2018)[3,4]
Per kWh emission factor	National average per kWh emission factor—2021 Annual Report of China Electric Power Industry compiled by China Electricity Council	Greenhouse gas emission intensity of electricity generation in Europe 2021 European Environment Agency (EEA): Greenhouse Gas Emission Intensity of Electricity Generation in Europe 2021
Power structure	2021 China Electric Power Yearbook	Eurostat database (2021)
Heating degree day (HDD)	HDD18, Average HDD18 weighted by the heating area of northern provinces	Eurostat database: Average HDD18* weighted by the heating area of administrative areas
Carbon emission factor for fuel	Coal: 2.64 kg CO_2/kgce; Natural gas: 1.63 kg CO_2/kgce; Oil: 2.08 kg CO_2/kgce; Municipal waste (non-renewable): 2.69 kg CO_2/kgce	

Note *Only the HDD18 at an average daily outdoor temperature ≤ 15 °C is counted

2.3.1 Heating Demands and Energy Consumption

Figure 2.5 illustrates the comparison of the average heating demands and the average heating degree days (HDD18) among countries: The heating demands per square meter for NUH in China is 0.37 GJ/m^2, and the average HDD18 weighted by the heating area of provinces is 2,788. The average HDD18 values of Finland and Sweden are obviously higher than those of other involved European countries and the NUH region. The average HDD18 values of Norway, Denmark, and Poland are in the range of 3,400–3,700 and those of France and the UK are lower than those of the NUH region.

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[3] European Commission, Directorate-General for Energy, Kranzl, L., Fallahnejad, M., Büchele, R. (2022). Renewable space heating under the revised Renewable Energy Directive: ENER/C1/2018–494: final report, Publications Office of the European Union.

[4] European Commission, Directorate-General for Energy, Bacquet, A., Galindo Fernández, M., Oger, A. (2022). District heating and cooling in the European Union: overview of markets and regulatory frameworks under the revised Renewable Energy Directive, Publications Office of the European Union.

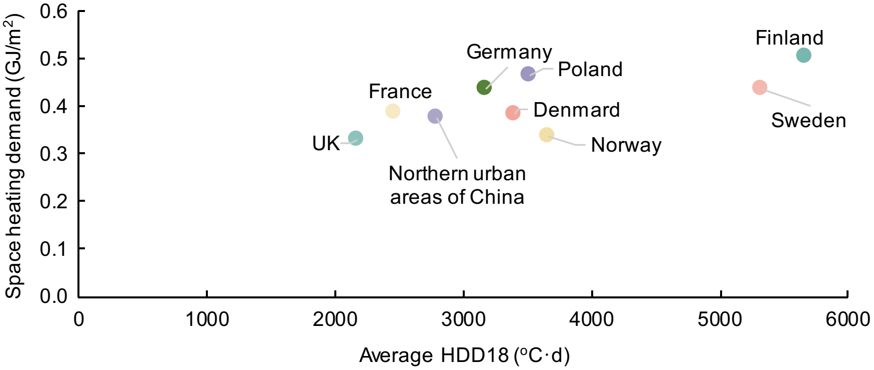


Fig. 2.5 Comparison of heat demands and heating degree days among countries

As indicated Fig. 2.5 in the heat demand per unit area in the four Nordic countries is lower although they have colder weather compared with the NUH region and other European countries. The primary reason for this is that Nordic countries generally have higher levels of building insulation. For instance, the building regulations of Sweden specify that the overall heat transfer coefficient of the apartment building envelope should be below 0.4 W/(m^2·K) after 2011, which is lower than the design standard for "fourth-stage energy efficient" buildings in Beijing, i.e. 0.6 W/(m^2·K). It should be noted that, due to the different statistical standards for data, the heat demands for NUH as shown in Fig. 2.6 represents the statistical data on the heat source side, while that for heating in each European country is calculated based on the building envelope insulation statistics, climatic conditions and indoor loads without considering heat loss in heating pipe networks and overheating. Therefore, the actual heat demands for heating in each European country may deviate from the calculated value indicated in the figure.

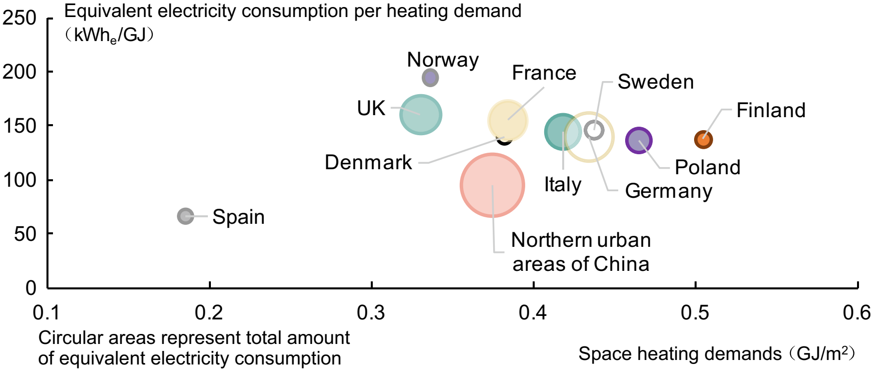


Fig. 2.6 Comparison of equivalent electricity consumption for heating among countries (electricity equivalent method)

Figure 2.6 shows the comparison of the heating demands for heating, equivalent electricity consumption per unit heating demand, and the total equivalent electricity consumption for heating in China's northern urban areas and European countries. The equivalent electricity consumption per unit heating demand for heating in China's northern urban areas is 95 kWh_e/GJ, less than that in all European countries compared. Because the calculation method of equivalent electricity is to convert the heat supplied from CHP into the reduced electricity generated from CHP compared with pure condensing thermal power, and CHP can be equivalent to electric heat pumps with a Coefficient of Performance (COP) of 4. This equivalent COP is higher than the annual average COP for the operation of most heat pumps under climatic conditions in Northern and Central Europe and much higher than that for general boilers and direct electric heating appliances. Therefore, under the framework of the electricity equivalent method, CHP may be considered to have higher energy conversion efficiency than other heating methods. The percentage of CHP in centralized heating sources in China is above 60%, equivalent to that in Denmark, Finland, and Poland, which have the highest percentage of CHP among European countries. Consequently, when the centralized heating rate in China's northern urban areas is higher than the overall centralized heating rate in the urban and rural areas of other European countries, the equivalent electricity consumption per unit heating demand for heating in China's northern urban areas is the lowest in the comparison. And that in Norway, the UK and France that mainly adopt decentralized heating is higher.

2.3.2 Carbon Emissions from Building Heating

The total carbon emissions from space heating in each country may be calculated based on the energy supply structures of building heat sources and the carbon emission factor for each type of fuel used. The total carbon emissions from NUH are 0.49 Gt CO_2, about 1.25 times that from heating in the eight European countries compared. As shown in Fig. 2.7, the carbon emissions per unit heating demand for NUH is 80 kg CO_2/GJ, equivalent to those for Poland, and the carbon emissions per unit area for heating is 30 kg CO_2/m^2. Norway, with 12 kg CO_2/GJ of carbon emissions per unit heating demand, has the lowest carbon emission intensity among countries adopting decentralized heating, and Sweden, with 18 kg CO_2/GJ of carbon emissions per unit heating demand, has the lowest carbon emission intensity among countries adopting centralized heating. Finland and Denmark have 35 and 38 kg CO_2/GJ of carbon emissions per unit heating demand for heating respectively. The carbon emissions per unit heating demand in the UK, Germany, and France which mainly adopt decentralized heating are approximately 48–68 kg CO_2/GJ.

As revealed in Fig. 2.8, the main heat source for NUH in China is coal-fired CHP (51%), and building heating method in Poland is also dominated by a coal-firing but has decentralized coal-fired boilers as the main method. The carbon dioxide emissions per unit calorific value of coal are about 1.6 times those of gas, therefore China's northern urban areas and Poland have the highest carbon emission intensity per unit

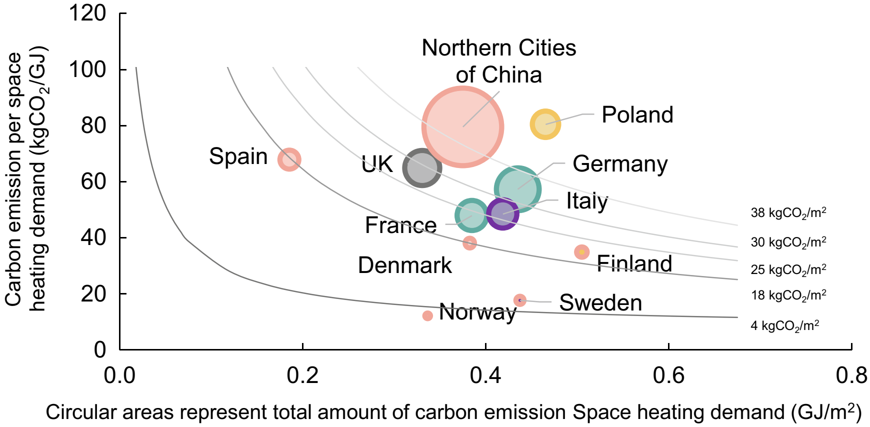


Fig. 2.7 Comparison of carbon emissions from heating among countries

heating demand for heating among the countries compared. Following Poland are the UK and Germany: About three-fourths of space heating for the UK is supplied from natural gas, and the energy supply ratio of biomass energy and zero-carbon electricity is less than one-tenth. Although Germany is less dependent than the UK on natural gas for heating, the total energy supply ratio of coal, oil, and gas has been three-fourths. The percentages of fossil fuels in building heat sources in Norway and Sweden are below 10%, the lowest in the countries compared.

It can be seen from Fig. 2.9 that Norway, Sweden, Finland, and France have higher percentages of electric heating. The power structures are compared among countries: Sweden and Norway only have about 2% of fossil-fueled thermal power, and most of the supplied electricity is zero-carbon electricity; zero-carbon electricity also makes up more than 80% of the power structures of Finland and France; consequently,

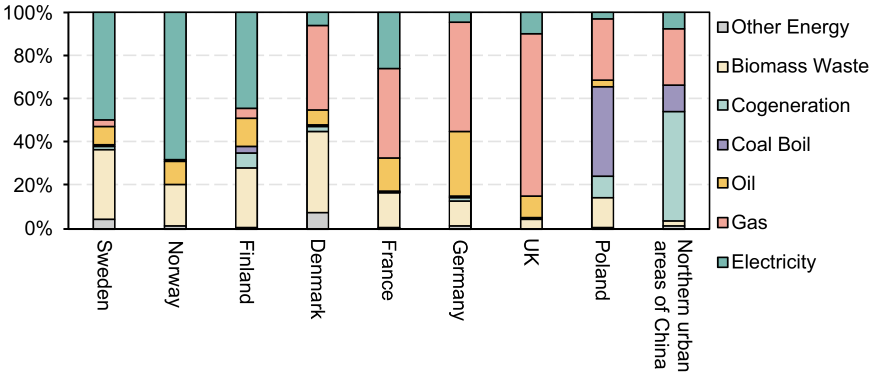


Fig. 2.8 Comparison of the composition of building heat sources among countries. *Note* other zero-carbon heat sources include geothermal energy, solar thermal, and industrial residual heat

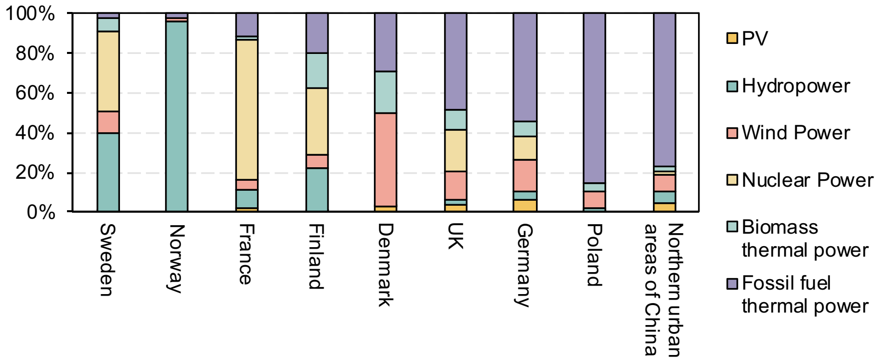


Fig. 2.9 Comparison of power structures among countries

the carbon emission intensity of electric heating in these four countries is very low. The power structure in China's northern region is still dominated by fossil-fueled thermal power (about 78%), and the proportion of zero-carbon electricity is expected to be further increased in the future to reduce indirect carbon emissions from electric heating.

European countries have selected the heating methods and energy types according to their own national conditions based on their own natural resource conditions and social and economic development. The major European countries have established improved heating systems suitable for the local heat source conditions and climatic features. At present, China and European countries are actively implementing the low-carbon transition of building heating. China's northern urban areas and the urban areas of Sweden, Finland, and Denmark have built perfect centralized heating systems and achieved a high proportion of CHP for space heating. Nevertheless, coal-fired CHP remains the main heat source for centralized heating in China, thus China's carbon emissions are much higher than those of the four Nordic countries. In the future, the northern urban areas in China should continue implementing the renovation of existing buildings to achieve the goal of reduced building heating demands and should combine the comprehensive collection, storage, and utilization of residual heat resources with the seasonal heat storage technology to utilize the year-round industrial surplus heat for building heating in winter and to realize low-carbon heating by relying entirely on the suplus heat from nuclear power, peak shaving thermal power, curtailed wind and solar PV power and process industries as heat sources.

Chapter 3
Present Situation of Urban Heating in China

3.1 Overall Situation of Urban Heating in China

Urban heating in China mainly consists of building heating, industrial heating, domestic hot water (DHW), and steam for functional buildings. The overall heat source structure of the foregoing categories is shown in the diagram below, and fossil energy is still in the majority (Fig. 3.1).

At present, the northern urban heating (NUH) area in China is 15.6 billion m^2, which is supplied with heat mainly by the centralized heating system and requires about 5.95 billion GJ of heat. The building floor area with a demand for heating in the Yangtze River Basin is about 27.7 billion m^2, which mainly has decentralized heat pumps, decentralized boilers, or electric heat for heating. In the future, the area of northern urban buildings with centralized heating will increase to about 21.8 billion m^2, and the heating area of buildings without centralized heating in rural and southern China will increase to 35 billion m^2. The buildings in the Yangtze River Basin, due to the low density of heat demands, will have decentralized electric heat pumps as the main heat source, while the northern urban buildings will still be supplied with heat by centralized heating. It is expected that 5.4 billion GJ of heat will be required for centralized heating in northern China and 2.1 billion GJ of heat will be required for building heating in the Yangtze River Basin by 2050.

In addition to heating, the heat consumption for DHW will be 0.85 billion GJ per year. Due to the scattered locations and time of DHW demands, heat should be made by decentralized electric heat pumps or direct electric heating methods and should not be supplied by a centralized heating system.

With reference to the existing different situations of developed countries and in combination with the structure of added value of industries in 2050 in China, the heat demand of the non-process industries in 2050 is estimated to be about 12.5 billion GJ in 2050, including about 7.6 billion GJ of demand for heat supply below 150 °C.

Generally, China will still have a huge demand for urban heating, of which 17.9 billion GJ of heat should be supplied in a centralized way and 2.95 billion GJ of

Building Energy Research Center of Tsinghua University,
Decarbonize Urban Heating System, https://doi.org/10.1007/978-981-99-7875-5_3

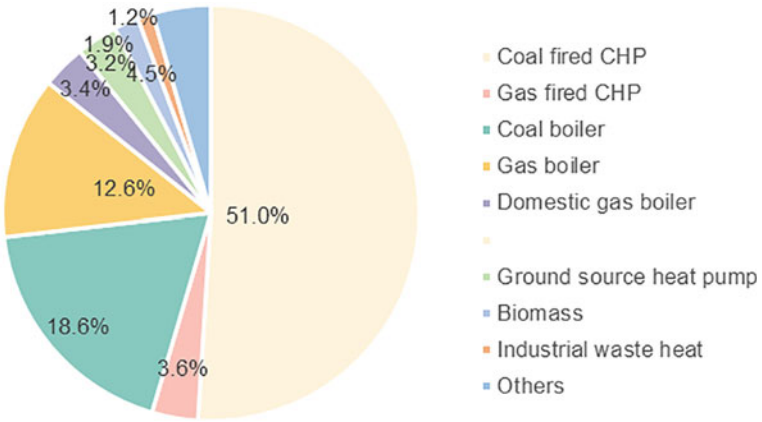


Fig. 3.1 Present situation of heat source for urban heating in China

Table 3.1 Estimation of urban heating demand in 2050

	Centralized supply		Decentralized supply (10^8 GJ)
	Heat supply below 150 °C (10^8 GJ)	Heat supply above 150 °C (10^8 GJ)	
Non-process manufacturing	76	49	
NUH	54		
Building heating in the Yangtze River Basin			21
DHW			8.5
Total	130	49	29.5

heat needs to be supplied in a decentralized way. The present situations of, and the demands for, the above-mentioned categories of heating will be detailed in the following chapters (Table 3.1).

3.2 Urban Building Heating in China

Currently, large- and medium-sized centralized heating systems (dominated by combined heat and power) serve as the main heating methods for northern urban heating (NUH) in China. With the growth of the urbanization rate, the NUH area will further increase. In the meantime, the demand potential for urban heating in the hot-summer and cold-winter (HSCW) zone in the middle and lower reaches of the Yangtze River basin is being unleashed rapidly. Urban heating in this zone is currently dominated by decentralized heating with air-source heat pumps, and some areas also gradually begin adopting such technologies as industrial residual heat, combined heat and power (CHP), and water-source heat pumps for centralized heating.

Compared to the NUH region, areas in the middle and lower reaches of the Yangtze River basin have a shorter heating period, a higher air temperature in winter, and a smaller difference between indoor and outdoor temperatures, and the residential building envelopes there are mostly light- and medium-type structures with poorer thermal insulation and storage performance; besides, the heating demand varies greatly among consumers, and residents often have the habit of opening windows for ventilation and a lower psychological expectation of indoor thermal comfort. Therefore, it is not suitable for the Yangtze River Basin to adopt the same “full time, full space” centralized heating mode as in northern China; otherwise, a huge waste of energy and resources will be caused. Next, discussions will be initiated respectively from the different heating demands and present situations of heating in the two regions.

The NUH region includes all urban areas of Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Henan, Shaanxi (north of the Qinling Mountains), Gansu, Qinghai, Ningxia, and Xinjiang as well as part of Sichuan. Urban areas can be subdivided into cities and small towns. Centralized heating for cities has always been the center of attention in the heating field in China; however, with the advancement of urbanization in China, the importance of heating for small towns is becoming apparent.

According to the *Clean Winter Heating Plan in Northern China (2017–2021)*, clean heating means a heating method for achieving low carbon emissions and low energy consumption through an efficient energy system by the use of clean energy and includes the whole process of heating to reduce pollutant discharge and energy consumption. Therefore, when getting to know the energy consumption situation of the building heating system, we should know not only the comprehensive energy consumption in building heating but also the heat consumption of buildings, the heat loss rate of the pipe network, the electricity consumption of water pumps in the pipe network, and the heat conversion efficiency of heat sources, thus getting the whole picture of the actual energy consumption in building heating.

3.2.1 NUH Area

According to the data in the *China Urban–Rural Construction Statistical Yearbook*, the centralized heating area in China had grown rapidly in the last decade from 2011 to 2020, with an average annual growth rate of 8.7%, and the urban centralized heating area in northern China was about 12.21 billion m^2 in 2020, of which the centralized heating area in cities accounted for 80.9% and that in small towns accounted for 19.1%. Recent years have seen the rapid development of centralized heating in small towns in China with the advancement of new urbanization, and the situations in small towns should be taken into full account during the study of centralized heating (Fig. 3.2).

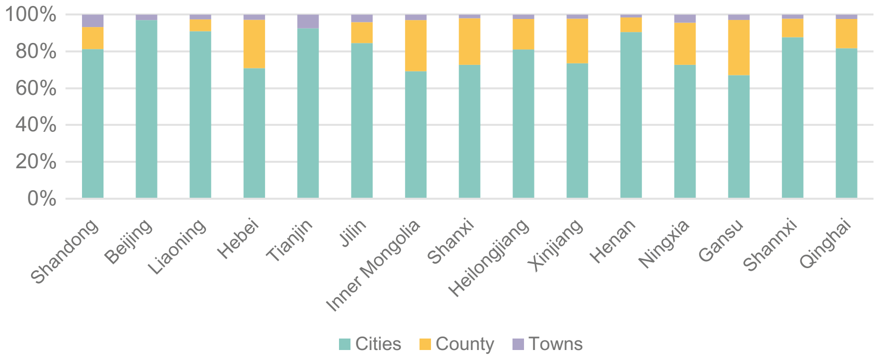


Fig. 3.2 Structure of centralized heating area

The centralized heating area given in the *China Urban–Rural Construction Statistical Yearbook* only counted the heating area covered by the for-profit centralized heating systems. However, in addition to this part, there are lots of buildings supplied with heat by not-for-profit centralized heating systems. For example, higher education institutions, troops, office compounds, and some large enterprises have their own independent heating management teams to operate their centralized heating systems, but the building floor area for which this centralized heating systems supply heat is not counted by relevant departments for a variety of reasons. Table 3.2 lists the centralized heating areas given in the *China Urban–Rural Construction Statistical Yearbook* (the Yearbook) for some typical cities and the current values of the centralized heating areas given in the local special plan on heating to make a comparison. Taking Beijing for example, the centralized heating area given in the Yearbook (2020 edition) is 659.35 million m^2, but the current value of the centralized heating area by the end of 2020 given in Beijing's 14th Five-Year Plan on Heating Development is about 895.21 million m^2 (approximately 1.36 times the former). That is to say, about 236 million m^2 of area are not counted, which are mainly composed of those not-for-profit centralized heating systems.

According to the estimate by Building Energy Research Center (BERC), Tsinghua University, the NUH area had reached 15.63 billion m^2 by the end of 2020. The not-for-profit centralized heating area was considered on the basis of the centralized heating area given in the *China Urban–Rural Construction Statistical Yearbook*. After correction, the centralized heating area in northern urban areas in 2020 was about 13.78 billion m^2 and the centralized heating rate was 88.2%.

3.2.2 Heating Proportions of Different Heat Sources

In 2020, China District Heating Association (CDHA) counted various data from 90 heating enterprises across the country. In combination with the area of heating by

Table 3.2 Heating areas in some typical cities in northern China (Unit: 10^4 m^2)

City	Statistical data in the yearbook	Data in the special plan on heating
Beijing	65,935	89,521
Changchun	26,563	29,797
Shenyang	35,391	49,800
Dalian	25,767	31,148
Hohhot	16,504	16,216
Tongliao	3595	6050
Zhengzhou	16,000	19,792
Kaifeng	3400	3792
Xi'an	29,139	31,099
Lanzhou	9253	9979

non-coal-fired and non-gas-fired heat sources in 2020 as counted below, the relative relationship between coal and gas proportions in the participating enterprises is utilized to calculate the total heating area of coal-fired and gas-fired heat sources in northern China, and the checked heat source structure for NUH in 2020 is shown in the right diagram in Fig. 3.3 compared to the 2016 heat source structure (left diagram in Fig. 3.3), the proportion of coal-fired CHP rises by 6%, the proportion of coal-fired boiler rooms drops by 13%, and the proportion of gas-fired heating does not change much. However, the proportion of heating by ground-source heat pumps, biomass, and other renewable energy shows an increase of about 6%. Considering the development of heating by the residual heat from nuclear power in recent years and the heating potential of industrial residual heat and renewable energy in northern China, the proportion of heating by traditional fossil energy will further decrease in the future.

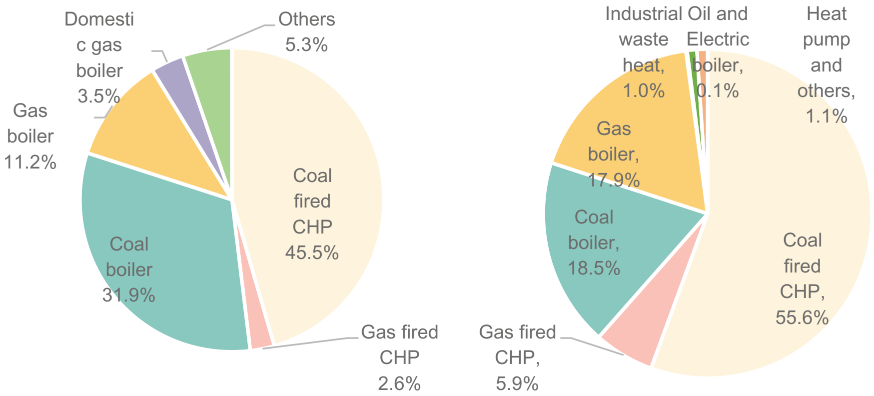


Fig. 3.3 2016 (left) and 2020 (right) heat source structures for NUH

3.3 Present Situation of Heat Consumption for NUH

3.3.1 Present Situation of Building Insulation

In the NUH region in China, there is still a considerable proportion of old residential buildings with poor indoor comfort, high energy consumption, and prominent heating contradictions. In 2007, China officially launched the heating measurement and energy-saving retrofit of existing residential buildings in the NUH region. During the 13th Five-Year Plan period, the energy-saving standard for new urban residential buildings in severe cold and cold areas in China reached 75%, approximately 10 million m^2 of buildings with ultra-low and near-zero energy consumption were constructed, and 514 million m^2 of existing residential buildings and 185 million m^2 of public and commercial (P&C) buildings completed the energy-saving retrofit. By the end of 2020, the newly built building stock of China's urban green buildings made up 77% of the total newly built building stock of that year, and the cumulative built floor area of green buildings exceeded 6.6 billion m^2. The cumulative built floor area of energy-efficient buildings exceeded 23.8 billion m^2, accounting for more than 63% of the total floor area of urban civil buildings. The new prefabricated buildings commenced across the country accounted for 20.5% of the total newly built building stock of that year.

Figure 3.4 reflects the completion of the energy-saving retrofit of existing buildings during the 13th Five-Year Plan period in the NUH region.

By the end of 2020, the NUH region had completed the energy-saving retrofit of 339 million m^2 of existing residential buildings in total during the 13th Five-Year Plan period. Figure 3.5 illustrates the completion of the energy-saving retrofit of existing

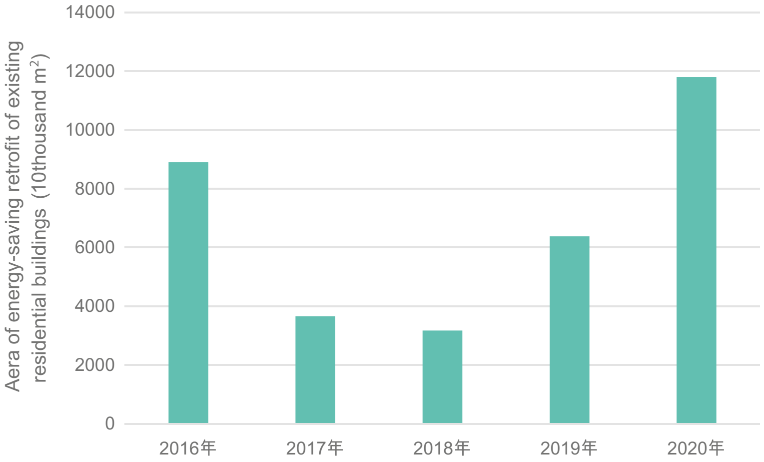


Fig. 3.4 Completion of the energy-saving retrofit of existing residential buildings in the NUH region during the 13th Five-Year Plan period

buildings during the 13th Five-Year Plan period in northern provinces, autonomous regions, and municipalities.

As shown in Fig. 3.6, the proportions of urban building floor areas classified by the energy efficiency grade in the NUH region in China in the present situation can be estimated based on the data from the survey of the heating situations of heating companies in provinces conducted by CDHA and BERC, Tsinghua University and in combination with the public information released by the Ministry of Housing and Urban–Rural Development.

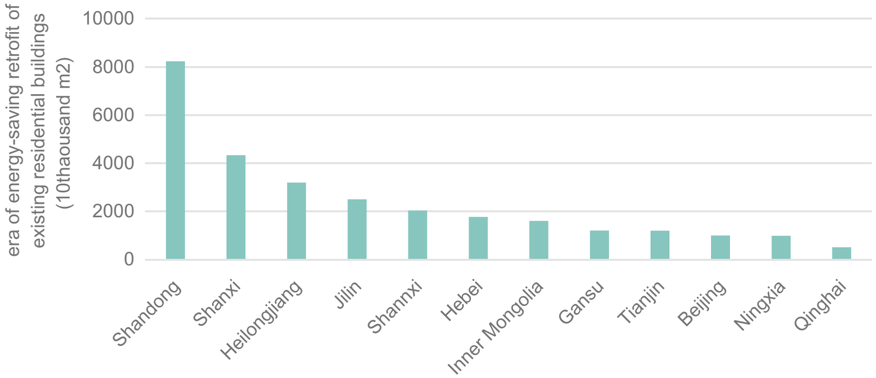
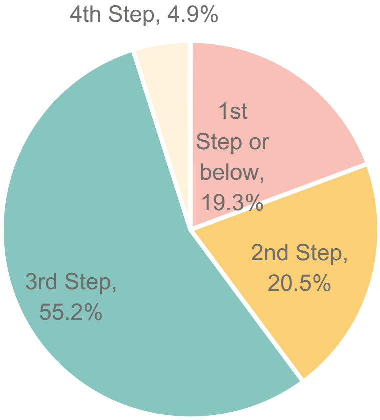


Fig. 3.5 Completion of the energy-saving retrofit of existing residential buildings in some northern provinces, autonomous regions, and municipalities during the 13th Five-Year Plan period

Fig. 3.6 Urban building floor areas under different energy-saving standards in the NUH region



3.3.2 Actual Heat Consumption of Buildings

Since 2017, Tsinghua University and CDHA have jointly performed statistical work on the operation of the heating industry, and the total network coverage area of statistical samples is 3.37 billion m^2, taking up about 27.6% of the total centralized heating area given in *China Urban–Rural Construction Statistical Yearbook*; after the deduction of the suspended area, the actual heating area is 2.68 billion m^2.

Figure 3.7 indicates the heat consumption per unit area of the participating enterprises in the 2019–2020 heating season, and the ordinate represents the cumulative frequency distribution of statistical data. According to the statistical results, the heat consumption per unit area of the participating heating enterprises on the heat source side is distributed in the 0.10–0.80 GJ/m^2 range, the median is 0.376 GJ/m^2, and 80% of the survey results are in the 0.27–0.50 GJ/m^2 range. The survey results of northern provinces are gathered in Table 3.3 Heating area after deduction of suspended area, average heat consumption, and average heating degree days of buildings surveyed in northern provinces, in which, the average heat consumption and the average heating degree days (HDDs) are obtained based on the weighted heating areas of relevant cities. It can be seen that the average heat consumption per unit area of all northern cities surveyed is about 0.377 GJ/m^2, and the corresponding number of heating degree days is 2,879.

Since the release of the Clean Winter Heating Plan in Northern China by ten ministries and commissions in 2017, the relevant places have accelerated the adjustment of the energy structure and actively promoted the centralized heating system for energy saving and consumption reduction. Figure 3.8 and the data measured at

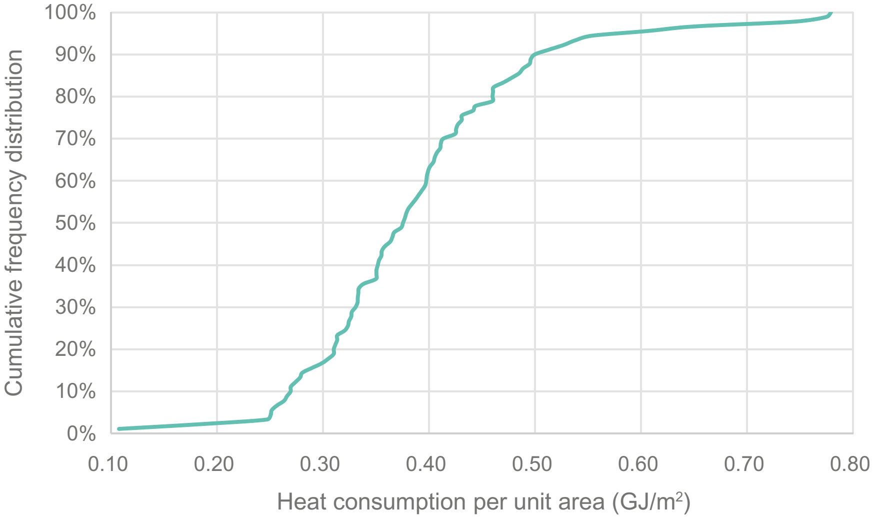


Fig. 3.7 Distribution of heat consumption per unit area of the participating heating enterprises in northern China in the 2019–2020 heating season

Table 3.3 Heating area after deduction of suspended area, average heat consumption, and average heating degree days of buildings surveyed in northern provinces

Province	Heating area after deduction of suspended area (10^4 m^2)	Average heat consumption (GJ/m^2)	Average heating degree days
Heilongjiang	20,133	0.537	4909
Xinjiang	10,417	0.514	3842
Ningxia	3119	0.470	3689
Inner Mongolia	13,930	0.437	3910
Gansu	6652	0.433	2782
Jilin	18,599	0.408	4082
Hebei	37,718	0.375	2486
Liaoning	17,283	0.369	3122
Shanxi	31,479	0.367	3248
Shandong	29,135	0.347	1893
Shaanxi	9470	0.343	1805
Tianjin	13,145	0.340	2194
Henan	15,538	0.316	1615
Beijing	35,152	0.273	2224
Total	261,770	0.377	2879

the heat source outlets are taken. In the 2019–2020 heating season, heating time was extended generally in the northern provinces, autonomous regions, and municipalities due to the COVID-19 pandemic, therefore the overall heat consumption levels of some provinces went up a little. However, compared with the 2017–2018 heating season, the energy consumption for heating in Beijing, Shanxi, Inner Mongolia, Shandong, Henan, and Gansu decreased somewhat, reflecting a huge success achieved through energy-saving and consumption reduction measures in recent years.

Moreover, the energy efficiency grade of buildings also has a significant impact on the heat consumption for system heating. Let's take Tianjin for example. Figure 3.9 illustrates the heat consumption per unit area at heating stations of residential buildings under different energy-saving standards in Tianjin in the 2019–2020 heating season. It can be seen that the average heat consumption per unit area decreases steadily with the increase of the energy efficiency grade of buildings.

Also, it can be observed that the actual heat consumption varies greatly with heating stations under the same climatic conditions and the same energy efficiency grade of buildings. At present, there is still massive overheating in the heating system, and greater potential for energy saving may be realized through enhanced regulation.

In conclusion, in the 2019–2020 heating season, the overall heat consumption level in the NUH region in China was about 0.377 GJ/m^2; in the meantime, overheating and uneven temperatures between buildings still exist in the heating system. For one thing, the energy-saving retrofit of existing old buildings should be promoted

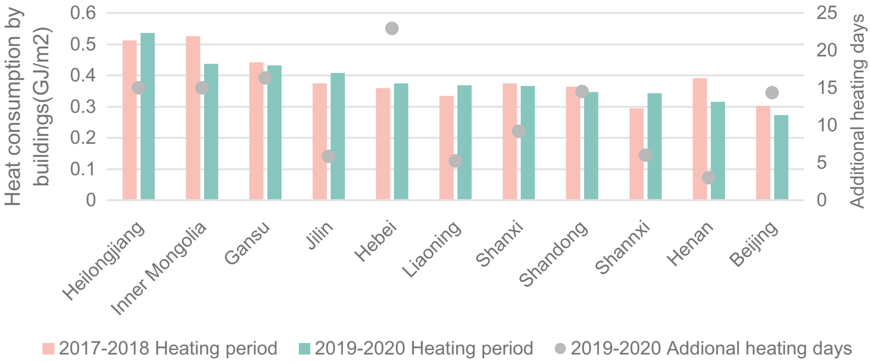


Fig. 3.8 Comparison of heat consumption in the 2017–2018 and 2019–2020 heating seasons in surveyed areas

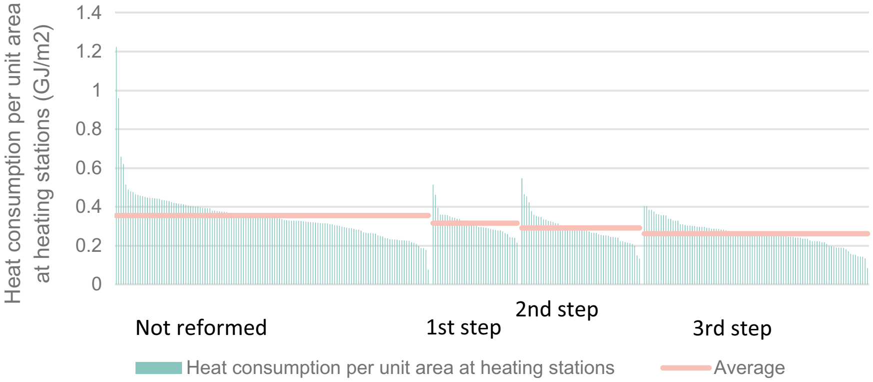


Fig. 3.9 Heat consumption per unit area at heating stations of residential buildings under different energy saving standards in Tianjin (Unit: GJ/m^2)

continuously, and the energy-saving standard should be followed strictly in new buildings; for another, the regulation of the heating system should be enhanced to put an end to overheating and reduce heat loss. These two aspects should be combined to achieve the objectives of energy saving and consumption reduction.

3.3.3 Reduction of Heating Loss

It should be noted that the heat consumption of a centralized heating system is not only related to the thermal insulation performance of the building but also subject to significant influence by the occupancy level of the building. Due to the heat transfer between two adjoining rooms, the suspension of heating will lead to a substantial increase in the energy consumption for heating of adjacent rooms. For the time being, the suspension of heating by consumers in northern China is prevalent.

As revealed by Fig. 3.10, the requests for suspension of heating were mainly made in the central cold area. Because of the great difference in the heat demands of consumers in this area, some consumers demanded the suspension of heating. The suspension of heating for consumers of the centralized heating system would lead to an increase in the actual heat consumption of buildings. As illustrated in Fig. 3.11, the heat consumption increases by about 0.1 GJ/m^2 for each 10% decrease in occupancy.

Hence, the heat transfer between adjacent rooms caused by low occupancy will lead to an obvious increase in the energy consumption of the system and have serious consequences on the fairness in heating between consumers. Currently, some cities do not charge consumers that suspend heating, but the suspension of heating causes other consumers to bear more heat fees, which is in severe breach of the principle of fairness in meter-based tariffs. For this reason, charging the consumers that suspend heating certain "suspension fees" not only reflects the fair settlement for all consumers in a building but also serves as an incentive means to promote energy saving in the heating system (Table 3.4).

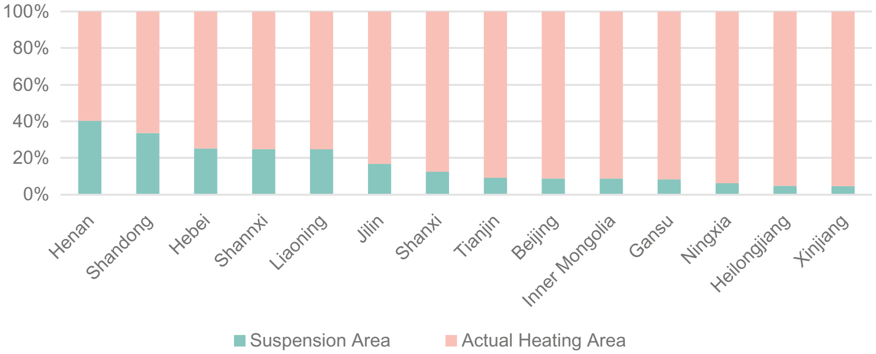


Fig. 3.10 Suspension of heating in the 2019–2020 heating season in northern provinces

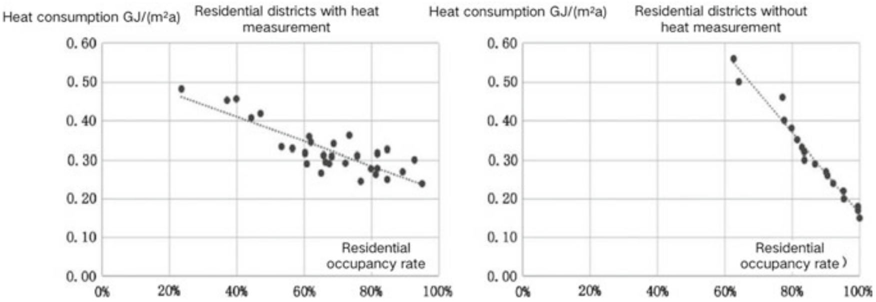


Fig. 3.11 Relationship between occupancy and unit consumption of heat

Table 3.4 Charging methods for suspension of heating in some northern areas

Province or city	Charging method for suspension of heating
Beijing	The heat consumers that suspend heating should pay the heat supplier the basic charge in accordance with relevant provisions, if any, or pay 60% of the "total heating fee" if there are no such provisions
Tianjin	A compensation fee for heat energy loss should be paid at 20% of the heating fee
Xi'an	An application for suspension of heating should be made, and a basic heat fee will be charged at 30% of the total heat price
Shijiazhuang	For vacant housing units, a heat loss fee should be charged at 20% of the total heat fee
Heilongjiang	An application should be made in advance, and a basic fee for the operation of heating facilities should be paid to the heat supplier
Shandong	An application should be made in advance, and the procedures for suspension of heating should be handled, and the heat supplier will not charge any fee

3.3.4 Prediction of Future Heating Demand

In 2020, Wen Zheng, Yichi Zhang, et al. from Tsinghua University calculated the current heating loads in 1,047 northern districts and county units by taking prefecture-level cities, districts, and counties as the units (Zheng W et al. 2020). Multiple factors including population development, urbanization rate, building floor area index, and energy-saving retrofit progress were taken into full account, and such data as permanent resident population, per capita floor area, and the heat consumption index for buildings were calculated reasonably to evaluate the current heating load levels in northern China. The calculation process is shown in Figs. 3.12, 3.13 and Tables 3.5, 3.6.

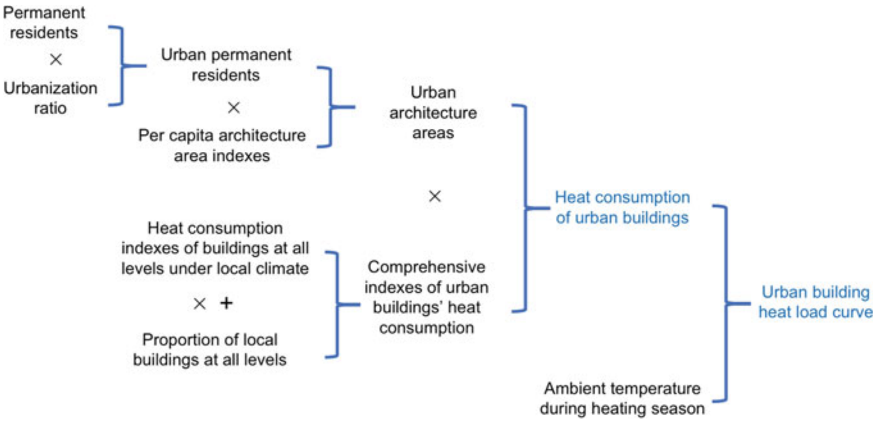


Fig. 3.12 Schematic diagram of the calculation process of urban heating load

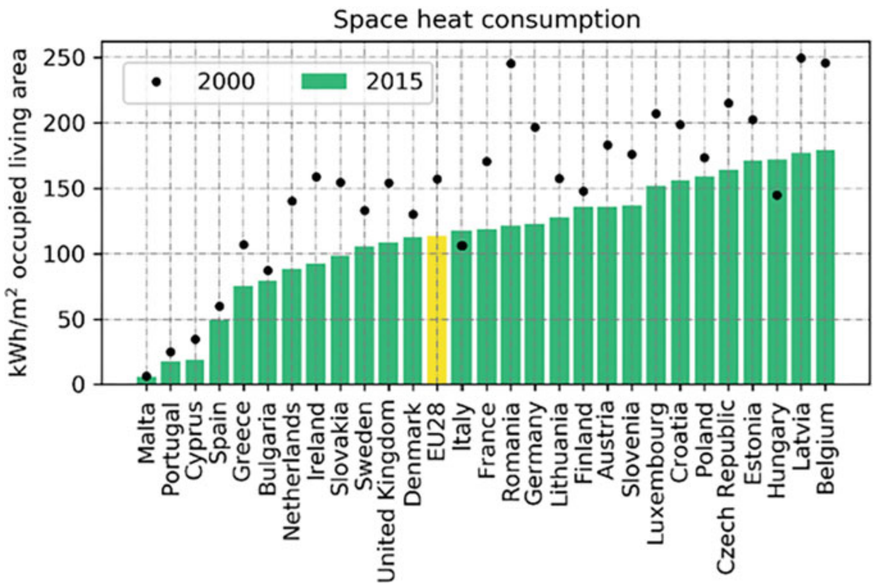


Fig. 3.13 Development of energy consumption for heating in 28 EU countries

Table 3.5 Predictions of heat consumption of northern buildings in different retrofit modes (Unit: 10^4 GJ)

Region	Fast retrofit		Medium-speed retrofit		Slow retrofit	
	2035	2050	2035	2050	2035	2050
Beijing	22,139	22,172	22,768	22,172	22,948	22,564
Tianjin	14,731	14,205	15,165	14,205	15,289	14,466
Hebei	47,907	54,718	49,454	54,718	50,130	55,612
Shanxi	31,674	32,769	32,564	32,769	32,993	33,271
Inner Mongolia	29,448	27,519	30,266	27,519	30,639	27,950
Liaoning	42,462	35,743	43,572	35,743	43,969	36,318
Jilin	27,197	27,630	27,857	27,630	28,103	28,055
Heilongjiang	40,953	40,145	42,044	40,145	42,490	40,787
Shandong	68,114	64,187	70,361	64,187	71,375	65,212
Henan	51,363	59,587	53,154	59,587	54,018	60,468
Shaanxi	22,954	23,514	23,779	23,514	24,161	23,881
Gansu	16,252	19,014	16,752	19,014	16,980	19,314
Qinghai	5052	5972	5200	5972	5355	6097
Ningxia	6166	7230	6345	7230	6415	7351
Xinjiang	19,699	23,112	20,278	23,112	20,536	23,479
Total	446,114	457,516	459,562	457,516	465,401	464,826

Table 3.6 Predictions of heating load demands of northern buildings in different retrofit modes (Unit: MW)

Region	Fast retrofit		Medium-speed retrofit		Slow retrofit	
	2035	2050	2035	2050	2035	2050
Beijing	33,628	33,677	34,583	33,677	34,856	34,273
Tianjin	22,376	21,576	23,034	21,576	23,223	21,973
Hebei	70,116	80,084	72,380	80,084	73,369	81,394
Shanxi	45,884	47,474	47,172	47,474	47,796	48,200
Inner Mongolia	28,791	26,905	29,591	26,905	29,955	27,327
Liaoning	51,255	43,145	52,595	43,145	53,074	43,838
Jilin	29,676	30,148	30,396	30,148	30,664	30,612
Heilongjiang	39,244	38,470	40,290	38,470	40,717	39,085
Shandong	119,015	112,153	122,942	112,153	124,713	113,944
Henan	71,901	83,414	74,409	83,414	75,618	84,647
Shaanxi	29,926	30,655	31,002	30,655	31,499	31,134
Gansu	20,762	24,290	21,401	24,290	21,692	24,673
Qinghai	5412	6397	5570	6397	5736	6530
Ningxia	6880	8067	7080	8067	7157	8202
Xinjiang	22,091	25,917	22,740	25,917	23,029	26,329
Total	596,956	612,371	615,185	612,371	623,099	622,162

The heat demand under the future "dual carbon" goals may be estimated based on the current heating load level through the comprehensive consideration of the energy-saving retrofit of existing buildings in China. There are three different energy-saving retrofit modes, i.e. fast, medium-speed, and slow retrofit modes, for buildings. In the slow retrofit mode, 30% of urban buildings will remain non-energy-efficient in 2035, and 25% will remain non-energy-efficient in 2050; in the medium-speed retrofit mode, 15% of urban buildings will remain non-energy-efficient in 2035, and all of the current non-energy-efficient buildings will complete retrofits in 2050; in the fast retrofit mode, all of the current non-energy-efficient buildings will complete retrofits by 2035. The following Tables 3.7 and 3.8 show the heat consumption and heating demands of northern buildings in 2035 and 2050 under three different retrofit modes.

In terms of the energy consumption per unit area of heating, the heat consumption per unit area of building heating in 2050 is expected to reach 0.21 GJ/m^2 in the fast retrofit mode, and the corresponding peak heating load is expected to be 28.13 W/m^2. Considering the total 15% loss of the primary and secondary networks and overheating, the heat consumption per unit area on the heat source side and the peak load will be 0.25 GJ/m^2 and 33.09 W/m^2 respectively, and energy can be saved by 34.5% compared with the current level.

With reference to the situation in foreign countries from 2000 to 2015, the average heat consumption per unit area for heating in 28 EU countries is expected to drop

Table 3.7 Predictions of heating load demands of northern buildings in different retrofit modes

Energy-saving retrofit mode	2035		2050	
	Heat consumption (GJ/m^2)	Heating load (W/m^2)	Heat consumption (GJ/m^2)	Heating load (W/m^2)
Fast retrofit	0.218	29.16	0.210	28.13
Medium-speed retrofit	0.225	30.05	0.210	28.13
Slow retrofit	0.227	30.44	0.214	28.58

Table 3.8 Predictions of heating load demands on the heat source side of NUH in different retrofit modes

Energy-saving retrofit mode	2035		2050	
	Heat consumption (GJ/m^2)	Heating load (W/m^2)	Heat consumption (GJ/m^2)	Heating load (W/m^2)
Fast retrofit	0.256	34.31	0.247	33.09
Medium-speed retrofit	0.264	35.36	0.247	33.09
Slow retrofit	0.267	35.81	0.251	33.62

to 0.305 GJ/m^2 by 2050, which is still higher than the foregoing expected value of energy consumption (0.25 GJ/m^2). Thus, it can be inferred that this value (0.25 GJ/m^2) is very close to the ultimate level of energy saving and consumption reduction that the current system can achieve.

3.4 Present Situation of Heating Networks for NUH

3.4.1 Pipe Network Length

According to the *China Urban–Rural Construction Statistical Yearbook*, the centralized heating pipelines in China totaled around 507,300 km in length by 2020, and all of them are hot water pipelines. Figure 3.14 illustrates the changes in the lengths of centralized heating pipelines in China over the years. Figure 3.15 shows the lengths of centralized heating pipelines in various regions of China in 2020. The length of primary pipe networks was 140,900 km and that of secondary pipe networks was 366,400 km, with a proportion of 28 and 72% respectively.

The aging of pipe networks is shown in Fig. 3.16. The proportion of old primary pipe networks with a service life of more than 15 years is 19.4%, while that of old secondary pipe networks is 32.2%.

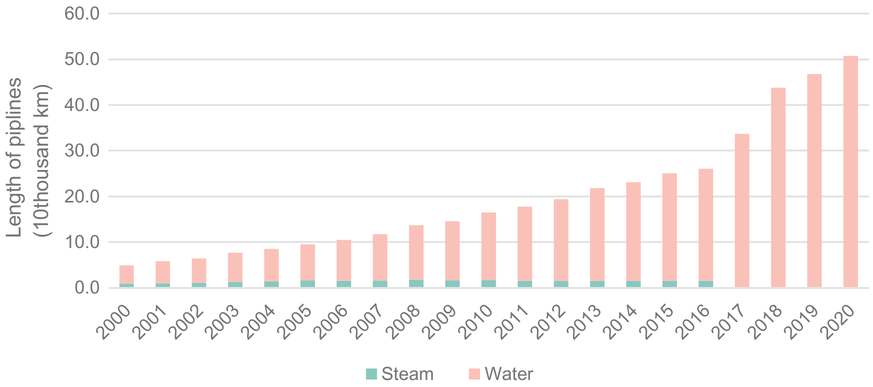


Fig. 3.14 Changes in the lengths of centralized heating pipelines in China over the years

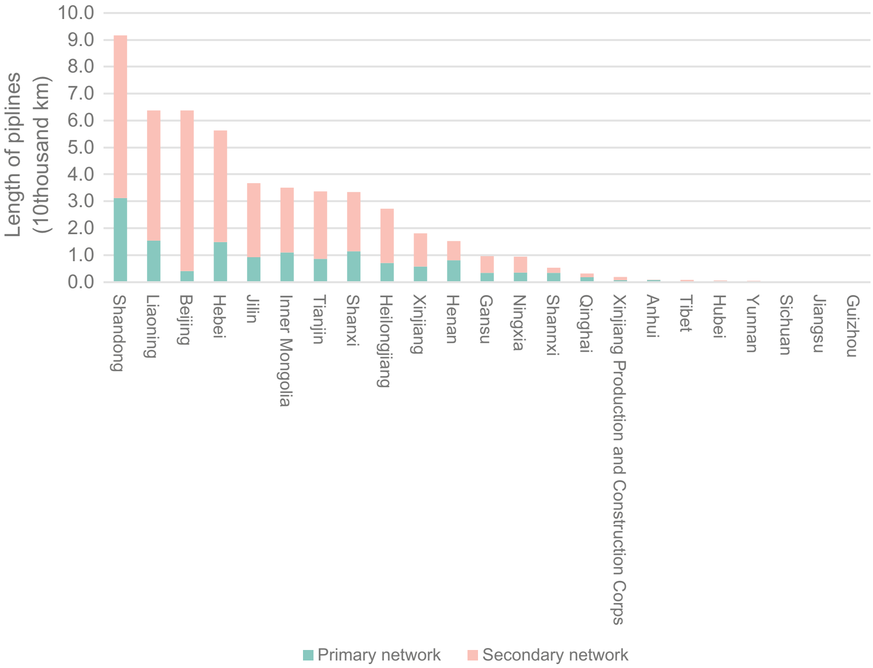


Fig. 3.15 Lengths of centralized heating pipelines in various regions of China in 2020

The renovation of old pipe networks in the primary and secondary pipe networks counted by the included enterprises from different provinces is shown in Figs. 3.17 and 3.18 respectively. The average proportion of the length of annually renovated pipe networks in the total length of the primary pipe networks is about 2%, indicating a slow renovation speed.

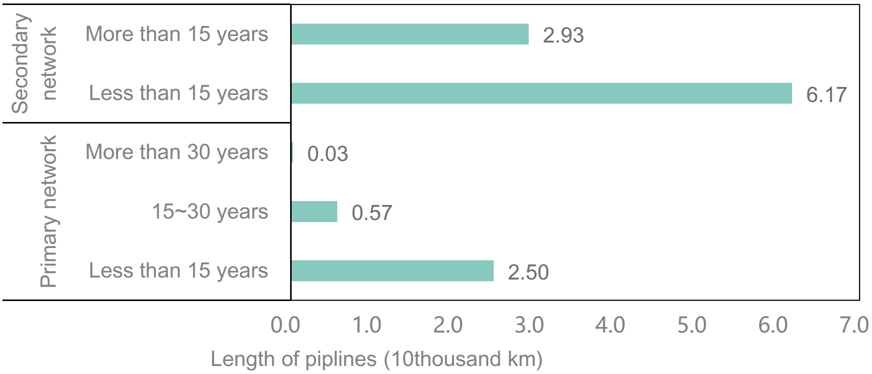


Fig. 3.16 Total lengths and aging conditions of pipe networks of enterprises included in the heating statistics in 2020

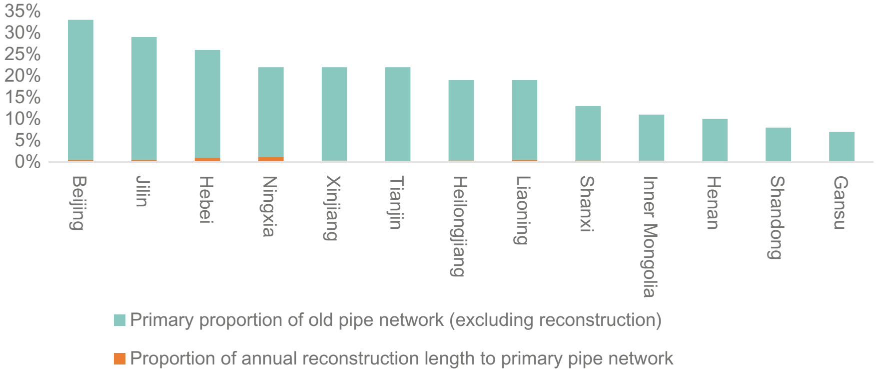


Fig. 3.17 Proportion of old pipe networks in primary networks of enterprises from different provinces and cities in 2020

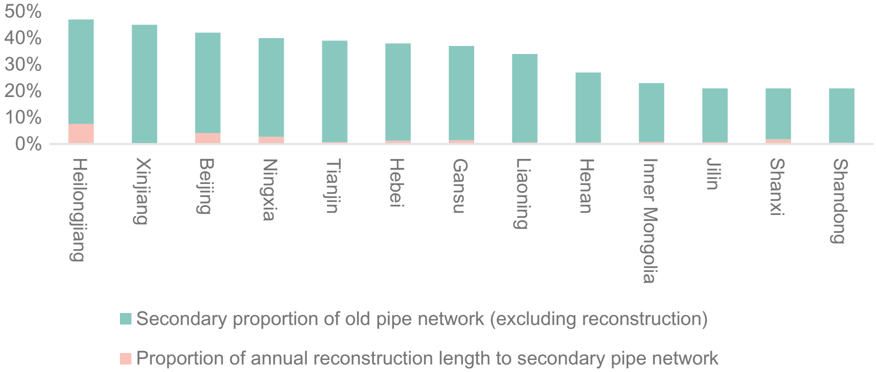


Fig. 3.18 Proportion of old pipe networks in secondary networks of enterprises from different provinces and cities in 2020

3.4.2 Operation Parameters

Indirect connection is adopted for most of the centralized heating systems in China. The water supply parameters on the primary side depend on the demands for heat transfer in pipe networks. With the promotion of low-temperature heating technology, more and more heating systems are developing towards low heating parameters. According to statistics, the average return water temperature in the primary network in the heating season was 44.3 and 46.8 °C respectively for severe cold and cold areas in 2020, representing a substantial decrease compared with the statistical data in 2016.

Table 3.9 lists the supply and return water temperatures in primary and secondary networks of centralized heating systems for typical cities and ranks the same based on the latitudes of the cities. In most cities, the average temperature of supply water in the primary network in the heating season is 80–90 °C, and the temperature of return water is 40–50 °C. The average temperature of supply water in the secondary network in the heating season is about 45 °C, and the temperature of return water is mostly 30–40 °C. The temperature level trends downward compared to the temperatures in previous designs (120/70 and 90 °C/50 °C). The temperature of return water is lower in places with higher latitudes.

In Datong and Taiyuan in Shanxi and Chifeng in Inner Mongolia etc., absorption heat exchange equipment were installed at some terminal heating stations to averagely reduce the return water temperature in the primary network in the heating season to 24 °C, and the overall return water temperature reaches 35–38 °C, thus the temperature difference between the supply and return water in the primary network can be increased effectively to improve the transmission capacity of pipelines and facilitate the recovery of residual heat from exhaust steam from power plants.

3.4.3 Electricity Consumption in Transmission and Distribution

Because the collected data about the electricity consumption in primary networks are few and varied, Fig. 3.19 only presents the data on electricity consumption in secondary networks of enterprises counted by CDHA. Given the influence of climatic conditions and the heating duration, the data of enterprises in cold areas and severely cold areas are separated for comparison. From Fig. 3.19, it can be seen that the electricity consumption per square meter in the secondary network in the heating season varies greatly from place to place. The average value of enterprises in cold areas is 1.28 kWh/m^2. The average value of electricity consumption per square meter in the heating season in severe cold areas is 1.44 kWh/m^2, slightly higher than that in cold areas. Compared with 2018, electricity consumption has a significant decrease of about 25%.

Table 3.9 Temperatures of supply and return water in pipe networks of centralized heating systems for typical cities

City	Average temperature of supply water in the primary network on the coldest day (°C)	Average return water temperature in the primary network on the coldest day (°C)	Average temperature of supply water in the primary network in the heating season (°C)	Average return water temperature in the primary network in the heating season (°C)	Average temperature of supply water in the secondary network in the heating season (°C)	Average return water temperature in the secondary network in the heating season (°C)
Hefei	85	67	79	66	55	50
Luoyang	–	–	–	52	–	–
Zhengzhou	96	47	83	43	44	37
Qingdao	94	54	84	51	44	39
Taiyuan*	90	28	–	–	45	40
Tianjin	98	53	79	46	47	40
Qinhuangdao	101	51	86	47	44	37
Chengde	120	61	93	43	41	35
Zhangjiakou	98	63	73	51	46	39
Fuxin	102	53	88	46	42	34
Jilin	91	37	78	34	41	30
Harbin	114	45	93	41	49	39

Source Special Statistical Data of China District Heating Association in the 2019–2020 heating season, in which the data of Taiyuan is from practical tests

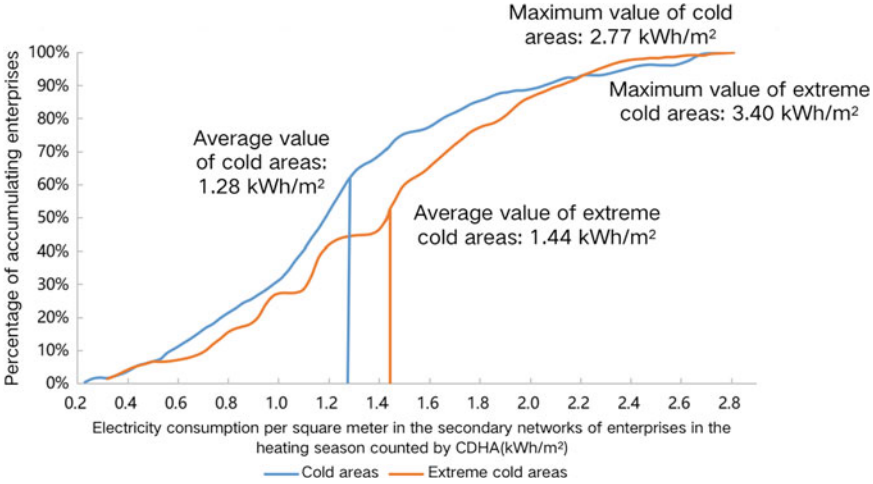


Fig. 3.19 Electricity consumption per square meter in the secondary networks of enterprises in the heating season counted by CDHA

However, the difference in electricity consumption from transmission and distribution is significant between heating enterprises. The reasons for the difference are generally as follows: 1. Unreasonable pressure loss at heating stations; 2. Unreasonable selection of water pump models for heating stations and low pump efficiency. 3. Heavy operation flow rate in the secondary network. If the electricity consumption in transmission and distribution in the secondary pipe network in northern China can reach about 1 kWh/m^2 through the future energy-saving retrofit, about 7.8 TWh of electricity may be saved annually, indicating a marked energy-saving effect.

3.4.4 Water Loss in Pipelines

Figures 3.20 and 3.21 illustrates the water loss per unit area in primary and secondary networks of enterprises counted as above respectively (unit: kg/(m^2·month)). Due to the different levels of pipeline installation and maintenance, as well as operation management, water consumption varies greatly from enterprise to enterprise. Because of the different scales of heating and pipe networks, the district boiler rooms, and CHP heat sources are counted separately in the statistics of water make-up volume in the primary network.

It can be seen from the statistical results that the average values of water make-up volume per unit area in the primary networks of district boiler rooms and CHP are 2.78 kg/(m^2·month) and 4.65 kg/(m^2·month) respectively. The average value of water make-up volume per unit area of heating stations is 8.3 kg/(m^2·month). Hence, the

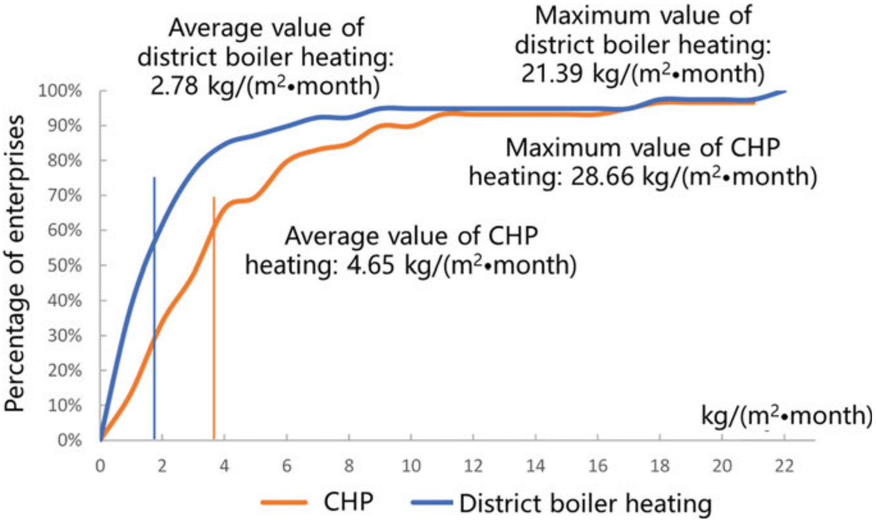


Fig. 3.20 Statistics of water make-up volume per unit area of primary networks of some northern enterprises

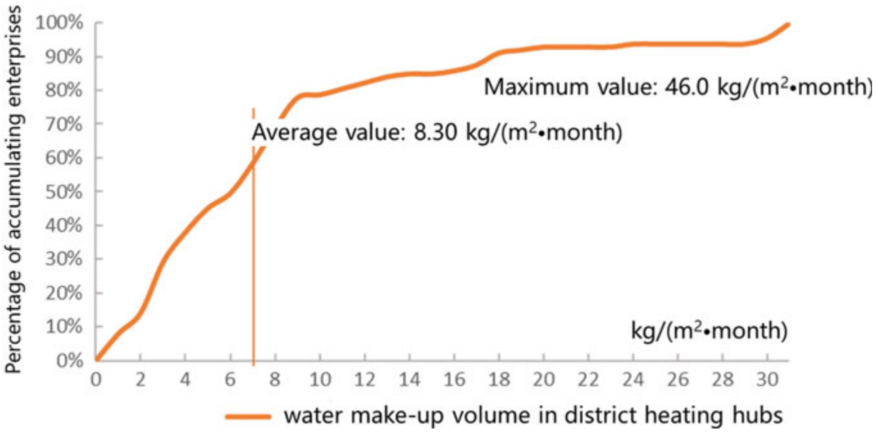


Fig. 3.21 Statistics of water make-up volume per unit area of secondary networks of some northern enterprises

water consumption per unit area of the secondary network is almost twice that of the primary network. The difference in water consumption is considerable between enterprises. This not only leads to a serious waste of water resources and heat but also brings in hard water and dissolved oxygen during frequent water replenishment, exacerbating the fouling and rust corrosion of pipelines and heat-exchange equipment and jeopardizing the quality of heating. Therefore, renovating old pipe networks and solving the water loss problem should be the priorities in the modernization management of the heating industry).

3.5 Present Situation of Heat Sources for Urban Heating

3.5.1 Present Situation of CHP Heating

(I) Overview of installed capacity of CHP

According to the statistical data in the *China Electric Power Yearbook*, China's installed capacity for heating (namely the installed capacity of CHP) maintained a growth rate of 40 million kW/year, and the installed capacity for non-heating purposes only increased by <20 million kW during the 13th Five-Year Plan period. As of 3.22020, China's CHP unit capacity was 560 million kW, accounting for 45% of the total installed capacity of thermal power in the country (the scope of statistics covered units with a capacity of more than 6,000 kW, including some thermal power units mainly serving the heating for industrial production) (Fig. 3.22).

The installed capacity of thermal power in all provinces of China in 2020 is shown in Fig. 3.23. The proportion of installed capacity for heating in the southern regions

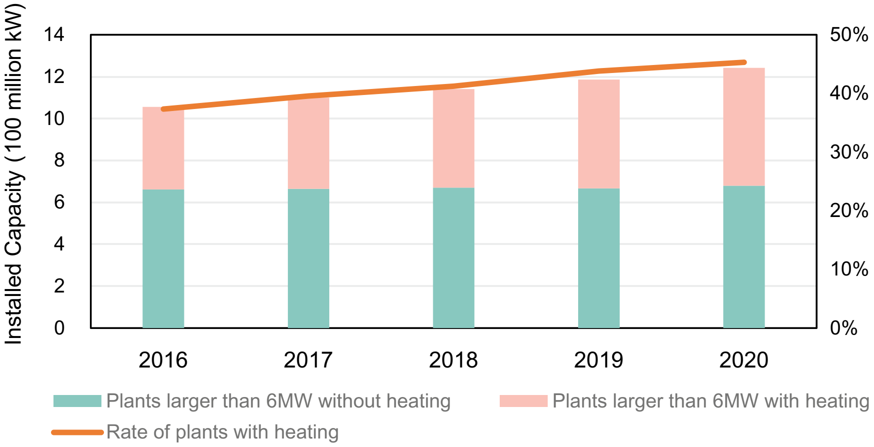


Fig. 3.22 China's installed capacity of thermal power in recent years

was <30%. The proportion of installed capacity for heating in the northern regions was generally above 50%. Thus it can be seen that the development of CHP varied greatly among provinces and the heating capacity should be further explored.

(II) Flexibility retrofit and consumption reduction of CHP

The flexibility retrofit of thermal power is the key to the achieve a high proportion of renewable energy in the power system. For the CHP units, in addition to the conventional technologies on the boiler side, the heat-power decoupling technologies may be adopted on the steam turbine side to achieve deep peak shaving. Such technologies include cutting off the heat supply to the low-pressure cylinder, using most of

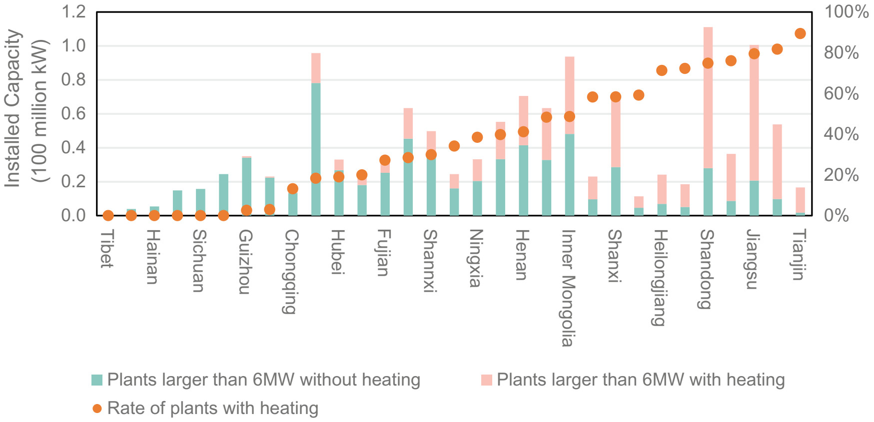


Fig. 3.23 Installed capacity of thermal power in all provinces of China (hundred million kW)

the exhaust steam from the medium-pressure cylinder to supply heat, installing a regenerative electric boiler on the heat source side, installing a heat storage tank as a supplement to the extraction steam for heating when the power grid is under low load, and absorption heat pumps.

In June and July 2016, the National Energy Administration (NEA) successively issued notices about two batches of pilot projects for thermal power flexibility retrofit, and a total of 22 projects, including the Dandong Power Plant and the Changchun Thermal Power Plant, became the first and second batches of pilot projects for thermal power flexibility retrofit. Among them, 15 projects were located in Liaoning, Jilin, and Heilongjiang, with a cumulative installed capacity of 11.97 million kW. By the end of 2019, nearly 50 power grids in northeast China completed the flexibility retrofits, and the peak shaving capacity increased by more than 8.5 million kW; among them, 14 power grids used regenerative electric boilers.

Looking nationally, by the end of 2021, approximately 900 million kW of China's coal-fired generating units completed energy-saving and carbon-reduction retrofits, over 100 million kW completed flexibility retrofits, 1.03 billion KW completed ultra-low-emission retrofits, and the average coal consumption for power supply of thermal power plants dropped to 302.58 gce/kWh.

On November 25, 2022, NEA released the *Basic Rules for the Electricity Spot Markets (Draft for Comments)* and the *Measures for the Supervision of the Electricity Spot Markets (Draft for Comments).* With the further development of the ancillary service market for peak shaving and the perfection of the electricity spot markets, the enthusiasm for flexibility retrofits and deep peak-shaving of power plants will see further increase, which will be more favorable to the further exploitation of the residual heat from thermal power plants and promote the development of the power system with a high proportion of renewable energy.

3.5.2 Present Situation of Heating with Industrial Residual Heat

Survey on two large domestic manufacturers of heat exchangers for heating with residual heat shows that they had completed and operated 86 industrial residual heat recovery projects since 2013, including an increase of about 44 million m^2 during the 13th Five-Year Plan period. The geographical distribution of the counted projects and the newly built projects over the years are illustrated in Figs. 3.24 and 3.25 respectively.

In the counted projects, the completed industrial residual heat projects involved 53 industrial enterprises, and 97% of the projects were located in northern China; the average heating capacity of a single project was about 25 MW. More than 90% of the projects were supplied with heat by steelworks, 88% of them were supplied with residual heat from slag washing water, and most of them had low-pressure steam

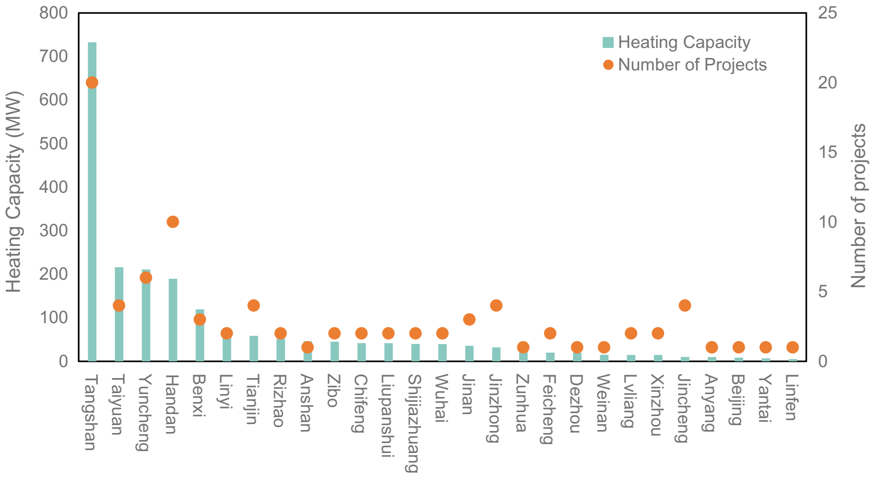


Fig. 3.24 Statistics of heating projects with industrial residual heat by region (accumulated values of 2013–2021)

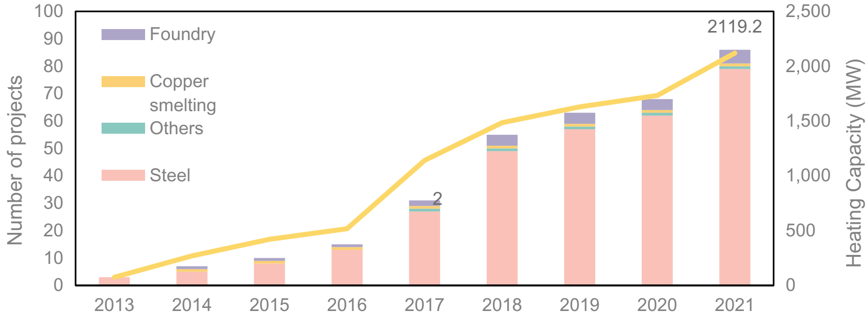


Fig. 3.25 Statistics of heating projects with industrial residual heat by completion time (cumulative values of 2013–2021)

as the supplementary heat source. Only <10 projects used residual flue gas heat, residual heat from ring cooling, and other low-grade residual heat for heating.

The floor area of heating with the industrial residual heat of the two manufacturers accounted for about half of the total in northern China. Thus, it could be calculated that the floor area of heating with industrial residual heat in China had been nearly 200 million m^2 by 2021, which is close to the 100 million m^2 of new areas as planned by the ten ministries and commissions in 2017. Compared with the increase in the floor area of heating with such heat sources as heat pumps and biomass, heating with industrial residual heat still needs vigorous promotion and strong support from policy measures related to environmental control, investment, and construction.

3.5.3 Present Situation of Heating with Gas

According to the *2021 Report on Natural Gas Development in China* published by NEA, in 2020, China's natural gas production was 192.5 billion m^3 and its natural gas consumption was 328 billion m^3, including 37–38% of urban gas consumption. The natural gas consumption for urban centralized heating was 15.59 billion cubic meters.

During the 13th Five-Year Plan period, there was an accumulated increase of 19 million consumers "switching from coal to gas", and the floor area of heating with natural gas reached 3.06 billion m^2, increasing by 1.1 billion m^2 compared to that of 2016 and accounting for 31% of the total increased floor area of clean heating. Centralized heating with gas-fired boilers, heating with wall-hung gas boilers, CHP, and other types of gas-fired decentralized heating accounted for 47, 44, 8, and 1% of the total floor area of natural gas heating respectively.

In terms of the natural gas consumption for heating, the natural gas consumption in northern China in 2022 was 167.33 billion m^3, approximately 50% of China's total natural gas consumption, based on the relevant data disclosed by government departments and the unofficial statistics given by relevant research institutions. If only the natural gas consumption of gas-fired boiler rooms and wall-hung gas boilers was counted, the total gas consumption for centralized heating in northern China was about 30.2 billion m^3, making up over 18% of the total gas consumption in northern China. The natural gas consumption for heating in northern regions is listed in Table 3.10.

From the perspective of the type of natural gas heat source, the percentage of gas-fired thermal power plants used for heating in China is not high, and natural gas-fired boiler rooms are most commonly used for heating. The Beijing–Tianjin–Hebei region is the main region adopting natural gas for heating, and there are very few centralized heating systems using natural gas as energy in northeast China. In northwest China, natural gas is widely used for heating in Xinjiang, Gansu, and Shaanxi. Given China's "more coal and less gas" energy endowment, natural gas is more suitable for peak shaving in centralized heating. In Beijing, policies have been put in place to ban new natural gas heating projects.

3.5.4 Present Situation of Heating with Shallow, Medium, and Deep Geothermal Energy

Figure 3.26 is the structural diagram of the direct utilization of geothermal energy in China. From this diagram, we can see that shallow geothermal energy for heating and cooling and medium and deep geothermal energy for heating are predominant and that ultra-deep geothermal energy is rarely used.

By the end of 2020, China had used geothermal energy for heating and cooling for about 1.39 billion m^2 of area, including shallow geothermal energy for heating

Table 3.10 Statistics of natural gas consumption for heating in northern China in 2022 (10^8 m^3)

	Province	Total natural gas consumption	Natural gas consumption for heating	Percentage of natural gas consumption for heating in the total natural gas consumption (%)	Percentage of the local natural gas consumption for heating in China's total natural gas consumption for heating (%)
1	Beijing	194.1	70.88	36.52	23.4
2	Tianjin	98.3	10.33	10.51	3.42
3	Hebei	206.3	46.93	22.75	15.54
4	Henan	120.2	13.2	10.98	4.37
5	Shandong	235.9	47.62	20.19	15.77
6	Shanxi	86.3	17.4	20.15	5.76
7	Heilongjiang	56.6	3.55	6.27	1.18
8	Jilin	38.4	1.38	3.59	0.46
9	Liaoning	82.4	7.57	9.18	2.51
10	Inner Mongolia	71.4	7.53	10.54	2.49
11	Ningxia	40.9	3.73	9.11	1.24
12	Qinghai	43.5	5.75	13.22	1.90
13	Gansu	42.4	8.1	19.11	2.68
14	Shaanxi	191.2	27.32	14.29	9.05
15	Xinjiang	165.3	30.7	18.57	10.17
	Total	1673.3	302.0	18.05	100.00

Note The natural gas consumption for heating in the table means the annual natural gas consumption of boiler rooms and wall-hung boilers for heating

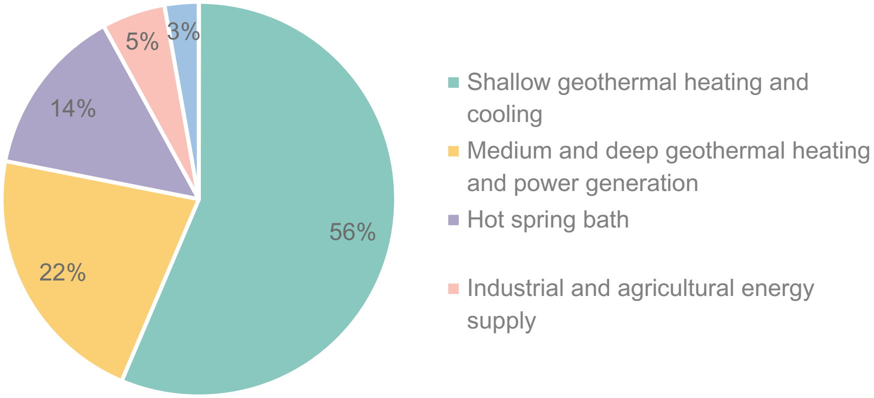


Fig. 3.26 Structural diagram of direct utilization of geothermal energy in China

and cooling for 0.81 billion m^2, and medium and deep geothermal energy for heating for 0.58 billion m^2. It is visible that geothermal energy has been used for heating in China on a large scale and with rapid growth. In terms of cost and efficiency, the construction cost per unit area of heating in medium and deep geothermal energy heating projects is 90–160 RMB yuan/m^2 and the operation cost is 5–10 RMB yuan/m^2.

3.5.5 Present Situation of Heating with Municipal Wastewater

With the advancement of urbanization and the increase in population, China's wastewater treatment volume and rate have been rising significantly. In 2020, the total wastewater treatment volume of cities above the county level in China reached 65.59 billion m^3, and the total wastewater treatment rate was 97.2% (Fig. 3.27).

According to the *China Urban–Rural Construction Statistical Yearbook 2020* issued by the Ministry of Housing and Urban–Rural Development, the city- and county-level wastewater treatment plants in China amounted to 4,326 as of 2020, with a treatment capacity of 230.37 million cubic meters per day, which laid a good foundation for the application of wastewater heat pumps.

Additionally, relevant statistics indicate that some cities have applied the heat energy of the wastewater source to urban centralized heating. By the end of 2021, the area of heating with reclaimed water-source (wastewater source) heat pumps in Beijing had reached 1.29 million m^2, and the area of heating with wastewater source heat pumps in Xi'an had reached 2.72 million m^2. In 2018, Harbin used wastewater at around 14 °C as a heat source and replaced coal-fired boilers with wastewater source heat pumps to supply heat to over 6,600 residential households for an area of 660,000 m^2, producing good operation results.

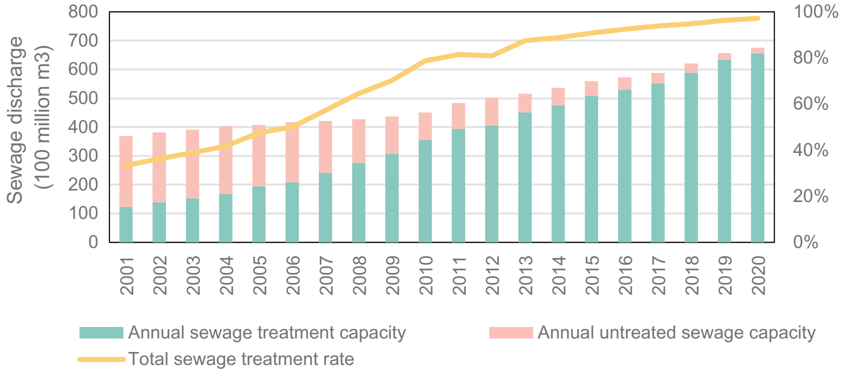


Fig. 3.27 China's wastewater treatment volume and rate

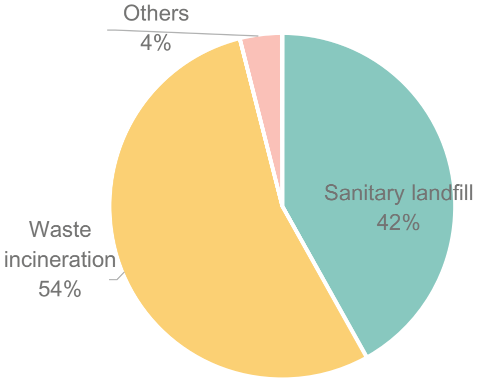
Overall, the area of heating with wastewater source heat pumps is still small in China. The annual residual heat from wastewater in northern cities above the county level is estimated to be around 0.5 billion GJ by taking a temperature difference of 5 K before and after heating, based on the wastewater treatment data in the *China Urban–Rural Construction Statistical Yearbook*. Heat energy from wastewater sources as an auxiliary and supplementary heat source still has certain development potential.

3.5.6 Present Situation of Heating with Municipal Waste

Municipal domestic waste and its treatment are not negligible in urban development. As urbanization continues and the population increases, China has seen an obvious increase in the volume and rate of harmless treatment to municipal waste. In 2020, China's total volume of municipal waste subject to harmless treatment reached 301 million tons, increasing by 19% compared to that in 2016, and its harmless treatment capacity reached 1.32 million tons per day. The percentage of incineration rose from 31% in 2016 to 54%. According to statistics, 504 waste-to-energy incineration projects had been put into operation in China by the end of 2019. From the changes in the installed capacity of waste-to-energy incineration over the years in China, as demonstrated in Fig. 3.28, we can know that the installed capacity of waste-to-energy incineration maintains to grow every year (Fig. 3.29).

However, it should be noted that the primary purpose of the development of waste-to-energy incineration is to consume municipal waste harmlessly, and heating is only an auxiliary function of it in winter. Based on the volume of waste incinerated as given in the *China Urban–Rural Construction Statistical Yearbook 2020*, the caloricity of combustible waste is taken as 5 MJ/kg, the boiler efficiency is taken as 90%, the generating efficiency is taken as 25%, and all of the waste is used for CHP, then about 550 million GJ of heat can be provided annually through CHP with waste

Fig. 3.28 Harmless treatment of municipal waste in China (2020)



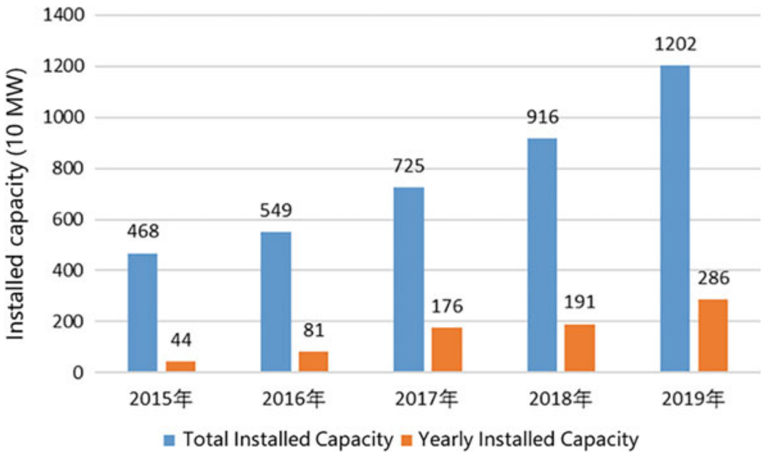


Fig. 3.29 Installed capacity of waste-to-energy incineration

incineration and is an important auxiliary and supplementary heat source for urban heating.

3.5.7 Present Situation of Heating with Agricultural and Forestry Biomass

According to industrial statistics, the annual output of main biomass resources in China is about 3.494 billion tons, and its exploitable potential for energy utilization is 460 million tons of standard coal. As of 2020, China had about 829 million tons of theoretical resources of straws, about 694 million tons of collectible resources, and 88.215 million tons of straws utilized as a fuel; China's total excrement of livestock reached 1.868 billion tons (excluding wastewater from cleaning), and total excrement utilized to produce marsh gas reached 211 million tons; The total available forest residues in China was 350 million tons, and 9.604 million tons of them were utilized as a source of energy; The cleared and transported domestic waste amounted to 310 million tons, including 143 million tons of waste incinerated; The annual output of waste oils and fats was about 10.551 million tons, and about 527,600 tons of them were utilized as a source of energy; The dry weight of the annual output of wastewater sludge was 14.47 million tons, and about 1.147 million tons of them were utilized as a source of energy.

China's straw resources are mainly distributed in northeast China, Henan, Sichuan, and other granary provinces, and the top five in total straw resources are Heilongjiang, Henan, Jilin, Sichuan, and Hunan, making up 59.9% of the national total; Livestock excrement is concentrated in the key breeding areas, and the top five are Shandong, Henan, Sichuan, Hebei, and Jiangsu, accounting for 37.7% of the national total;

Forest residues are concentrated in southern mountain areas, and the top five are Guangxi, Yunnan, Fujian, Guangdong, and Hunan, making up 39.9% of the national total; Domestic waste is concentrated in central and eastern densely-populated areas, and the top five are Guangdong, Shandong, Jiangsu, Zhejiang, and Henan, taking up 36.5% of the national total; Wastewater sludge is concentrated in regions with a higher level of urbanization, and the top five are Beijing, Guangdong, Zhejiang, Jiangsu and Shandong, accounting for 44.3% of the national total.

As of 2021, China's installed capacity of power generation with biomass energy (including agricultural and forestry biomass, domestic waste incineration, and biogas) reached 37.98 million kW, the generating capacity reached 163.7 TWh, the annual output of briquettes fuels was 22 million tons, the annual output of fuel ethanol was 2.9 million tons, and the area of clean heating with biomass was about 310 million m^2, increasing by around 10 million m^2 compared to that in 2020.

3.5.8 Present Situation of Electric Heating

Electric heating technologies fall into two categories, i.e. direct electric heating and heat pump. In 2020, China's total installed capacity of power generation with non-fossil energy reached 980 million kW, making up 44.7% of the total installed capacity; The generating capacity of non-fossil energy reached 260 million kWH, accounting for more than 1/3 of the total electricity consumption of the whole society. As the proportion of clean electricity increased, the heating area of such electric heating methods as electric heat storage boilers, air-source heat pumps, water-source heat pumps, and ground-source heat pumps also grew rapidly.

Among them, electric heat storage boilers were mainly applied in two aspects: One was the flexibility retrofit of thermal power plants, which worked together with the ancillary market for power peak shaving to realize the deep peak shaving of power plants while guaranteeing the heat supply. The other was the utilization of wind power, solar PV power, and other renewable power for district heating.

In terms of region, the heating area of air source, ground source, and other forms of heat pumps also increased greatly. By the end of 2019, the total installed capacity of renewable energy generation in Zhangjiakou reached 15 million kW, accounting for more than 70% of the total installed capacity in the region. The heating area of wind power exceeded 8 million m^2. According to the data from the Beijing Municipal Commission of Development and Reform, as of the end of 2021, the heating area of renewable energy in Beijing was over 100 million m^2, in which the heating areas of air source heat pumps, ground source heat pumps and wastewater source heat pumps were 65, 35 and 1.29 million m^2 respectively, and carbon emissions were reduced by 1.75 million tons per year.

In terms of the total amount, with the promotion of the "switching from coal to electricity" policy in the northern region and the increasing heating demand in non-centralized heating areas in northern and southern regions, the heating area of air source heat pumps in residential buildings grew rapidly during the 13th Five-Year

Plan period. As estimated by the China Academy of Building Research, the heating area of air source heat pumps in northern China was about 725 million m^2 in 2021, which was a relatively large scale.

3.6 Present Situation of Urban Heating in the Yangtze River Basin

3.6.1 Heating Demand and Method in the Yangtze River Basin

The Yangtze River Basin traverses western, central, and eastern China, connects southern and northern China, and passes through 9 provinces (Yunnan, Guizhou, Sichuan, Hunan, Hubei, Jiangxi, Jiangsu, Zhejiang, and Anhui) and 2 municipalities (Chongqing and Shanghai), where the population, gross regional product, civil building floor area account for 42, 45 and 48% of the national total respectively (Zhang and Su). From the point of view of climate zone, the vast majority of areas in the Yangtze River Basin are in the HSCW zone. The outdoor meteorological conditions in winter are mostly cold and wet, the average temperature of the coldest month in most areas is 0–5 °C, and the temperature in non-heated rooms is only 2–5 °C higher than the outdoor temperature. Therefore, to meet the demands of people for thermal comfort in their work and living environments, buildings in this zone need to be provided with corresponding heating facilities.

Since the 12th Five-year Plan period, the state has continued to increase the support for the study of heating in the HSCW zone. Jiang Yi, an Academician of the Chinese Academy of Engineering, suggests that all categories of building operation energy consumption should be allocated as the quantitative goals and upper limits for the energy-saving work based on the total energy capacity and environmental capacity available to China in the future and the demands for energy in all respects of social and economic development. In terms of the measured data on energy consumption, if the centralized heating mode is adopted in the Yangtze River Basin, the annual power consumption of large heat pumps will be about 40 kW · h/m^2 and the energy consumption of CHP will be about 15 kgce/m^2, also equivalent to 45 kW · h of electricity; if the CHP for heating and the decentralized air-conditioning are adopted, the annual energy use intensity will also amount to 40 kW · h/m^2. In contrast, if the decentralized air source heat pumps that enable the realization of the “part time and part space” manner are used, the electricity consumption is likely to be controlled within 30 kW · h/m^2.

In 2016, “Building Heating and Air Conditioning Solutions and Corresponding Systems in the Yangtze River Basin” was listed as a project in the National Key Research and Development Program, “The annual electricity consumption of heating, ventilation and air conditioning (HVAC) in residential buildings in the HSCW zone should be controlled within 20 kW · h/m^2” was set as the quantitative goal, and the limit on the energy use intensity of HVAC in residential buildings in this zone was further identified. The heating method for the middle and lower reaches of the Yangtze River should be determined in combination with the local natural resource endowment and view of both energy efficiency and economy.

From the perspective of energy consumption, the drawbacks of the large-scale centralized heating system, including high energy consumption from transportation, large heat loss, and going against the energy-saving behaviors, have shown up fully in the operation of the NUH system. The indoor and outdoor temperature difference in winter is small in the Yangtze River Basin, so the use of the "full time, full space" centralized heating method adopted in northern China would lead to a huge waste of energy and environmental pollution. Besides, due to the short cold period, the utilization rate of heating equipment will be very low, causing immense waste. From the perspective of resource endowment, natural gas, and electricity are the major energy types. Residents generally have the habit of opening windows for ventilation every day, the use of the centralized heating method will lead to a lot of heat loss.

Consequently, for urban heating in the Yangtze River Basin, it is not suitable to adopt the northern method of large-scale municipal centralized heating; instead, the "part time and part space" heating strategy should be adopted to utilize the method of heating driven by clean energy and dominated by decentralized heating. The use of decentralized heat sources and terminals for household or room heating is characterized by a small construction scale, short period, and low investment, and their operation can be started and stopped depending on the specific demands of consumers. They are flexible, convenient, and more suitable for areas that have natural gas and electricity as the main heat sources, a low heating demand, a short heating duration, as well as a demand for flexible regulation and control.

However, considering such factors as the difficulty in securing natural gas resources, the large peak-valley difference in seasonal demands, and the high cost, the decentralized heating method dominated by air source heat pumps should be advocated among consumers when promoting the decentralized heating system in the Yangtze River Basin. Urban distributed district heating may be developed for residential compounds where residual heat or renewable energy resources are abundant in the surrounding areas and residents have a high willingness to pay. For rural families in southern China, air-source heat pumps should remain the dominant method of decentralized heating. With the large-scale promotion of rooftop PV in the future, direct electric heat with storage may be used for heating. For rural areas with rich biomass resources in southern China, biomass boilers should be promoted according to local conditions to meet the heating, cooking, and DHW demands simultaneously.

In 2013, Tsinghua University surveyed the use of heating appliances in 761 households in the Yangtze River Basin, among which 85% had split air conditioners, 80% had local heating appliances, and <1% used the centralized heating of the residential compound. Over the past two decades, the urban heating market in the Yangtze River Basin has developed from a small scale to a large scale and from a slow speed to a rapid speed. By the end of 2019, the floor area of urban residential buildings alone was around 7 billion m^2 in the HSCW zone, including about 8 million households using wall-hung gas boilers for heating, 4.9 million households using various radiators for heating, and approximately 8.2 million households using appliances including small heaters and electric heaters. The floor area of centralized heating was about 80–100 million m^2, and the main technologies utilized were industrial residual heat, CHP, and water-source heat pumps.

3.6.2 *Practical Heating Case*

(I) Introduction of the basic information on the case

Take Heating Company D in Wuhan as an example. Its centralized heating system uses the extraction steam from a thermal power plant as the heat source, which is far from the concentrated areas of heat consumers, and the consumers are small in number and scattered. The temperature of supply water in the initial heating station and the secondary network may be adjusted depending on the outdoor temperature (Figs. 3.30 and 3.31).

Based on the practical household tests, it is found that the room temperature of households in residential compounds is about 21 °C in general, higher than the room temperature standard of 18 °C. The typical room temperatures in the heating season are shown in Fig. 3.32. It can be seen that the room temperature is above 20 °C for most of the time in the heating season, and the highest room temperature can reach nearly 25 °C.

(II) Energy consumption and economic analysis of heating in the case

In the 2013–2014 heating season, Company D supplied heat to 5,646 households, and the total number of households in the residential compounds supplied with heat was 12,957, so the heating rate was 43.6%. In the 2013–2014 heating season, Company D supplied heat to all consumers from December 1 to March 1 and supplied heat to some consumers after March 1 and before December 1. The converted heat consumption

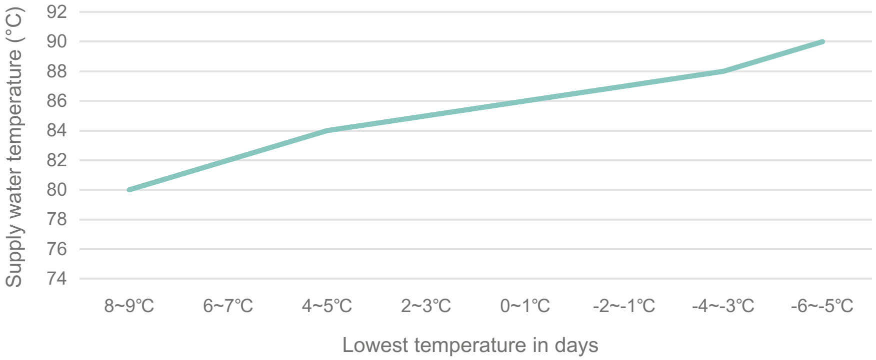


Fig. 3.30 Strategy for adjustment of temperature of supply water in the initial heating station

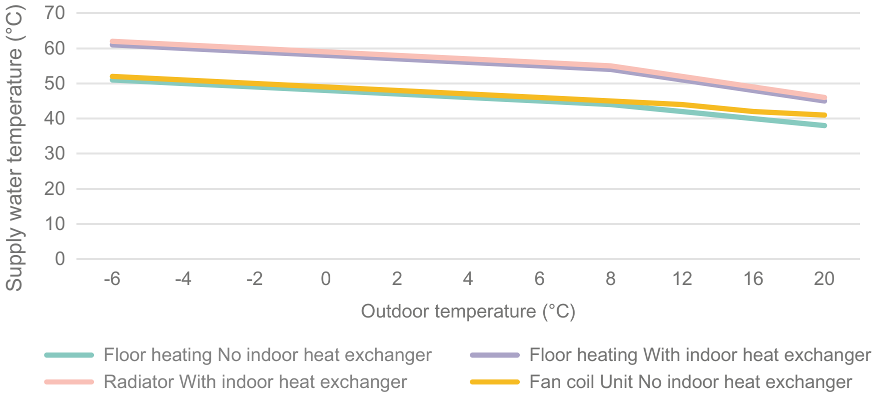


Fig. 3.31 Strategy for adjustment of temperature of supply water in the secondary network

Fig. 3.32 Test results of typical room temperatures in the heating season in a household adopting centralized heating in Wuhan

per unit area was 0.345 GJ/m^2, the average heating index was 33.84 W/m^2, and the electricity consumption per unit area in the initial heating station was 0.93 kWh/m^2.

The actual heating methods of the vast majority of consumers at present are closer to the "full time, full space" mode. If households can be guided to properly control the frequency of opening windows while ensuring indoor air quality, considerable energy-saving effects will be achieved.

The heat consumption data of two residential compounds supplied with heat by Heating Company D are compared with those of Residential Compound A in Wuhan which uses water-source heat pumps for heating. All residents in Compound A use fan coils for heating, which can be started and stopped by consumers depending on demand, and the corresponding heating fees are charged based on the heat consumed. The test was conducted from January 27 to February 26, 2013.

The comparison of heat consumption of the three residential compounds is given in Table 3.11.

Table 3.11 Comparison of heat consumption of residential compounds under test

January 27–February 26, 2013			
Name of compound	**huafu	**wan	Compound A
Heat consumption (kWh/m^2)	26.3	36.1	8

As can be observed from the comparison data, the heat consumption of the two compounds under test is much higher than that of Compound A. The reasons for this may be as follows:

(1) The area-based tariff is used for the compounds under test, and the consumers generally do not regulate and control the heating terminals. In contrast, the heating costs in Compound A are directly linked with the heat consumption, and the consumers have the awareness of actively adjusting the heating terminals;
(2) The compounds under test adopt the floor heating or radiator heating method. These two heating methods fall into radiant heating, in which the wall surfaces need to be heated up to get an ideal indoor thermal environment. This peculiarity of floor heating forces the heating equipment to operate for a long time. In contrast, Compound A uses fan coils as the heating terminals, which heat the air directly, and the room temperature rises rapidly to meet the demand for short-term heating;
(3) The heating rate is generally low in the compounds under test, which is lower than 50% in **huafu and only 28% in **wan. This means that there is heat transfer between adjacent rooms in most households. However, in Compound A, most residents (80%) adopt the heating method and are thus subject to little influence from the heat transfer between adjacent rooms.

Take the 2013–2014 heating season as an example. An economic analysis of heating is made for Heating Company D. The percentage of heat cost alone is up to 50.1%. Given factors including equipment overhaul, materials, labor, and rental, it is difficult to make a profit. According to the company, it is actually operating at a loss at present (Table 3.12).

As can be found through the comparison of the heat consumption per unit area among three compounds adopting different heating methods, the heat consumption of the compound adopting the "full time, full space" heating mode is more than 3–4 times that of the compound adopting the "part time and part space" heating mode. Hence, effective approaches to the reduction of energy consumption in the Yangtze River Basin will be as follows: guiding the heating behaviors of households; encouraging them to switch off the heating measures when there is no one in the

Table 3.12 Heating cost and charged prices of Heating Company D in the 2013–2014 heating season

Cost of energy for heating (RMB/m^2)				Heat price for the consumer (RMB/m^2)
Heat charge	Electric charge	Water charge	Total	
15.96	1.40	0.05	17.14	31.88

room; and reducing the frequency of opening windows while ensuring the indoor environment. With reference to the average heat consumption of Company D in the 2013–2014 heating season, ideally, the energy consumption per unit area of decentralized heating is only 0.06 GJ/m^2.

According to the statistics of the Ministry of Housing and Urban–Rural Development, the floor area of buildings with potential heating demand in the 9 provinces and 2 municipalities in the Yangtze River Economic Belt was approximately 27.7 billion m^2 in 2015. In consideration of the further increase in the floor area of civil buildings in the future, the floor area of buildings with potential heating demand in the Yangtze River Basin is expected to reach 35 billion m^2 by 2050. If this region can be guided effectively through policies to adopt the “part time and part space” decentralized heating mode for buildings, properly reduce the target room temperature, and shorten the heating duration, the total energy consumption of heating in the Yangtze River Basin will not exceed 2.1 billion GJ in 2050 through the calculation based on the 0.06 GJ/m^2 of energy consumption per unit area.

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Chapter 4
Industrial Heating and Residual Heat Emission

4.1 Characteristics and Classification of Industrial Non-Electric Energy Use

In the current industrial classification, the classification methods vary with demands. For example, the industries can be classified into light and heavy industries by product purpose and into discrete and continuous industries by mode of production. To reflect the present situation of industrial heating and residual heat more accurately, we classify industries into two categories based on the characteristics of non-electric energy use for processes in different industries. One is the process industry: Fossil energy is used as fuels and even raw materials to take part in the production of industrial processes, and the energy use in this industry category often has an extremely high demand for temperature and produces rich residual heat resources; The other is the non-process industry: Fossil fuels are primarily used to generate steam, high-temperature hot water, etc. as the heat sources for process, and this category of industry usually has a heavy demand for medium- and low-temperature heat. The specific definitions of the two categories of industries are as follows:

The process industry means the industry using fossil energy as fuels or raw materials, including steel and cement clinker. In the process industry, it is necessary to cool the product stream from the high-temperature reaction or conversion process; therefore, excess heat is discharged at different temperatures to generate rich industrial residual heat resources.

The non-process industry means industry uses hot water and steam as the main heat sources for processes, including food manufacturing, beverage manufacturing, and textile industry. The non-process industry usually has a heavy demand for medium- and low-temperature heat, and hot water or steam is required for heating.

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Table 4.1 Classification of manufacturing industries

	Process industry	Non-process industry
Industry	Ferrous metal smelting and rolling processing, nonferrous metal smelting and rolling processing, nonmetallic mineral products, oil, coal, and other fuel processing, and some chemical raw materials and chemical products manufacturing	Textile, papermaking, and paper products, agricultural and sideline food processing, food manufacturing, wine, beverage, and refined tea manufacturing, pharmaceutical manufacturing, chemical fiber manufacturing, rubber and plastic products, other chemical raw materials and chemical products manufacturing, equipment manufacturing, and other manufacturing
Major product	Steel, copper, aluminum, cement, crude oil processing, coke, synthetic ammonia, calcium carbide, ethylene, methanol, etc	Dairy products, paper, cloth, beverages, pharmaceuticals, chemical fibers, rubber, plastics, caustic soda, soda ash, chemical fertilizer, etc

By the above-mentioned definitions, the 31 major manufacturing industries in the Industrial Classification for National Economic Activities are classified, as shown in Table 4.1. It can be seen that the process industry mainly consists of.

In 2020, the total non-electric energy consumption of the process and non-process industries was about 1.68 billion tons of standard coal, resulting in about 4.55 billion tons of carbon emissions, in which the percentages of the process and non-process industries were 84 and 16% respectively.

4.2 Present Situation of Non-Electric Energy Use and Residual Heat in the Process Industry

The process industry consumes a lot of fossil energy which not only serves as fuel to provide heat for the production process but also partly serves as raw materials to take part in the production, and we cannot merely consider the heating demand. Hence, in this section, both the raw material consumption and the fuel consumption are considered to reflect the consumption of fossil energy in the process industry in a comprehensive manner.

In 2020, the total consumption of terminal fossil fuels in petrochemical, some chemical, nonferrous metal, ferrous metal, and nonmetallic mineral manufacturing was equivalent to 1.41 billion tons of standard coal. The percentages of these five process industries in the total fossil energy consumption are illustrated in the diagram below (Fig. 4.1).

The non-electric energy use and residual heat potential of major products in the five process industries in 2020 are summarized in the Table 4.2. The theoretical residual heat resources of the process industries amounted to about 11.2 billion GJ, and steel and cement industries had huge residual heat potential:

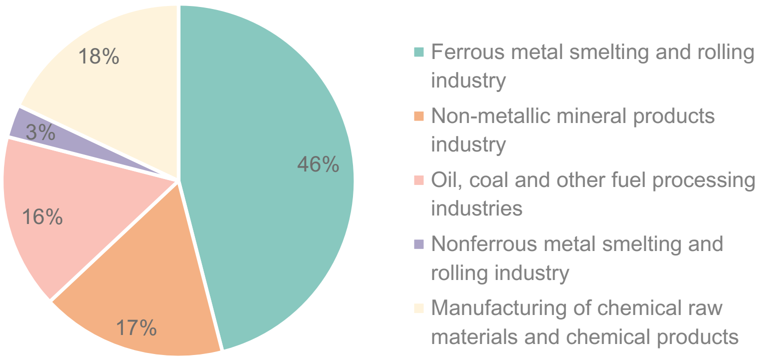

Fig. 4.1 Non-electric energy use structure of the process industry

4.3 Present Situation of Heating in the Non-Process Industry

The present situation of heating in the non-process industry is analyzed based on the *China Energy Statistical Yearbook*: In 2020, the non-process industry consumed about 8 billion GJ of heat in total, equivalent to about 278 million tons of standard coal and leading to about 710 million tons of carbon emissions. The heating demands were mainly concentrated in some chemical raw materials and chemical products manufacturing, textile, papermaking and paper products, agricultural and sideline food processing, food manufacturing, chemical fiber manufacturing, pharmaceutical manufacturing, wine, beverage, and refined tea manufacturing, and rubber and plastic products. The heating demand of the nine industries accounted for about 79% of the total, producing about 590 million tons of carbon emissions (Fig. 4.2).

To better understand the heating demand of the non-process industry, we surveyed the process flows, heat use procedures, and temperature distribution in the textile, papermaking, pharmaceutical, rubber, food manufacturing, and other industries.

For chemical engineering manufacturing falling under the non-process industry, the major products include chlorine alkali, synthetic rubber, polystyrene, and PVC, the main heat use procedures include drying, evaporation, melting, and reaction, and the main temperature demands of heating are concentrated in a range of 150–200 °C.

Food and beverage manufacturing includes agricultural and sideline food processing, food manufacturing, and beverage manufacturing, and under these three major categories of industries, there are such sub-industries as dairy products, sugar manufacturing, meat product processing, and juice manufacturing. The main heat use procedures are evaporation, drying, disinfection, cleaning, etc., and the temperature demands are generally below 150 °C.

Table 4.2 Non-electric energy use structure and residual heat potential of major products in process industries (2021)

Product	Coal (kgce/t)	Coke (kgce/t)	Oil (kgce/t)	Gas (kgce/t)	Steam kgce/t	Theoretical residual heat potential MJ/t	Technical residual heat potential MJ/t	Output in 2021 (10^8 t)	Total non-electric energy consumption (10^8 tce)	Theoretical residual heat potential (10^8 GJ)
Steel	103	423	/	/	/	6256	4824	9.24	4.86	57.77
Cement clinker	116	/	/	/	/	1073	856	15.79	1.83	16.94
Coke	1240	/	/	/	/	2307	2307	4.64	5.75	10.70
Oil refining	/	/	94	/	/	580	574	7.04	0.66	4.08
Copper	97.7	/	24.3	21.2	/	30,800	30,240	0.08	0.01	2.36
Calcium carbide	/	681	/	/	/	8848	6208	0.28	0.19	2.48
Electrolytic aluminum	/	420	/	/	/	6000	/	0.39	0.00	2.31
Synthetic ammonia	1163	/	/	/	/	2262	1720	0.50	0.58	1.13
Methanol	1180	/	/	/	282	/	/	0.67	0.98	/
Ethylene	/	589	/	/	97	/	/	0.22	0.15	/

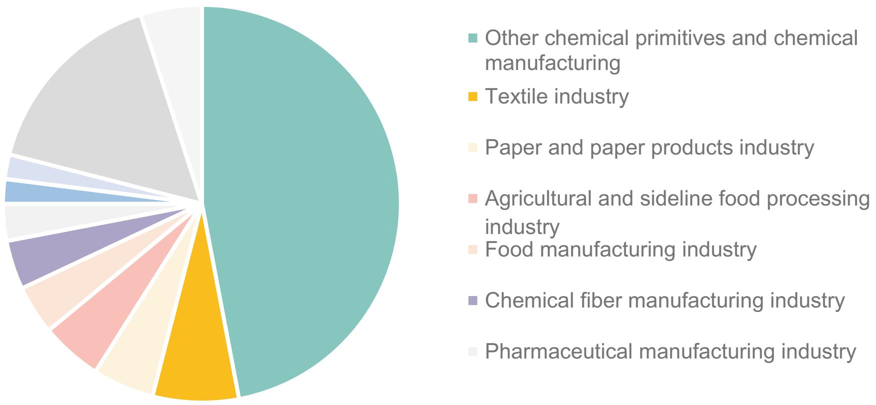

Fig. 4.2 Structure of heating in the non-process industry

For the textile, printing, and dyeing industry, the main process flows include spinning, weaving, printing, and dyeing. The main heating procedures are slashing, cooking, drying, printing, and dyeing, and the temperature demands are generally below 150 °C.

The major products of chemical fiber manufacturing are polyesters, the production process links that use heat directly include the esterification reaction system, the pre-polycondensation system, and the final polycondensation system, and the temperature demands of heating are high, generally above 200 °C.

The main links using steam in pharmaceutical manufacturing include reactive extraction, concentration, and preparation, and the temperature demands are mostly below 150 °C.

The main links using steam in rubber and plastic manufacturing include calendaring, extrusion, and vulcanization, and the temperature demands are concentrated below 150 °C.

The main heat use links in the paper manufacturing industry include bleaching and drying, and the temperature demands are concentrated below 150 °C.

The temperature demands of nine major non-process industries are divided by the temperature demands of the production processes of major products (Table 4.3).

Looking at the heating demands of the nine industries, it is found that 93% of heating demands in the non-process industry at present are concentrated below 200 °C and that 50% are concentrated below 150 °C, which can be met totally by using heat pumps and other low-carbon heat sources. Among them, 26% of heating demands in chemical raw material and chemicals manufacturing are concentrated below 150 °C; in addition, 86% of heating demands in other non-process industries are concentrated below 150 °C (Fig. 4.3).

Table 4.3 Structure of temperature demand of heating in the non-process industry

	Major product	50–100 °C (10^8 GJ)	100–150 °C (10^8 GJ)	150–200 °C (10^8 GJ)	> 200 °C (10^8 GJ)	Subtotal (10^8 GJ)
Some chemical raw materials and chemical products manufacturing	Chlorine alkali, synthetic rubber, polystyrene, PVC	0.0	10.0	27.0	0.8	37.8
Textile industry	Yarn, cloth	3.3	2.5	0.0	0.0	5.7
Papermaking and paper products	Paper pulp, paper board	0.2	4.0	0.0	0.0	4.2
Agricultural and sideline food processing	Sugar	0.2	3.4	0.0	0.0	3.6
Food manufacturing	Dairy products	0.8	2.3	0.0	0.0	3.1
Chemical fiber manufacturing	Polyester	0.0	0.0	0.0	2.9	2.9
Pharmaceutical manufacturing	Chinese formulated products	1.8	0.5	0.0	0.4	2.7
Wine, beverage, and refined tea manufacturing	Juice	1.4	0.5	0.0	0.0	1.9
Rubber and plastic products	Tire, plastics	0.1	1.1	0.4	0.0	1.6
Subtotal		7.7	24.2	27.4	4.1	63.5

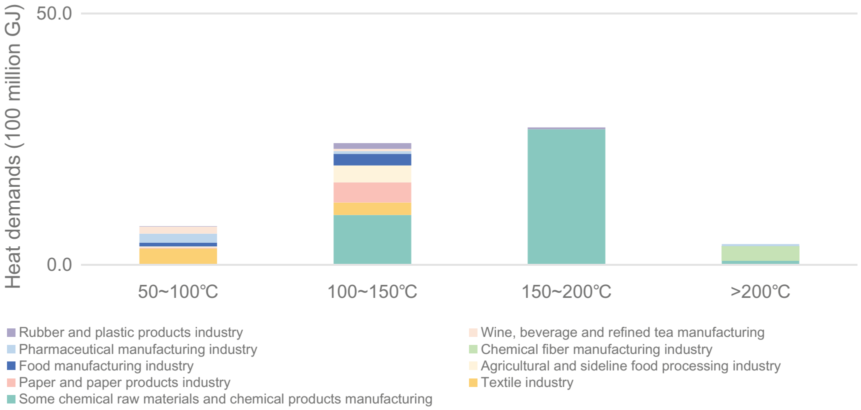

Fig. 4.3 Structure of temperature demand of heating in the non-process industry in 2020

The characteristics of the chemical industry, food industry, and light industry are as follows: 1. There is a wide range of products, energy use is relatively decentralized, the downstream demands are complicated, and the industrial demands are hard to be quantified with the specific product output; 2. As high-value-added industries, they will be the key components of the added value of the future secondary industry, and the future energy consumption demand may be predicted based on the added value of the industry. Therefore, in this study, the structure of added value of industries in 2050 and the energy consumption per unit of value added are determined mainly with reference to the existing different situations of developed countries and in combination with the future orientation of China to becoming a manufacturing powerhouse. Meanwhile, the key fossil energy alternatives in the industries are analysed, the future promotion rate is planned based on the feasibility analysis, and finally, the industrial energy use in different scenarios is obtained. The final estimates are as follows: The heating demand of the four industries in 2050 will be about 12.5 billion GJ, including about 7.6 billion GJ of heating demand below 150 °C.

Chapter 5
DHW Heating and Steam for Functional Buildings

5.1 DHW Heating

5.1.1 Analysis of DHW Demand

(1) DHW demand of residential buildings

According to the *China Population and Employment Statistical Yearbook*, China's urban population in 2020 was approximately 900 million. In the practical project case study, the DHW consumption was about 20–40 L per person per day. By taking the DHW consumption at 20 L per person per day, the temperature after water mixing at about 40 °C, and the tap water temperature at 15 °C, the total heat demand of DHW for urban residential buildings was estimated to be about 690 million GJ (Fig. 5.1).

(2) DHW demand of schools

According to the *Educational Statistics Yearbook of China*, China had 537,100 schools of all levels and types, 289 million students, and 17.9218 million full-time teachers in 2020. In recent years, the Ministry of Education has stopped publishing the number of boarders, so the numbers of teachers and students boarding in schools were estimated based on the dormitory area. The total area of relocation dormitories for teachers in primary, junior middle, and senior high schools were about 59 million m^2, and the total area of students' dormitories in primary, junior middle, common senior high, and secondary vocational schools as well as higher education institutions was about 63.66 million m^2. Based on the per capita area of relocation dormitories for teachers taken at 35 m^2 and the per capita area of students' dormitories taken at 8 m^2, the number of teachers boarding in schools was estimated to be about 1.69 million, accounting for about 9.4% of the total number of teachers, and the number of students boarding in schools was 79.57 million, making up about 27.5% of the total number of students. By taking DHW consumption at 35 L per person per day,

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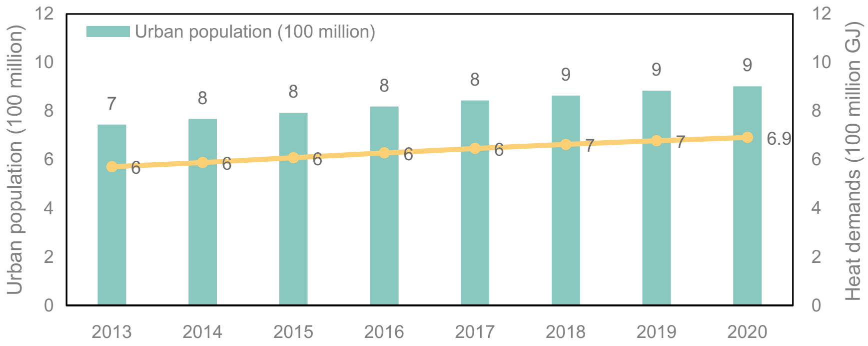

Fig. 5.1 DHW demand of residential buildings in China during 2013–2020

the total heat demand of DHW for dormitories in schools was estimated to be about 89 million GJ.

(3) DHW demand of hospitals

According to the *Statistical Bulletin on Health Development in China 2021*, China had 7.413 million hospital beds, the rate of utilization of which was 72.3%, and 8.478 million health workers in 2020. By taking the DHW consumption of patients at 70 L per bed per day and that of the medical staff at 65 L per person per day, the total heat demand of DHW for hospitals was estimated to be about 34 million GJ.

(4) DHW demand of hotels

According to the statistical data of the National Bureau of Statistics, China had about 4.5 million hotel rooms and 7.15 million hotel beds in 2020. Based on the *Statistical Report on Star-rated Hotels in China*, the average hotel occupancy rate was 55% during 2013–2019 and fell to 39% in 2020 due to the COVID-19 pandemic. By taking DHW consumption at 110 L per person per day, the total heat demand of DHW for hotels was estimated to be about 12 million GJ.

The DHW demand of all of the above-mentioned types of buildings in 2020 is collected, as shown in Table 5.1. The total DHW demand of these types of buildings was about 830 million GJ.

5.1.2 *Present Situation of DHW Heating*

Urban DHW is classified into residential DHW and P&C DHW by the building type and into centralized heating and decentralized heating by the heating method.

(1) Present situation of DHW heating for residential buildings

Table 5.1 Estimates of heat demand of DHW

	Per capita DHW consumption		Basic parameter			DHW consumption	
	Value	Unit	Indicator	Value	Unit	Value	Unit
Urban residential building	20	L/(person day)	China's urban population	9	10^8 people	6.9	10^8 GJ
School building	35	L/(person day)	Number of students and teachers boarding in schools	8126	10^4 people	0.89	10^8 GJ
Hospital building	70	L/(bed day)	Number of beds actually used	536	10^4 beds	0.14	10^8 GJ
	65	L/(person day)	Number of medical staff	848	10^4 people	0.2	10^8 GJ
Hotel building	110	L/(bed day)	Number of beds actually used	279	10^4 beds	0.12	10^8 GJ

Residential DHW is classified into centralized DHW and decentralized DHW by the heating method. At present, most of the residential buildings in China use the decentralized DHW system, and only a small proportion of them use the centralized DHW system.

The main heat sources of the centralized DHW system are coal-fired boilers, gas-fired boilers, and heat pumps. When the centralized DHW supply system is used, the average daily hot water consumption of residents is 45–60 L per person per day. The effective heat utilization rate of the centralized DHW system is lower than that of the decentralized DHW system mainly due to the huge heat dissipation in the transmission pipe network, especially the heat dissipation in the secondary pipe network, which accounts for 35–56% of the total energy consumption. The higher the average daily water consumption of households is, the higher the effective heat utilization rate will be. When the average daily water consumption of households is high, the centralized DHW supply system has certain advantages. When the average daily water consumption of households is low, the decentralized DHW supply system is obviously economical and energy-saving.

The main heat sources of the decentralized DHW system are electric water heaters, gas water heaters, and solar water heaters. When the decentralized DHW system is used, the average daily hot water consumption of residents is 30–40 L per person per day. According to the data from the National Bureau of Statistics, the number of water heaters owned by every 100 households in China was 90.4 units in 2020, and the number of water heaters owned by every 100 urban households was 100.7 units, as shown in Fig. 5.2. The percentages of various water heaters in China are illustrated in Fig. 5.3. At present, electric water heaters are used for most decentralized DHW

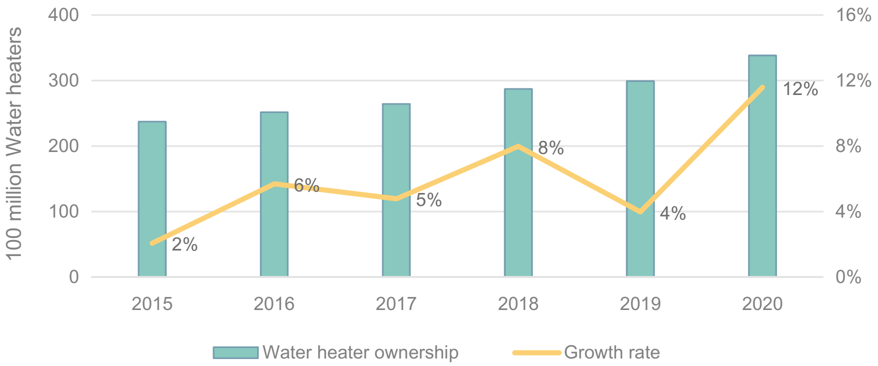

Fig. 5.2 Number of water heaters owned by urban households

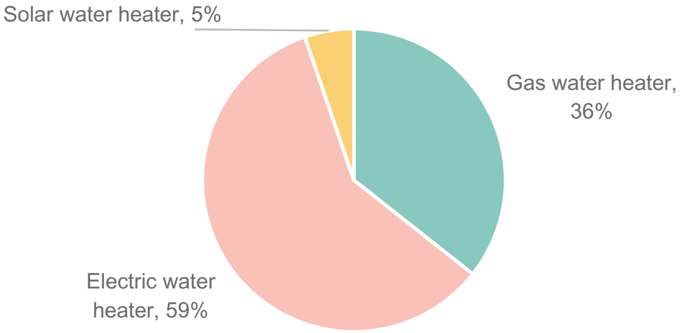

Fig. 5.3 Percentages of various water heaters owned by households in China

systems, accounting for 59% of the total number of water heaters, and followed by gas water heaters, accounting for 36% of the total.

(2) Present situation of DHW heating for school buildings

DHW in schools is mainly supplied as bathing water and potable for students, and in some schools, DHW also needs to be supplied to the canteen and other buildings. There are three main methods of supply: centralized hot water supply, local centralized hot water supply, and decentralized hot water supply.

According to statistics, the per capita energy consumption and water consumption of undergraduates are four times and two times those of the national residents respectively, so the DHW systems of schools have great potential for energy saving. At present, split electric water heaters or air source heat pumps are mostly used to supply hot water in southern China. In northern China, most schools use gas-fired boilers to supply heat, coal-fired boilers have been phased out due to serious pollution, and some schools recycle the residual heat resources, including the residual heat from the cooling of generator units, as the heat sources of hot water. In addition, air source heat pumps and solar water heaters with low pollution and good energy-saving effects have been developed rapidly and used to supply DHW in many schools.

(3) Present situation of DHW heating for hospital buildings

DHW in hospitals are mostly supplied by gas-fired or oil-fired boilers, which use natural gas as the major form of energy; besides, as hospitals have steam for disinfection, laundry, and other special functions, centralized steam boilers are used as the main method of heat supply. A small number of hospitals also use municipal hot water or use the indirect heat transfer of municipal steam to produce hot water. Some large- and medium-sized hospitals also use solar water heaters and other renewable energy to supply DHW to reduce fuel consumption and operation cost.

The DHW heating methods of a total of 21 grade A tertiary hospitals from four regions in China were surveyed, and the DHW supply methods of hospitals by zone are shown in Fig. 5.4. In severe cold and cold areas of China, the climate is cold, so the main heating methods for DHW in hospitals are boilers, lithium bromide direct-fired units, and electric water heaters as well as a small number of solar water heating systems, and renewable energy is less utilized. In the HSCW zone of China, the percentage of renewable energy for heating in hospitals increases evidently, in addition to boilers and lithium bromide direct-fired units. In the hot-summer and warm-winter (HSWW) zone of China, the climate is warmer, and solar energy resources are abundant, so the percentage of utilization of renewable energy (such as solar energy, water source, and air source) further increases compared to that in the HSCW zone, and various heating methods are almost uniformly distributed.

(4) Present situation of DHW heating for hotel buildings

DHW is mostly supplied 24 h a day in hotels. Currently, large and high-star-rated hotels mostly use gas-fired boilers as the main heat source and install air-source heat pumps or solar water heaters as the auxiliary heat source to preheat DHW. Some hotels use normal-pressure hot water boilers and heat exchangers, which are relatively common heating methods at present. Because hotel laundries need steam, some

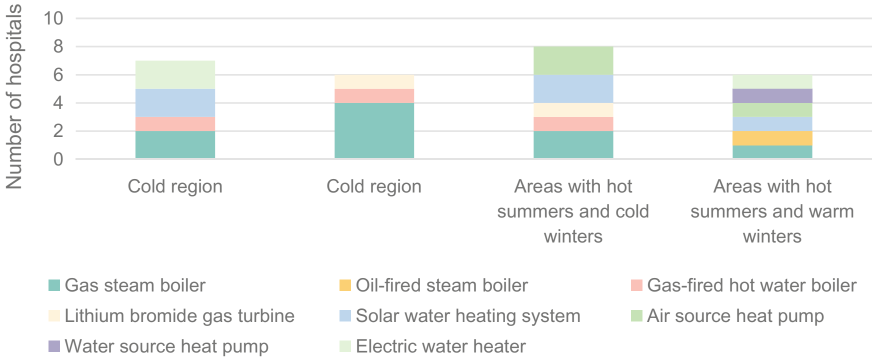

Fig. 5.4 Comparison of DHW supply methods of hospitals by zone

hotels directly use a set of centralized gas-fired steam boiler, which generates DHW through the steam-water heat exchanger. A few hotels use the municipal heating network to produce DHW in the heating season and use self-contained boilers in the non-heating season. The vacuum hot water boiler with a built-in heat exchanger, which can directly produce hot water at a required temperature, is a new trend in the field of hotel heating.

5.2 Supply–Demand Analysis of Steam for Hospitals

5.2.1 Steam Demand of Hospitals

By the end of 2020, the total floor area of China's hospital buildings was 760 million m^2, accounting for about 5.4% of the newly built building stock of P&C buildings in China. Due to the special medical service attribute of hospitals, the main heat use sub-categories include the heating system, the DHW system, the steam system of the sterile supply room, the laundry, and the canteen's steam or hot water system. The heating demand of the heating system and the DHW system have been analyzed in the above subsection, and this subsection is mainly to analyze the steam heat consumed for special functions (disinfection, laundry, and cooking) and accordingly estimate the steam heat consumed for special functions in hospitals in China.

The steam heat consumed by the sterile supply room, the laundry, and the nutrition department is mainly related to the number of patients taking surgery, the occupied beds (number of beds × sickbed occupancy rate), and the number of people using energy (number of people using energy = daily number of visits + number of beds × sickbed occupancy rate + number of health workers) respectively. Based on the number of occupied sickbeds, the daily average number of visits, the number of health workers, and the number of inpatients taking surgery in China in 2020 as given in the *China Health Statistical Yearbook*, it is calculated that the total steam consumption for special functions in hospitals is 22,502,200 GJ and that the gas consumption is about 658 million Nm^3.

5.2.2 Present Situation of Steam Supply in Hospitals

At present, the steam for special functions in hospitals is supplied by steam boilers for the most part and is municipal steam for a small part. Overall, the solution to heating systems in many hospitals is to install a set of centralized steam boilers to meet the heating demands of all grades. As a result, the overall heating efficiency is low.

The heating efficiency of steam boilers varies greatly in different hospitals, which is mainly related to the use of steam, in addition to being subject to different degrees of

Table 5.2 Percentages of heat use of sub-categories in hospitals by zone

Hospital category	Zone	S/N	Percentages of heat use of sub-categories (%)					
			Disinfection	Laundry	Nutrition department	DHW	Heating	Heat loss
Category I	HSCW	C1	70	–	–	–	–	30
	HSWW	D1	80	–	–	–	–	20
Category II	Severe cold area	A2	11	19	33	–	–	37
	Cold area	B3	29	–	18	–	–	53
Category III	Severe cold area	A1	23	–	–	11	–	66
	Cold area	B2	1	–	–	27	–	72
Category IV	HSCW	C3	3	–	–	33	19	45
	HSCW	C4	2	8	8	20	20	42

influence from routine maintenance including steam pipe insulation. Here, hospitals are classified into four categories based on the use of steam boilers. Category I: hospitals in which steam boilers are only used for the sterile supply room; Category II: hospitals in which steam boilers are not just used for the sterile supply room but are not used for DHW and heating; Category III: hospitals in which the use of steam boilers involves DHW but not heating; Category IV: hospitals in which the use of steam boilers involves both DHW and heating. The heat use conditions of sub-categories in all categories of hospitals are listed in the table below. As can be known from Table 5.2, Category I hospitals have the least heat loss in the use of steam, while Category III and IV hospitals directly exchange steam for hot water for DHW and heating, which is essentially a waste of heat source grade and should be avoided as far as possible.

5.3 Supply–Demand Analysis of Steam for Hotels

5.3.1 Steam Demand of Hotels

By the end of 2020, the newly built building stock of hotel buildings in China was 623 million m^2, accounting for about 4.4% of the newly built building stock of P&C buildings in China. The steam for hotels is mainly concentrated in the laundry. The main equipment consuming steam in the laundry includes ironing machines, dryers, and water extractors. According to the survey data, the annual steam consumption per unit occupied bed in hotels is 7,033 kg/(occupied bed a). In 2020, the total number of beds in star-rated hotels in China was 7.19 million, and due to the COVID-19 pandemic, the average occupancy rate was only 39%; thus, it could be estimated that the steam consumption of hotel laundry in hotels in China was 19.722 million tons. Based on 0.7 MPa saturated steam and temperature of tap water at 20 °C, it is calculated that the actual steam heat consumption is 52,817,900 GJ and the gas consumption is about 1.544 billion Nm^3.

5.3.2 Present Situation of Steam Supply in Hotels

Currently, the steam for hotels is mostly supplied by steam boilers. A small number of hotels in northern China use municipal steam, and heat pumps are rarely used to supply steam in hotels.

Take a five-star hotel in the Pudong New Area of Shanghai for example. Three sets of 7 t/h gas steam boilers are used to supply heat for heating, DHW, and laundry equipment. Since steam boilers are used as the heat source for the DHW system of the hotel, steam is also used for heat transfer to make 50–55 °C DHW, causing a serious waste of grade. According to relevant estimates, the heating efficiency of steam boilers is only about 70%. Considering the natural gas price and the heat loss in heat exchangers and transmission pipelines, the heating cost is approximately RMB 0.63 per kWh. If steam boilers are replaced with heat pumps, the heating cost is about RMB 0.28 per kWh, far below the boilers' heating cost, thus the DHW cost can be reduced significantly.

In view of the problems of the current centralized steam boilers in hospital and hotel buildings such as poor steam quality, much condensate water, being unfavorable to disinfection and sterilization, and low heating efficiency, it is recommended that decentralized heating systems should be adopted for the sub-categories in the future. The specific recommendations are as follows:

1. Hot water boilers may replace steam to supply heat for DHW and heating, and abundant renewable energy may be used for heating according to the local conditions, such as air-source heat pumps, water-source heat pumps, solar energy, etc.
2. Decentralized heating systems may be used for the sub-categories. For sterile supply rooms, it is recommended that small-capacity gas steam boilers (steam generators), heat pump-type steam generators, etc. should be installed nearby to start the boilers for the preparation of steam at any time. For laundries, it is recommended that steam generators should be installed nearby or special laundry equipment with electric drying should be used. For kitchens, special steam boilers should be configured separately.
3. Since the steam condensate is generally at a high temperature, it is recommended that heating recovery units should be used for the recovery.

Chapter 6
Challenges Facing Urban Energy Transition Under the Carbon Peak and Neutrality Goals

To achieve the goals of carbon peaking and carbon neutrality (the carbon peak and neutrality goals), China needs to complete the transition from fossil energy to zero-carbon energy. In this regard, cities are the "main battlefields" to reach the carbon peak and neutrality goals since most energy is consumed by buildings, transportation, and industry in cities and surroundings. How the urban energy supply system develops is crucial to achieving the carbon peak and neutrality goals. The urban energy supply system mainly meets the following demands:

- Electricity demand, including electricity consumption of urban buildings, industry, transportation, and other municipal facilities;
- Heating demand, including heating for the building and industrial sectors;
- Natural gas demand, including natural gas for fuel, power, raw material, or supplementary electricity purposes.

The urban energy supply system consists of an electricity transmission and distribution system, a gas supply system, and a heat supply system. The three systems have been independent of each other for a long time. However, under the vision of carbon neutrality, the three systems will undergo radical changes in their structures and need to work together and support each other. The urban energy supply system must be studied and planned as a whole system to finish the overall task of low-carbon energy supply.

The urban energy system involves the transition from primary energy to end-use energy, the transmission and distribution from the source of supply to the demand side, and the reception and conversion at terminals. The possible carbon emissions will be generated mainly in the energy conversion process of the urban energy supply system. Natural gas becomes the main source of direct carbon emissions in the final consumption of urban energy. Avoiding the use of natural gas as much as possible is one of the important tasks to realize carbon neutrality.

In the field of natural gas application related to buildings, it is entirely possible to replace gas with electricity and heat. Cooking has seen a gradual trend toward

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the comprehensive development of electric cooking. There is no doubt that the way forward for producing domestic hot water (DHW) will be the replacement of gas with electricity, and the gas for both urban heating and industrial steam can also be substituted with electricity and heat. Natural gas, as the fuel for automobiles and other means of transport, will also be replaced with electricity.

Therefore, natural gas will be substituted in all of the above-mentioned areas. However, in specific places including factories and power plants, it is necessary to reserve a small amount of natural gas as a chemical raw material and to fuel thermal power plants for seasonal peak shaving and safe standby of power grids. Dedicated gas pipelines can be provided in these factories and power plants for them to use gas in a centralized manner. The gas pipe networks mainly oriented toward building demands in cities will be likely to be canceled gradually. Electricity and heat supplies will be at the core of the urban energy supply system. How to realize the zero-carbon transition of power generation and heat sources becomes critical to the comprehensive realization of the carbon neutrality goal for the urban energy supply system.

6.1 Power Transition for New Power System

In cities, with the gradual replacement of fossil energy, electric energy will be more widely used. Nevertheless, thermal power generation with high carbon emissions is still the major means of power generation in China. Therefore, the zero-carbon transition of power is the foundation for establishing a new power system and also the key to the realization of carbon neutrality for the urban power supply system.

The coal-fired power plants will be gradually replaced by wind power, solar PV power, hydropower, and other renewable energy as well as nuclear power. The obvious characteristic that distinguishes renewable energy generation from thermal power is that the generating capacity of the former depends on the natural climatic conditions, leading to a prominent contradiction between supply and demand. Cities, as the main consumers, guarantee the effective consumption of renewable energy generation through the dynamic change of their demands, which is core to realizing carbon neutrality.

The dynamic balance between electricity supply and demand can be divided into short-term balance and long-term balance. The short-term balance mainly refers to the supply–demand issue of intraday electricity. Some short-term problems of balancing electricity supply and demand can be solved effectively by multiple methods of energy storage. Moreover, a flexible building energy terminal that is formed by the connection of a building and an intelligent charging pile system with electric vehicles will largely relieve the short-period contradiction between supply and demand for the urban electric power supply system.

However, it is very difficult for the above-mentioned energy storage and regulation measures to relieve the long-term contradiction between electricity supply and demand. In China, on the whole, wind power is abundant in spring and winter, power generated by solar PV is plentiful in summer and scarce in winter, and hydropower resources are rich in summer and autumn. Nuclear power is suitable for carrying the base load. The supply–demand relationship between renewable energy generation and electrical power loads exhibits an obvious seasonal difference. The seasonal imbalance between electricity supply and demand can be addressed by the following four means: energy storage; a further increase in the installed capacity of zero-carbon power generation; the retention of some thermal power plants and the installation of Carbon Capture and Storage (CCS) systems; and the change in electricity demands.

Energy storage methods such as pumped storage and chemical battery energy storage require heavy investment and are uneconomical for long-term power regulation. One of the seasonal regulation methods is to develop regulated hydropower with a storage capacity to store the hydropower resources in the wet season for power generation in the dry season. This method has been adopted in Northern European countries to effectively solve the difficulty in seasonal peak shaving of electricity. However, in China, hydropower resources account for a relatively small proportion and can only solve less than a quarter of the seasonal regulation problems.

Increasing the installed capacity of wind power, solar PV power, etc. can make up for the deficiency in power generation during the period of peak power load in winter and summer. But excessive generation may also lead to more curtailment of wind/solar PV power in other seasons.

Some thermal power plants can be retained for peak load of electricity in winter and summer and use coal, natural gas, biomass, etc. as fuels. The carbon dioxide emitted after the burning of the fuels can be captured by CCS. Negative carbon emissions are achieved by using CCS to recover CO_2 after power generation with biomass fuels. Therefore, as long as biomass fuels in thermal power reach a certain proportion, zero and even negative carbon emissions can be realized. Analyses indicate that both the investment and operation costs of the CCS system are lower than the costs of hydrogen generation and storage.

In addition, electricity consumption can be decreased in winter and summer and increased in spring and autumn. To reduce the peak power load in winter, heating methods with higher energy efficiency should be adopted as much as possible. The electricity consumption of heating heat pumps can be reduced effectively by utilizing the waste heat from thermal power plants, nuclear power plants, and other industries.

6.2 Challenges Facing Low-Carbon Transition of Heating

How to realize zero-carbon heating is another key issue in realizing the carbon neutrality goal for the urban energy supply system. At present, the great majority of heat sources consume fossil fuels. Only about 10% of them use electricity and industrial waste heat for heating. It is necessary to think hard about such questions as how to achieve the carbon peak and neutrality goals in the heating field, how to obtain zero-carbon heat sources, and how to follow the path of carbon neutrality.

Whether coal is to be retained is the first focus of concern for the industry. At present, there are still lots of coal-fired boilers. Under the carbon peak and neutrality goals, coal-fired boilers with low energy conversion efficiency and high carbon intensity are the first to be shut down and replaced. If coal-fired thermal power plants can effectively recover all waste heat emitted by them, their energy consumption and carbon emissions will decrease significantly compared to coal-fired boilers. Most authorities suggest that thermal power plants will still play an irreplaceable role in the power system, which means that thermal power plants will remain in place for a long time.

Although the state and local governments have vigorously promoted natural gas heating in recent years, the current scale is still relatively small due to two main reasons. One is the high cost of gas; the other is the insufficient security for the gas supply. Therefore, natural gas is not the future direction of development.

The constraint imposed by carbon neutrality on the future use of fossil energy makes electrified heating, including direct electric heating and electric heat pumps, highly valued. Direct electric heating is to convert electric energy directly into heat energy and requires a small investment, thus being beneficial to the consumption of curtailed wind and solar PV power. Electric heat pumps extract low-grade heat from the soil, air, rivers, lakes, and seas, with high energy efficiency.

However, due to the low density of the heat offered by low-temperature heat sources in the natural environment, it is difficult to meet the demands of urban buildings with a high floor area ratio. Therefore, this heating method is more applicable to rural areas with a low building density and southern cities where the density of heating loads is relatively low.

In 2019, the Building Energy Research Center (BERC), Tsinghua University proposed a "Clean Heating 2025" mode for northern urban heating (NUH). The main characteristics of the mode are as follows: First, heat sources are dominated by the abundant thermal power plants and other industrial waste heat in China; second, the low return water temperature is adopted during transmission in the heating network; third, heat and power coordination; fourth, natural gas-fired boilers are used as the heat source for peak shaving.

This clean low-carbon heating mode can reduce the carbon emissions from heating by 80% without a significant increase in the heating cost compared to heating with coal-fired and gas-fired boilers. This mode has been demonstrated in some Chinese cities, with a prominent effect of energy saving and emission reduction. However, this mode still cannot be treated as the final mode for the comprehensive realization of carbon neutrality in China because carbon dioxides are still emitted from the use of natural gas for peak shaving.

There are two paths to zero-carbon heating abroad, i.e. the centralized heating route in Northern European countries and the electric heat pump heating route adopted in the United States and other countries. Both paths make full use of the low-grade heat energy and utilize the relatively centralized low-grade heat energy whenever possible. Northern Europe witnesses the large-scale utilization of the waste heat emitted by biomass and garbage power plants, the industrial waste heat, the ocean thermal energy, and other thermal energy warmer than air, all of which, whether used directly or after being heated by heat pumps, need to be transmitted to buildings through heating networks. Since cities of a certain size in Northern European countries have set up pipe networks for heating, the heating networks can be fully utilized to transmit the above-mentioned centralized low-grade heat energy to consumers, thus realizing zero-carbon heating at a low cost. This is also the fifth-generation heating mode advocated in Northern Europe and other regions. For countries like the United States without heating network facilities, air source and ground source heat pumps and even direct electric heating are used generally, but considering the investment and operation costs, they are less economical than the low-grade heat transmitted in a centralized manner.

In the field of industrial heating, fossil energy is still dominant among heat sources. Steam generation with electric boilers has such problems as low energy efficiency and high cost. Industrial heating requires higher temperature parameters, but steam generation with air source and ground source electric heat pumps has a low Coefficient Of Performance (COP) and a high cost, thus it is very hard to adapt to the requirements of industrial heating.

In summary, from the perspective of heating, heat pumps can avoid the direct use of fossil energy but are subject to the low temperature and low density of heat available from low-temperature heat sources. Therefore, getting high-density low-temperature heat sources has become the key to the development of low-carbon heating.

Chapter 7
Low-Carbon Heating Mode Dominated by Waste Heat Utilization

7.1 Analysis of Future Power and Heating Source Structure

7.1.1 Power and Heating Systems Under Energy Transition

In China, the current power supply and heating sources are mainly dominated by thermal power generation and coal combustion, leading to higher carbon emissions. In the future, the main task is to promote the large-scale and high-proportion transition to new energy sources in the power system and provide zero-carbon heat sources for building heating and non-process industrial production to achieve carbon neutrality. With the construction of a new type of power system primarily based on renewable energy and the gradual popularization of electrified heating, urban energy will be mainly concentrated in the fields of electricity and heating, making carbon emissions from power and heat generation a key factor in achieving urban carbon neutrality. Therefore, it is necessary to further understand the development of power sources in the future power system and the interplay between electricity and heating.

This chapter considers two scenarios for achieving zero-carbon heating by 2050: one is based on centralized heating with waste heat utilization, and the other is based on comprehensive electrification for heating. A simplified model is established to reflect the changes and balance of electricity supply and demand on a daily basis. Based on this, the capacities and operation of various power generation technologies are determined, along with the optimal heating combinations. The model is applied to different regions in China, and specific calculations are made for each region.

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7.1.2 Renewable Energy Resources and Power Output Characteristics

In China, the onshore wind energy resource at a height of 100 m has a potential development capacity of 86.9 billion kilowatts, mainly concentrated in the “Three North” regions (Northwest, North China, Northeast). The offshore wind resource, at water depths of 5–50 m and a height of 70 m, has a potential capacity of approximately 500 million kilowatts.

The maximum technical development potential for hydropower in China is about 500–600 million kilowatts, of which 355 million kilowatts have been developed so far (conventional hydropower only, excluding pumped storage). With the completion and operation of the Jinsha River Wudongde, Baihetan, Yalong River Lianghekou, and Dadu River Shuangjiangkou hydropower stations, in addition to the existing Yarlung Zangbo River and Nu River hydropower bases, the development of major hydropower bases in China has been basically completed. By 2050, the installed capacity of conventional hydropower in China will reach 510 million kilowatts.

The power output characteristics of various renewable energy sources lead to temporal and spatial mismatches in power supply and demand. Wind and solar energy exhibit significant seasonal variations, with around 60% of wind power concentrated in spring and winter, and around 60% of solar power concentrated in summer and autumn. Additionally, at the regional level, wind and solar power output characteristics differ, with the northwest, north, and northeast regions having better wind resources, while the northwest and north regions have better solar resources. Centralized photovoltaic and distributed photovoltaic show distinct seasonal differences in output; centralized photovoltaic exhibits a 25% difference in average output between winter and summer, while distributed photovoltaic shows a 50–60% difference.

Furthermore, hydropower exhibits a "summer surplus and winter shortage" seasonal characteristic, and its generation capacity varies according to seasonal changes. Each year is divided into periods of abundant water, normal water, and water scarcity. Taking Sichuan province as an example, the abundant water period is from June to October, the normal water period is in May and November, and the water scarcity period is from December to April of the following year. During the abundant water period in summer, hydropower generation can be high due to the abundant water supply, while during the water scarcity period in winter, hydropower generation may decrease or even stop. Hydropower stations with annual regulation or above can store excess water during the abundant water period for use during the water scarcity period. According to statistics for water and hydropower stations in different river basins operated by the State Grid Corporation, the proportion of hydropower stations with annual regulation or above in the Yangtze River basin and Yellow River basin is 43.6% and 21.7%, respectively.

Nuclear power is an important source in the future zero-carbon power system. As of April 2020, China had a total of 18 nuclear power plants (including those under construction) with a total installed capacity of 45.9 million kilowatts. Among them, the number of nuclear power units in northern regions has been increasing, with 17 units in commercial operation or under construction, and a total installed capacity of 16.71 million kilowatts. According to relevant nuclear power plans, China's coastal areas can accommodate nuclear power resources ranging from 178 to 206 million kilowatts.

7.1.3 Regional Power System Model and Power Balance Results for Future New Power System

(1) Regional Power System Model

To analyze the impact of future power systems on heating in northern regions, the country is divided into 21 power grid regions. The 17 provinces and regions in the north are treated as independent areas, while the southern region is divided into four areas: Southwest Grid, Southern Grid, East China Grid, and Central China Grid (excluding Henan). The regions are numbered as follows: 1. Xinjiang, 2. Qinghai, 3. Ningxia, 4. Gansu, 5. Shaanxi, 6. Southwest, 7. Southern, 8. Central China (excluding Henan), 9. East China, 10. Henan, 11. Shaanxi, 12. Shandong, 13. Southern Hebei, 14. Western Inner Mongolia, 15. Northern Hebei, 16. Beijing, 17. Tianjin, 18. Eastern Inner Mongolia, 19. Heilongjiang, 20. Jilin, 21. Liaoning. The model includes 14 types of power generation installations: 1. Coal-fired power, 2. Coal-fired power with Carbon Capture, Utilization, and Storage (CCUS), 3. Gas-fired power, 4. Gas-fired power with CCUS, 5. Biomass power, 6. Biomass power with CCUS, 7. Onshore wind power, 8. Offshore wind power, 9. Centralized photovoltaic, 10. Distributed photovoltaic, 11. Nuclear power, 12. Run-of-river hydropower, 13. Daily regulated hydropower, 14. Seasonal regulated hydropower. The model also considers the transmission and distribution limitations between regions and presents the daily power supply and demand balance for each region.

In this subsection, the model does not consider heating demand. The optimization objective is to minimize the total cost of the power supply system, including investment costs for power sources, transmission grids, and energy storage, as well as operational costs. The online capacity of thermal power generation (coal-fired, gas-fired, and biomass) and nuclear power cannot exceed the installed capacity. Biomass power generation must meet the constraints of available biomass resources in each region, while nuclear power must meet the constraint of 7,000–8,000 operating hours per year. The carbon emission limitation requires net emissions from coal-fired and gas-fired power plants to be equal to the CO_2 captured by CCS from biomass power plants. In addition, nuclear power and conventional hydropower are not involved in the optimization calculations. Nuclear power is assumed to have a development capacity of 178–206 million kilowatts along the coastal areas, and conventional hydropower is assumed to have a development scale of 500 million kilowatts.

(2) Future Power and Heat Demand

In China, the heat demand includes high-density heat demand for winter heating in northern urban areas and heat below 150 °C for non-process manufacturing, totaling 13 billion GJ, equivalent to 3.6 trillion kWh of heat. The future choice between centralized heating with low-grade waste heat utilization and comprehensive electrification will significantly impact the quantity and characteristics of future power load requirements. This will be further analyzed in the following simulations. For the future scenario with a total electricity consumption of 14 trillion kWh in 2050, including electricity for industrial steam production above 150 °C and electricity for rural heating in the north and decentralized heating in the south, the electricity demand for heating in northern urban areas (5.45 billion GJ) and non-process industries (7.6 billion GJ) for heat preparation and transportation are not included. The electricity load exhibits distinct winter and summer peaks, with a daily peak total load of 1.92 billion kilowatts.

(3) Power Balance Results for Future New Power System

According to the analysis method of the regional power system model, the electricity load and renewable power generation are optimized on a daily basis. Under the scenario of 14 trillion kWh total electricity consumption, the total installed capacity required for the optimized power system is 730 million kilowatts, of which 610 million kilowatts are from wind and solar power, accounting for 83.7% of the total capacity. The proportion of wind and solar power in total electricity generation is 71.8%, with a wind and solar curtailment rate of 5.7%. The daily maximum electricity demand for thermal power is 480 million kWh nationwide, considering the variation in output throughout the day, the reserved peaking thermal power capacity should be between 550 to 600 million kilowatts, accounting for 7.5% to 8.2% of the total installed capacity, generating 0.8 trillion kWh of electricity, representing 5.7% of the total annual electricity generation. By implementing Carbon Capture and Storage (CCS) for emissions from coal-fired and gas-fired power plants and achieving a biomass fuel proportion above 25%, the amount of CO_2 captured from biomass power plants can exceed the CO_2 emissions from coal and gas power plants, achieving overall zero emissions.

The key challenge for the power system is to address the seasonal and daily fluctuations in power supply and demand. With the increasing proportion of fluctuating renewable energy generation, such as wind and solar power, in the future, the hourly and seasonal fluctuations in the system will increase. This requires strategies to manage intra-day peaks using pumped storage and electrochemical storage, and to adjust seasonal fluctuations using hydro and thermal power. Figure 7.1 shows the daily variation in electricity demand for various power sources nationwide, indicating significant curtailment of wind and solar power during late winter and spring, and limited curtailment during autumn. Thermal power plants serve as peaking power sources to balance the seasonal mismatch between renewable energy supply and power demand, primarily compensating for the electricity deficit in winter and summer. Seasonal adjustments account for

25% of the total hydroelectric power generation, increasing the average power output in winter by 60 million kilowatts compared to the full runoff method.

7.1.4 Future Integrated Planning and Analysis of New Power and Heating Systems

(1) Future Integrated Optimization Model of New Power and Heating Systems.

To meet the heat source requirements for centralized heating, low-grade waste heat and discarded heat from nuclear power plants, peaking thermal power plants, industrial processes, data centers, and large substations can be recovered and integrated into the required heating parameters through heat pumps. However, to address the temporal mismatch between heat source emissions and heat demand, large-scale seasonal energy storage is required. Although the total amount of waste heat resources and discarded wind and solar heat exceeds the total heat demand, there are spatial, geographical, and temporal matching issues. Therefore, this study also establishes a regional heating balance model to examine whether each region has sufficient waste heat resources and determine the required seasonal heat storage capacity for each region.

(2) Waste Heat-Based Heating Scheme.

Based on the model calculations, the future retained peaking thermal power plants will produce 5.08 billion GJ of waste heat annually, and nuclear power plants will emit 7.2 billion GJ of low-grade waste heat annually. In addition to waste heat from power plants, there are also 4.8 billion GJ of industrial waste heat and 4.2 billion GJ of heat from data centers, substations, and sewage that can be utilized. Furthermore, up to 2.26 billion GJ of discarded wind and solar energy can be converted into heat. The total heat source resources amount to 23.5 billion GJ, which is sufficient to meet the 13 billion GJ demand for urban heating in northern areas and heat below 150 °C for industrial processes.

Based on the data from previous chapters, the future waste heat resource and heat demand for each region are compiled. After considering the potential conversion of discarded wind and solar energy into heat, only Beijing, Tianjin, Heilongjiang, and Jilin have heat demand exceeding waste heat resource in these regions. Ningxia and Henan have a relatively balanced waste heat resource and heat demand. Other regions have abundant heat source resources.

Large-scale seasonal heat storage facilities can efficiently recover waste heat and discarded wind and solar energy throughout the year, balancing the temporal mismatch between heat supply and heating demand, significantly improving the flexibility and reliability of the heating system. Based on the 21 energy-consuming regions, the daily variation of waste heat production and heat demand for building heating and industrial production in each region is determined. As building heating requires more heat in winter and far exceeds the heat demand, while heat supply in spring, summer, and autumn greatly exceeds heat demand, a large-scale seasonal heat

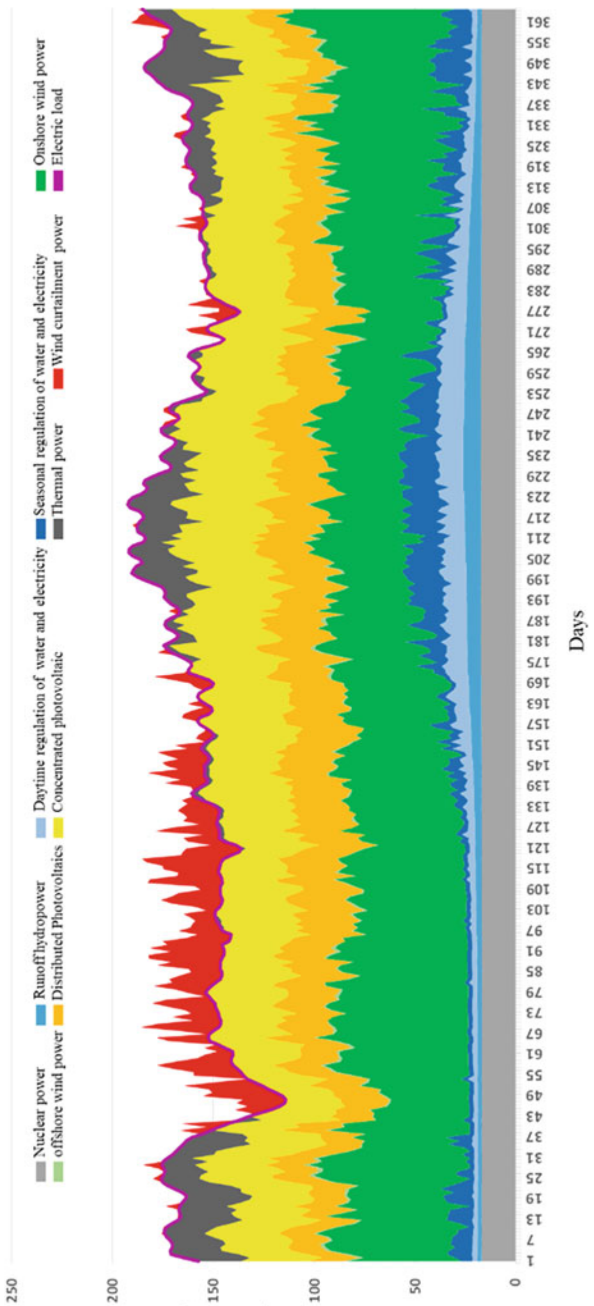

Fig. 7.1 Daily variation of power generation demand for various power sources nationwide

storage system, in the form of large heat storage tanks, can store excess heat from spring to autumn for use in winter. The storage medium for heat storage is water, which has low cost, with a storage cost of 100–150 yuan/m^3. In regions with abundant heat sources, it is essential to choose the lowest-cost heat storage and minimize the long-term storage time to reduce heat losses, thus reducing the investment in seasonal heat storage. For regions with a scarcity of heat sources, larger heat storage capacity is needed based on demand matching. Additionally, waste heat can be extracted using electric heat pumps or seasonal discarded wind and solar energy can be converted into heat using electric boilers. This heat can be stored through seasonal heat storage to alleviate the contradiction of inadequate waste heat resources in some regions.

According to the optimized model results, a large-scale seasonal heat storage capacity of 1.14 billion GJ is required nationwide, assuming a heat storage temperature of 90/20 °C. This requires the construction of large heat storage tanks with a total capacity of 4.32 billion m^3, necessitating an investment of 5.5 trillion yuan. Most regions in the southern area do not require seasonal heat storage. Based on the daily variation of real-time heat storage throughout the year, the stored heat is almost depleted by late winter, and then waste heat and discarded wind and solar energy are stored. Some provinces release a portion of the stored heat in summer to avoid consuming peak electricity during that season, and then they release peak heat for load balancing during the severe cold period in winter.

7.2 Dominant Waste Heat Utilization as the Footing for Urban Heating

To figure out how to achieve carbon neutrality in heating, the heating and power systems must be put together for analysis. The comprehensive use of air-source heat pumps, ground-source heat pumps, and other electric heat pumps will lead to a significant increase in the electrical power load in winter, an exacerbation of the shortfall in zero-carbon electricity in winter, increased investments in power generation, transmission, consumption, and other links, and a substantial rise in the heating cost.

In fact, there will be abundant thermal power plants and nuclear power plants for peak shaving, and other waste heat resources in China. China holds immense potential to recycle these resources, which can be used as the main heat sources for NUH and industrial heating. In terms of the efficiency and economy of waste heat recycling, thermal power, and nuclear power have outstanding advantages. Waste heat from the cold end of a steam turbine can be recycled effectively by such means as extracting steam from the steam turbine, raising the backpressure of exhaust steam, and local provision of additional heat pumps.

According to the analysis of the supply–demand balance in the power system, as the seasonal peak shaving power supplies in the future power supply structure under carbon neutrality, thermal power plants will need an installed capacity of about 500 million kW. The corresponding waste heat emissions will be close to 5 billion GJ. The waste heat from these thermal power plants may serve as important zero-carbon heat sources in the future.

Another main source of waste heat emissions is coastal nuclear power. Although the future installed capacity of nuclear power will reach only 200 million kW, the annual waste heat emissions will be more than 7 billion GJ. This waste heat, if emitted directly, will cause thermal pollution to the surrounding environment. This waste heat from nuclear power plants can be utilized to make up for the shortage of zero-carbon heat sources in coastal areas and alleviate pollution to the coastal ecology. All of the above-mentioned waste heat from thermal and nuclear power plants, if utilized, can offer approximately 12 billion GJ of heat per year and thus can serve as the main heat source to provide zero-carbon low-grade heat for NUH and industrial heating in China.

There is also plenty of waste heat available in the industrial field. In the future, the steel, non-ferrous, and building material industries will be scaled down but still retained in a sufficient proportion, while the chemical industry, as the primary provider of various materials, will develop enormously. A lot of waste heat will be emitted from the production processes in these industries. In addition, some emerging industries will also discharge a large amount of waste heat. For example, data centers that have grown fast in recent years will emit nearly 2 billion GJ of waste heat in the future. The considerable amounts of heat emitted from waste incineration in each city can also be recycled.

The above-mentioned industrial and other waste heat, if recovered, will provide at least about 7 billion GJ of heat per year. Compared with the waste heat from power plants, this waste heat is more scattered and more expensive to recycle, but its temperature is between 30 °C to 50 °C and is easier to recycle than geothermal and ambient air sources.

In the future, the industrial heat demands in China can be classified by grade. The demand for high-temperature heat above 150 °C is mostly concentrated in the process industries, at about 5 billion GJ per year; the demand for low-temperature heat below 150 °C is mainly from the non-process industries, at about 7.6 billion GJ per year.

In the future, the floor space of NUH in China will be close to 22 billion m^2. With the gradual promotion of building energy efficiency, the building heating demands will reach about 5.4 billion GJ in total.

In conclusion, the heat required for industrial heating (below 150 °C) and NUH will be 13 billion GJ. In terms of the balance between supply and demand, the amount of waste heat resources will be greater than the heating demand. Hence, the waste heat can serve as the main heat source to address the needs of industrial heating (below 150 °C) and NUH.

Moreover, when wind and solar PV power grow up and become the main power sources according to the planning for zero-carbon electricity, there will be certain wind and solar curtailments in spring and autumn. Based on the current patterns of seasonal changes in electricity consumption, it is reckoned that the optimal range of wind and solar curtailments will be 5–8%.

The future wind and solar PV power in China will total 9 PWh, and even the 5% wind and solar curtailments will reach 0.45 PWh. How to deal with so much curtailed wind and solar PV power at a low cost is also an issue that must be taken seriously.

If this portion of electricity is directly converted into heat, the regulation and storage of the heat through seasonal heat storage to supply heat for building heating and industrial production may be the best solution in terms of comprehensive economy. The curtailed wind and solar PV power may provide up to 2 billion GJ of heat and may also play an important role in the future zero-carbon heat source system.

7.3 Construction of the Low-Carbon Heating Mode Dominated by Waste Heat Utilization

The urban low-carbon heating mode means the utilization of the waste heat generated in various production processes to meet the needs of urban and industrial heating and thus improve energy efficiency and reduce carbon emissions. However, to realize this mode, it is necessary to overcome the three mismatches below:

First, a temporal mismatch between the waste heat resource and the heating load. There are obvious differences in terms of season, daytime, and nighttime because the waste heat emissions from such sources as power plants and factories vary with production conditions and urban heating is primarily affected by climate.

Second, a spatial mismatch between the waste heat source and the heating load. To avoid environmental pollution, large thermal power plants, nuclear power plants, and other sources of high-temperature waste heat are usually far away from urban centers, but the traditional transfer methods have limitations on distance. How to transfer the distant waste heat to cities is a technological challenge.

Third, a temperature mismatch between the waste heat resource and the heating demand. Most of the waste heat resources are discharged at a lower temperature, in the 20–50 °C range, but the heating networks require a larger temperature difference between the supply and return water to ensure the transfer capacity; besides, the end consumers have different temperature requirements, for example, buildings require a temperature of about 40–60 °C, and industrial consumers require higher temperatures; and factors including volume utilization rate and safety also need to be considered for the seasonal heat storage system. The temperature difference between systems needs to be coordinated.

To sum up, the key to the construction of the urban low-carbon heating mode dominated by waste heat utilization lies in solving the three mismatches, and on this basis, multiple energy forms can be complemented by each other and integrated together.

7.3.1 Storing Heat to Solve the Temporal Mismatch Between Waste Heat and Heating

We can use the thermal, nuclear, and industrial waste heat and the spring wind and solar PV power to supply heat. However, these resources are unstable and change with the generating capacity and production output, and the heating demand also changes with the season and air temperature. For instance, thermal power plants discharge more waste heat during peak shaving in winter and summer, while nuclear power plants and some industries emit waste heat throughout the year. However, heating is required only in winter and needs to be regulated depending on air temperature. To solve the temporal mismatch, we need to accomplish seasonal heat storage. Furthermore, the abandoned wind and solar PV power in spring and autumn can also be converted into heat for storage, which also needs seasonal heat storage.

One seasonal heat storage method is to build large water storage tanks with heat-insulating top covers. Stored water is layered naturally, with the high-temperature hot water at the top and the low-temperature cold water at the bottom. When there is excess heat, the bottom cold water is extracted, heated, and then stored at the top. When heating is required, the top hot water is extracted for heat release and then sent back to the bottom. This enables the storage and utilization of heat. This method has been used for solar heating in Northern European countries.

There may be concern about whether seasonal heat storage is cost-effective, whether lots of heat is lost during long-time heat storage, whether a heavy investment in heat storage equipment leads to an increase in cost, etc. If the calculation is done based on a water temperature of 90/20 °C, the investment in heat regenerators will be only RMB 3 per kWh, but the investment in chemical cells will reach up to RMB 1,000 per kWh, indicating a difference of more than 300 times between the two. Even if the method of increasing heat by 6 times via heat pumps after electricity storage in cells is considered, the cost difference between the two will be more than 50 times. Hence, heat storage is more economical. Furthermore, the cost of heat storage will drop with the growth of scale, because the per unit surface area gets smaller and the investment per unit volume gets lower when the heat regenerator grows in size. With regard to heat loss during long-time heat storage, the Fourier number reflecting the unsteady-state heat transfer of the heat regenerator is directly proportional to time and inversely proportional to the square of the scale. When the scale is increased by a factor of 10, the time will be magnified by a factor of 100, so a half-year will not be a very long period of heat storage. Therefore, a heat regenerator that is big enough in volume will have a relatively small loss of heat even in seasonal heat storage. In addition, an increase in the difference in heat storage temperature may also lead to an increase in the density and efficiency of heat storage and is favorable to heat transfer and the recovery of industrial waste heat. Therefore, we should use seasonal water storage tanks and lower the return water temperature to below 20 °C when building a new zero-carbon heating system.

The investment and operation costs of the heat regenerator are about RMB 50–90 per GJ, and the waste heat in the non-heating period will be wasted if there is no seasonal heat storage. The waste heat is zero-cost, and it is cost-effective if the cost of heat storage is lower than that of the conventional heat source. The cost of RMB 50–90 per GJ is equivalent to that of a natural gas-fired boiler, so heat storage is economically acceptable. Besides, the replacement of natural gas-fired boilers with heat storage can also help reduce carbon emissions. From a safety point of view, natural gas may be insufficient in winter, but heat storage facilities may release heat at any time and thus be more reliable. Seasonal heat storage facilities, if any, can not only address the seasonal imbalance between supply and demand but also eliminate the contradiction between supply and demand resulting from the intraday waste heat fluctuations.

7.3.2 Developing the Large-Temperature-Difference and Long-Distance Transfer Technology to Solve the Spatial Mismatch in Waste Heat Utilization

Most coal-fired thermal power plants and boilers in northern cities are old and will be phased out. So, they need to be replaced by waste heat as the main heat source in cities. However, waste heat is often far from cities and needs to be transmitted through long-distance heating networks. There is a concern that this will cause such problems as high investment, high energy consumption, and losses. Long-distance heat transfer is economically feasible due to the following reasons: First, waste heat recycling projects are generally large in scale and require large-diameter transfer pipelines, whose cost per unit of heat is lower than that of small-diameter pipelines. Second, the large-temperature-difference heat transfer technology, namely reducing return water temperature to increase the temperature difference between supply and return water, is adopted to improve the transfer capacity and reduce the cost. The current water supply temperature is generally under 130 °C, and the return water temperature may be lowered to below 30 °C and even below 20 °C through the absorption heat exchange process. In this way, the temperature difference between supply and return water may be increased from 60 K to above 100 K, causing an increase in the transfer capacity by nearly 70% and thus a significant reduction in the long-distance transfer cost. Third, in terms of heat sources, the cost of waste heat recycling is lower than that of natural gas-fired boilers, coal-fired boilers, and even the extraction of steam from thermal power plants. Since the return water temperature is low, the waste heat can be recovered through direct heat exchange. As shown in Fig. 7.1, in a heating period of 4 months, the economical heating distance for the large-temperature-difference heating network exceeds 200 km compared with natural gas-fired boilers. The large-temperature-difference heating network is also economically feasible compared to other conventional methods within a distance of 80 km. If there are seasonal heat storage facilities on the heat user side, the pipelines can be operated based on the time for waste heat generation rather than the time of

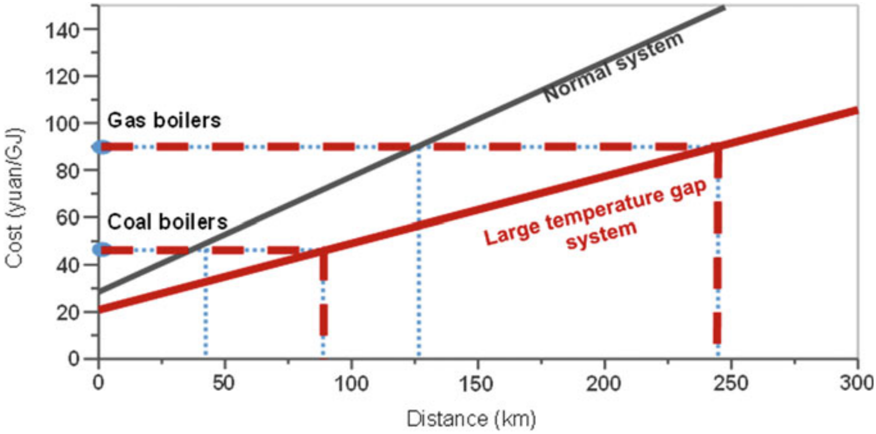

Fig. 7.2 Relationship between long-distance heating cost and transfer distance

demand. In this way, the annual operation time and economy of pipelines can be improved (Fig. 7.2).

Large-temperature-difference and long-distance heating projects have been widely applied in many cities, and the Gujiao-Taiyuan Large-Temperature-Difference and Long-Distance Heating Project is a typical example. In this project, the waste heat from the Gujiao Power Plant is used to heat the 76 million m^2 of buildings in Taiyuan City 40 km away and two long-distance pipelines with a diameter of 1.4 m are built, including a 15 km mountain tunnel. The investment in this project is RMB 6.7 billion, but the heat investment per square meter of buildings is equivalent to about RMB 90 only, the heat loss due to radiation and the energy consumption along the way are very low, and the comprehensive heating cost (transfer to urban areas) is less than RMB 40 per GJ, which is lower than that of coal-fired boilers. After the start of this project, similar projects have been implemented one after another in Yinchuan, Shijiazhuang, and other cities to utilize the waste heat from power plants for the realization of clean and low-carbon heating.

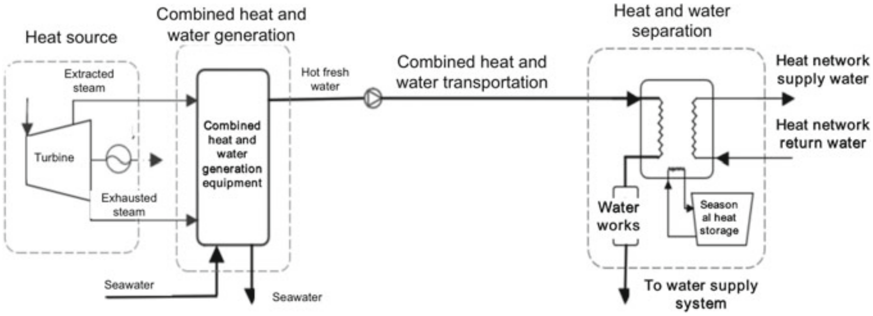

Fig. 7.3 Schematic diagram of combined heat and water technology

Since nuclear power plants are mostly distributed in coastal areas, the combined heat and water technology can be adopted to greatly reduce the cost of long-distance transfer of waste heat. This technology consists of three main parts, i.e. combined heat and water generation, combined heat and water transportation, and heat and water separation, as shown in Fig. 7.3. For combined heat and water generation, the extraction steam is utilized for the desalination of seawater, and then hot fresh water is generated and transmitted to cities. For combined heat and water transportation, fresh water and waste heat can be transmitted simultaneously with only one pipe. For heat and water separation, waste heat is extracted from the fresh water and released to the heating network through absorption heat exchange at the city end, and then the fresh water at a normal temperature is fed into the urban water supply system. This technology can not only solve the problem of water shortage in coastal cities but also reduce transmission costs. The economical transfer distance may reach 400 km compared with that for natural gas heating. According to analyses, the waste heat from nuclear power plants in northern coastal areas can be fully utilized to supply 5 billion m^2 of buildings with zero-carbon heat and to generate 4 billion tons of fresh water per year. This technology has been successfully operated and verified in the Haiyang Nuclear Power Plant and is ready for popularization and application.

7.3.3 Adopting the Temperature Change Technique to Solve the Temperature Mismatch in the Links of Waste Heat Utilization

To utilize waste heat for building and industrial heating, a unified heating network system needs to be established to connect multiple heat sources and sinks. To coordinate the demands of all aspects, the water supply temperature may be set at 90–95 °C, and the return water temperature may be set at 20–25 °C. However, the temperature of waste heat varies, and the temperature requirements for heating purposes are also different. Therefore, the temperatures of water in the heating network need to be adjusted through some equipment when being accessed or used. The equipment mainly consists of heat exchangers and heat pumps. They can be used for raising or lowering the grade of hot water, generating high-pressure steam, etc. In this way, the temperature mismatches encountered in heat transfer can be solved.

Typical heat transfer and grade improvement may fall into the following four scenarios:

(1) The average temperature of waste heat sources is higher than that of supply and return water in the heating network, and the temperature difference for heat transfer is sufficient;

The waste heat from thermal and nuclear power is mainly from the exhaust steam of steam turbines and generally at a temperature of 30–50 °C and may be heated by the extraction steam to a temperature higher than that of water supply in the heating network. To this end, the waste heat from exhaust steam is recycled efficiently through multistep heating of the circulating water in the heating network. When the circulating water in the heating network is heated to a temperature higher than the above-mentioned range, the first solution is to raise the backpressure of the steam turbine to heat the water in the heating network. The water in the heating network may be directly heated to above 120 °C by the further use of the extraction steam at 0.3–1.0 MPa. This steam sacrifices a certain generating capacity for high-temperature heat to heat the heating network and is equivalent to an electric heat pump with a COP of 4–6. In addition, the extraction steam can also be used for driving the absorption heat pump to recover the waste heat from the exhaust steam. The circulating water is heated first to a relatively high temperature (for example, 90 °C) and then heated by the extraction steam to 120 °C, thus further improving the efficiency of waste heat utilization in the power plant. Also, a steam ejector may be used to recover the waste heat from the exhaust steam. Despite its functions similar to those of the absorption heat pump and its relatively low investment, the steam ejector is subject to great limitations by variable working conditions. For the utilization of waste heat from multiple steam turbines, the backpressure of the steam turbines may be raised in sequence to heat the return water in the heating network through series connections, then the absorption heat pump may be adopted selectively, and finally, the steam is extracted for heating. This multistep heating method may reduce energy consumption by 50% compared to the extraction steam for heating from traditional steam turbines and is equivalent to heating by a heat pump with a COP of 7–10.

In the utilization of industrial waste heat, including waste heat from slag washing water in steel mills, the waste heat temperature may also be higher than the average temperature of supply and return water in the heating network. In this case, the temperature transducer based on the second-class absorption heat pump may be used to recover the waste heat and heat the circulating water in the heating network to a temperature higher than that of the waste heat; when necessary, the peak shaving heat source or electrically-driven heat pump may be combined to further heat the circulating water to a temperature required for water supply in the heating network.

(2) The average temperature of waste heat sources is lower than that of supply and return water in the heating network, or the temperature difference for the heat transfer with the heating network is insufficient;

A lot of low-temperature waste heat is generated in industrial production and may be raised to higher temperatures by heat pumps. The temperature and amount of industrial waste heat vary with industries; therefore the suitable methods of waste heat collection need to be selected on a case-by-case basis. If there is both industrial waste heat and the waste heat from a power plant in a heating system, we may first utilize the former for low-temperature heating and then utilize the latter for high-temperature heating, thus achieving the most optimized energy efficiency and economy.

(3) The average temperature required on the demand side is lower than that of supply and return water in the heating network, and the temperature difference for heat transfer is sufficient;

The required temperature of heat for building heating in northern China is low, but the temperature of hot water in the urban heating network is very high. We can use the absorption heat exchanger to reduce the temperature of return water in the heating network, use the temperature difference between the water supply of the primary network and that of the secondary network to drive the absorption heat pump, and lower the temperature of return water of the primary network to below 20 °C without consuming extra energy. This not only improves the transfer capacity of the heating network but also creates conditions for the recovery of waste heat. In the future, the decentralized temperature reduction method for returning water should be popularized, such as installing absorption heat exchangers in buildings.

(4) The average temperature required on the demand side is higher than that of supply and return water in the heating network.

High-temperature steam is required for industrial heating, but most of the current heat sources are coal and natural gas with high carbon emissions. To achieve zero carbon, we may consider the following methods:

- Steam generation with electric boilers: This method is characterized by low efficiency, high electricity consumption, and high cost.
- Extraction of low-temperature waste heat with electric heat pumps: In this method, air, geothermal energy, and other low-temperature energy in nature are used to drive electric heat pumps, which increase the water temperature to generate steam. However, this method has heavy investment and a low COP, and the natural heat sources at low temperatures have low grade and density, making them difficult to meet the industrial requirements for high grade and large capacity.
- Steam generation and transmission to industrial consumers by thermal and nuclear power plants: In this method, clean energy from thermal and nuclear power plants can be utilized to generate high-temperature steam, which is transmitted to industrial consumers through steam pipelines. Nevertheless, it is difficult to transmit steam over long distances through steam pipelines due to large heat radiation and pressure loss.

Hence, we propose a new method of industrial heating: The waste heat from thermal and nuclear power plants and the industrial waste heat are collected, transferred to industrial consumers over long distances through circulating hot water, and subject to temperature change at the user end to make steam. The specific operation is as follows:

- Heat water to above 90 °C at the collection locations of the waste heat from thermal and nuclear power plants and the industrial waste heat, and then transmit the water through **circulating long-distance pipe networks** to industrial consumers;

- Generate steam of different grades **by temperature rise and flashing in stages** or **by compression after flashing** at industrial consumers depending on demand;
- Return the remaining low-temperature circulating water to the collection locations of the waste heat from thermal and nuclear power plants and the industrial waste heat for reheating.

This new heating method has the following advantages:

- Zero-carbon emissions can be achieved;
- The energy efficiency and heating economy of the system can be improved;
- Heating parameters can be adjusted flexibly based on the requirements of different consumers;
- The investment cost can be reduced by sharing some facilities with urban heating.

For the non-process industry in northern China, this new heating method is more advantageous.

The grade and pressure requirements vary in industrial heating, so we can also adopt different heating methods based on the practical situation:

- Low-grade heating demand can be met by waste heat and heat pumps locally, thus saving the cost of long-distance transfer;
- High-temperature and high-pressure steam can be transmitted directly by thermal and nuclear power plants but is subject to distance limitations;
- New industrial projects with high-pressure steam requirements may be built near nuclear power plants or use biomass boilers, electric boilers, and other clean energy;
- The chemical industry demanding a lot of stable and high-parameter steam may consider the direct supply of steam from modular nuclear reactors.

These methods are conducive to realizing zero carbon emissions and carbon emission reduction in industrial heating.

7.4 Mode and Planning of Low-Carbon Heating Dominated by Waste Heat

Based on the foregoing analyses, we establish a low-carbon heating mode dominated by waste heat. This mode has five characteristics, namely waste heat utilization, long-distance heat supply, low-temperature return water, heat and power coordination, and heat storage for peak shaving

(1) Recovery of waste heat. Make full use of various waste heat.
(2) Low-temperature return water. Reduce the temperature of return water in the heating network to efficiently utilize waste heat and improve the transfer capacity of the heating network.

(3) Long-distance heat supply. Use the large-temperature-difference and long-distance transfer technology and the combined heat and water technology to supply cities with heat at a low cost.
(4) Heat and power coordination. Utilize heat storage to realize the mutual coordination and support between the heating network and the power grid.
(5) Heat storage for peak shaving. Seasonal heat storage replaces fossil-fuel boilers for peak shaving and serves as a safe standby.

In the future, the development of the urban heating system in China will be dominated by waste heat utilization. However, waste heat utilization is not only affected by the total amount of resources but also limited by factors including spatial distribution and the difficulty in collecting waste heat. Therefore, urban heating should be planned based on specific cases.

Table 7.1 shows the heat supply of future heat sources. The waste heat from thermal and nuclear power, which has the advantages of high efficiency, low cost, and easy implementation, shall receive priority in recycling. Industrial waste heat including waste heat from the process industry, data center, and power transformer shall be recycled. Wind and solar PV power curtailed in non-heating seasons can be converted into heat. The consumption of electric energy is required in centralized heating, which mainly involves the electric energy required for making steam for non-process industries, the electric energy required for the collection and transmission of industrial waste heat, and the electric energy required for a few decentralized heating methods such as electric boilers. For civil heating, air source, ground source, and other decentralized heating methods may be used in regions that cannot be covered.

China's coastal areas are dotted with many nuclear power plants and large thermal power plants. The eastern coastal areas and the surrounding areas are developed areas and also the gathering places of industries and populations in China, with concentrated demands for industrial and domestic heating. Therefore, for one thing, based on the industrial layout planning, petrochemical and other consumers with high heat consumption and a great demand for high-parameter steam are built near nuclear power plants. The waste heat from nuclear power plants is converted directly

Table 7.1 Composition of heat source for future urban heating in China

	Heat supply (10^8 GJ)	Heat supply after deduction of heat loss (10^8 GJ)
Thermal power	30.9	29.0
Nuclear power	28.7	27.0
Industrial waste heat	25.4	23.9
Curtailed wind and solar PV power	13.4	12.7
Other electricity consumption in centralized heating	29.8	29.3
Decentralized heating	8.2	8.2
Total	136.4	130.0

into steam for transmission to these industrial consumers of high-pressure steam. For another, the long-distance heat supply technology is adopted to transfer the waste heat through hot water transmission to a wider range of areas to meet the non-process industrial heating (above 150 °C) and urban heating demands. In combination with the characteristic that power plants are distributed along the coast, the combined heat and water technology may be utilized to increase the economical transfer distance of the waste heat from these power plants to over 300 km. Based on the coastal nuclear power layout and planning, this economical transfer distance may be utilized to radiate the waste heat from nuclear power plants to cities and large industrial heat consumers in coastal areas and even inland areas. Thus the heating demand for industrial and civil purposes in eastern China will be met. Moreover, the 10 billion tons of desalinated seawater supply per year will effectively relieve the water shortage in eastern China. In areas south of Shandong, heating is mainly to meet the industrial demands for steam; while in areas north of Shandong (included), heating is to meet both domestic and industrial demands. The eastern coastal areas and the areas further inland have the densest population and industries in China, and the majority of industrial and civil heating can be supplied by the waste heat from nuclear power plants.

Heating in the central and western regions of China relies more on the waste heat emitted from thermal power plants and the process industry. Thermal power plants are uniformly distributed in the central and western regions. The waste heat from thermal power plants can serve as the main heat source, which can be utilized together with the waste heat from other process industries of a certain scale and transferred through the long-distance hot water networks to meet the main demands of central and western provinces and cities demand low-carbon heating. In Jilin and Heilongjiang provinces in northeast China, the capacity of thermal power plants at present is relatively small, and new thermal power plants with a certain capacity may be built in the future to utilize the abundant biomass resources in this region as the fuel to achieve zero-carbon electricity generation and heating; also, the construction of nuclear power plants with a proper capacity may be considered in this region for mutual support with the utilization of the waste heat from thermal power, thus achieving zero-carbon heating for urban areas in this region (Fig. 7.4).

In terms of the time sequence of construction, as shown in Fig. 7.4, although thermal power plants are gradually transformed into peak shaving power sources for power grids, they will remain one of the main power sources for the next 10 to 20 years and discharge a lot of waste heat, which can be recovered at a low cost and with little difficulty. Thus, by 2035, the top priority of low-carbon heating will be the deep recovery of the waste heat from thermal power plants to replace the traditional coal-fired boilers and medium- and small-sized thermal power plants. In addition to the utilization of waste heat from exhaust steam, natural gas-fired power plants have more need to recover the flue gas heat with greater potential. Independent natural gas-fired boilers will be used to recover the flue gas heat in the short term and will be gradually shut down in the long term. The qualified gas-fired boilers (near the heating networks) will be interconnected with the heating networks for peak shaving for the heating networks and will be phased out with the development of seasonal heat storage. For

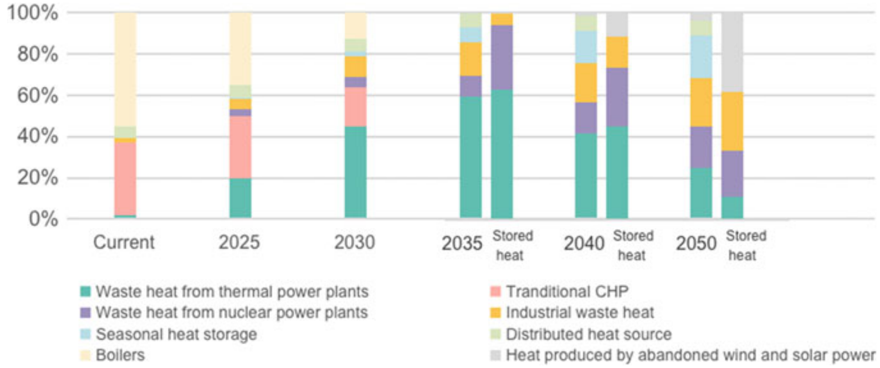

Fig. 7.4 Time sequence of development in the urban heating plan

future heating, the increasing heat demand will be met mainly through the recovery of the low-grade waste heat of existing heat sources, and new heat sources will be built as few as possible. The projects for comprehensive recovery of waste heat from nuclear power are combined with the time sequence of construction of seasonal heat storage. The 14th Five-Year Plan period will witness the implementation of industrial heating and projects that combine large-scale heating with seasonal heat storage. The heating mode based on the waste heat from nuclear power will be popularized and applied comprehensively from the start of the 15th Five-Year Plan. Non-process industrial heat sources and heating networks are constructed to replace the existing small coal-fired power plants, mainly in Shandong, Jiangsu, Zhejiang, Fujian, and other provinces where non-process industries are concentrated. They have been constructed in succession since the start of the 14th Five-Year Plan. In the link of the heating network, comprehensive reconstruction of heating networks is carried out to reduce the return water temperature. The return water temperature will be lowered to below 20 °C through the installation of absorption heat exchangers or some electric heat pumps at terminals.

Coal-fired and gas-fired boilers as the main heat sources at present will be fully shut down by 2035. From 2035 onward, the power system will have the coal-fired power plants shut down gradually, or have their operation time reduced significantly, and the proportion of heating by the waste heat from thermal power plants will also be reduced gradually. Then, large seasonal heat storage can be built on a large scale to store the low-grade waste heat from non-heating seasons for a supplement. The utilization of the waste heat from nuclear power will be promoted comprehensively with the popularization of seasonal heat storage and the continual improvement of the combined heat and water technology. The overall reduction of the supply and return water temperatures in the urban heating networks will enable the utilization of industrial waste heat to become more economical and to develop on a large scale. Meanwhile, renewable energy generation will gradually become dominant. A significant amount of curtailed wind and solar PV power will be converted into heat for urban heating, and coupled with heat storage, the utilization of curtailed wind and solar PV power will contribute over 10% of the heat after 2035.

The heating system is expected to achieve carbon neutrality in all respects by 2050. At that time, low-density buildings that are difficult for heating networks to cover will adopt air-source and ground-source heat pumps and other decentralized heating methods for heating; apart from this, the heat sources for NUH and industrial heating (below 150 °C) in China will be mainly the waste heat from thermal power, nuclear power, and other industries, and the heat converted from the electricity consumed for recycling the waste heat and from the curtailed wind and solar PV power.