



Carbon Neutrality Strategy and Advancements in China's Building Sector

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Abstract: China has established the goal of achieving carbon neutrality by 2060 as a national policy. Avoiding the repetition of developed countries' mistakes in carbon emission reduction, which were preceded by high energy consumption before their carbon peak, has become a critical issue. Given that construction-related carbon emissions account for one-third of total societal carbon emissions, the construction sector bears an important responsibility in assisting the country in achieving its carbon neutrality goal. This paper provides an overview of the current status of carbon emissions in China's construction sector, carbon emission reduction policies, technical pathways, and the development and application of new low-carbon technologies, while forecasting the future direction of technological development.

As a developing country, China's per capita building energy consumption and energy consumption per floor area are significantly lower than those of developed countries. Therefore, unlike developed countries, China's strategy for achieving low-carbon or zero-carbon goals in the construction sector requires a novel indoor environmental approach to fulfill the demands for health, comfort, and carbon reduction. Reforms must be implemented on both the supply side and consumption side of building energy.

This paper outlines the technical pathways for carbon emission reduction in the Chinese building sector, encompassing the full electrification of buildings, the efficient utilization of renewable and natural energy sources, and the recovery of waste and residual heat. Additionally, several distinctive low-carbon building technologies are introduced. With regard to future development, this paper highlights that delivering personalized and precise indoor environmental services, along with employing information technology for intelligent identification and control of indoor thermal demands, will constitute key components of next-generation indoor environmental control technologies.

Therefore, the strategy and technology for indoor environmental control will undergo significant transformations. Achieving breakthroughs in certain key core technologies necessitates advancements in multiple domains. The paper highlights that these objectives will be attained through interdisciplinary collaboration and the integration of modern digital technologies.

Keywords: Building Sector, 'Dual Carbon' goals, Building energy consumption

1 Introduction

On September 22, 2020, at the 75th Session of the United Nations General Assembly China officially announced the commitment to strive for peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Since then, the 'Dual Carbon' goals (carbon peaking and carbon neutrality) have become a national strategy, holding significant importance for advancing green and low-carbon development in China.

According to the 2022 global construction industry energy consumption and carbon emission accounting report released by the United Nations Environment Programme in 2024, building operation and construction-related energy consumption accounts for 34% of global energy consumption, with 30% attributed to building operation. Carbon emissions associated with building operation and construction account for 34% of global carbon emissions, of which 27% is attributable to building operation^[1]. As indicated in the *2025 Annual Report on China's Building Energy Efficiency Development*^[2], China's building-related carbon emissions in 2023 accounted for 29% of the nation's total carbon emissions.

Carbon emissions in the construction industry are primarily driven by energy consumption during building operation and construction, with operating energy consumption being the dominant factor. Among these, HVAC system energy consumption accounts for 40–50% of a building's total operating energy, ranking as the largest contributor, followed by the lighting system. By 2023, when calculated in terms of electricity equivalence, the total annual energy consumption for building operations in China and the United States reached 3,864 billion kWh and 4,283.7 billion kWh, respectively. This indicates that the United States' annual building operational energy consumption was 1.1 times that of China. Furthermore, China's per capita building energy consumption was approximately one-fifth of the United States', and its energy consumption per square meter of floor area was less than half of the United States' (see Figure 1)^[2]. However, in 2014, these two ratios were one-seventh and one-third, respectively (calculated in terms of standard coal equivalence; see Figure 2)^[3]. Although developed countries still exhibit significantly higher per capita building energy consumption and energy consumption per unit floor area compared to China, the gap has narrowed considerably over the past decade. This is attributed to the fact that developed countries have already passed their carbon emission peaks, whereas China is not expected to reach its "carbon peak" until 2030.

Figure 1 and Figure 2 are respectively cited from References [2] and [3]. Both of these references provide detailed explanations, in considerable length, regarding the data sources selected for comparison and the methods used for data processing. Due to the complexity of the method, in order to avoid excessive length, this article will not elaborate on it here.

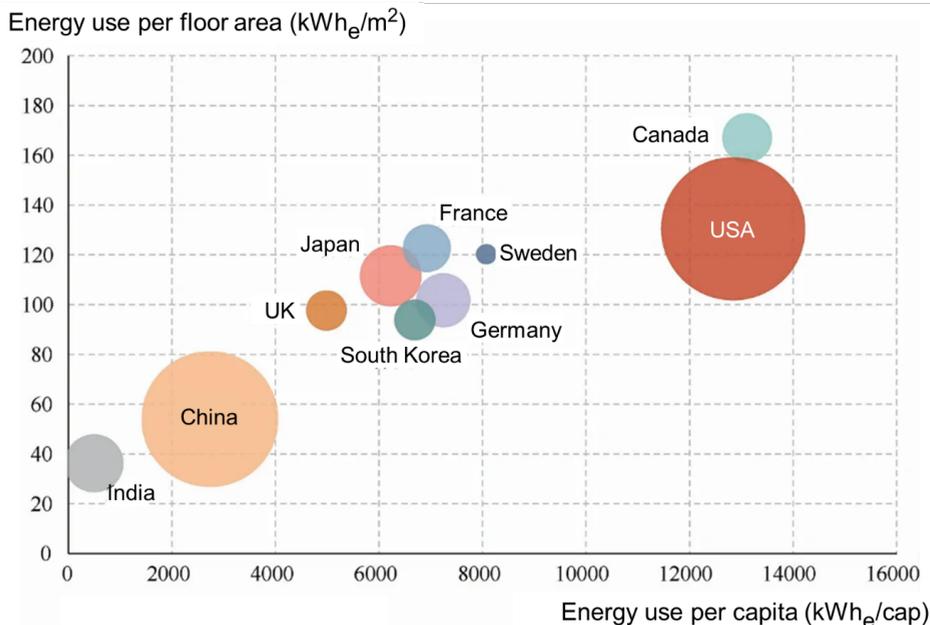


Figure 1: Building sector energy use indicators for selected countries (2023 electricity equivalence)^[2]

Note: The size of the bubble represents the total energy use of the building sector in each country.

Data Sources: CBEEM Model from the Building Energy Research Center at Tsinghua University, IEA Energy Balance Sheets of Various Countries, Energy Efficiency Indicators Database (2024 Edition), World Bank WDI Database, and Satishu Kumar's Study from India (2019).

In addition, China's time window from "carbon peak" to "carbon neutrality" is much shorter than that of developed countries, making it a major challenge to avoid a significant increase in China's construction energy consumption and carbon emissions in the next few years to catch up with developed countries, so as to achieve the goal of carbon neutrality by 2060. As building carbon emissions account for nearly 1/3 of the carbon emissions of the whole society, the building sector has the obligation to play an important role in achieving the country's goal of "carbon neutrality", which is also a new development trend in the field of green buildings in China.

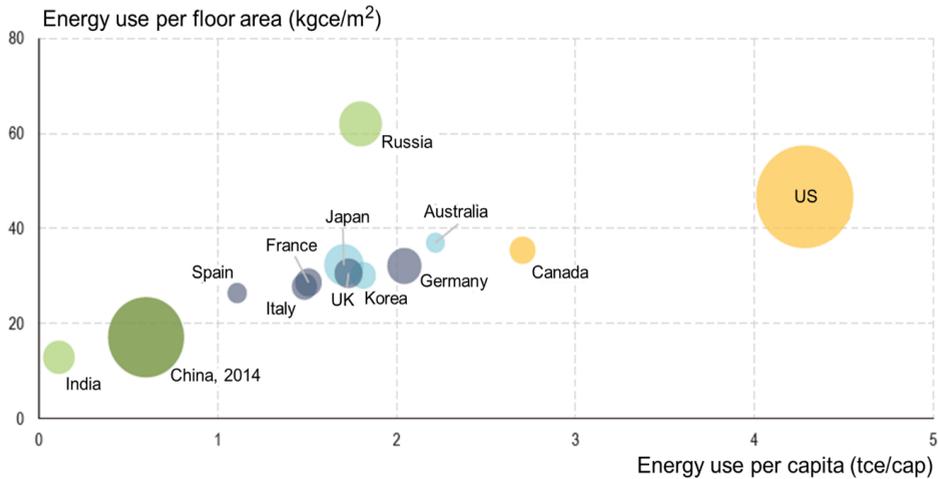


Figure 2: Building sector energy use indicators for selected countries (2012, standard coal equivalence)^[3]

Note: The size of the bubble represents the total energy use of the building sector in each country. The data of China is from 2014.

Data Source: Energy use: IEA (2016b); Population: WB (2016); Floor area: NRCAN (2016), DOE (2015), Odyssee (2015), EDMC (2014), Statistics Korea (2016), DEWHA (2008), COAG (2012), Rosstat (2016), PNNL (2012), NSSO (2013), Deshmukh (2015), BERC (2016b).

Although China's economy has achieved rapid development in the past 30 years, in essence, China is still a developing country, and the level of economic development in various regions is unbalanced. The indoor environment quality of buildings in many relatively backward areas is far from meeting comfort requirements. Therefore, in the next few decades, it is an important task to comprehensively improve the comfort and health level of indoor environment. The premise of reducing the carbon emission of buildings is not to reduce the quality of indoor environment. In addition, China's rapidly growing advanced manufacturing industries such as chips, lithium batteries, photovoltaics, liquid crystals, and pharmaceuticals need to reduce carbon emissions while ensuring a high-precision production environment (ultra-clean, constant temperature and humidity, and low humidity). In the production workshop of such products, the energy consumption of air conditioning system accounts for 40 ~ 60%, which becomes a key link in energy conservation and carbon reduction.

There are two main ways to achieve "carbon neutrality" in the building sector. One is the reform of the building energy supply side, and the other is the reform of the building energy consumption side. Reforms in these two aspects will lead to industrial innovation in the field of HVAC and bring new development opportunities.

2 China's Carbon Emission Reduction Policies and Strategy in the Building Sector

In response to the Chinese government's "dual carbon" goals, the national and local governments have issued many policies and regulations respectively. On October 24, 2021, the Central Committee of the Communist Party of China and the State Council issued the "*Comprehensive Opinions on the Full, Accurate, and Integrated Implementation of the New Development Philosophy for Achieving Excellence in Carbon Peaking and Carbon Neutrality Initiatives*", which includes a special chapter entitled "*Improve the quality of green and low-carbon development in urban and rural construction*", which puts forward the requirements for accelerating the scale of Ultra-low energy building, Near-zero energy building, and Low-carbon buildings. The State Administration of Agency Affairs, the National Development and Reform Commission, the Ministry of Housing and Urban-Rural Development and other departments have all issued work guidelines for energy conservation and carbon reduction in urban and rural buildings. All municipalities and provinces nationwide have also formulated and issued corresponding implementation plans. These plans include specific targets for the scale of low-energy and low-carbon building renovations as outlined, along with financial subsidy mechanisms for projects that successfully implement low-carbon renovations. For example, The Beijing Municipal Government will provide awards of up to RMB 6 million (approximately USD 823,308) for ultra-low energy buildings that meet the acceptance standards or projects that obtain the three-star green building certification, contingent upon the project size.

The prerequisite for achieving "carbon neutrality" in the building sector is the realization of zero-carbon electricity by the State Grid. Specifically, this involves developing a power supply system primarily based on wind power and photovoltaics, complemented by hydropower and nuclear energy, with peak-shaving thermal power serving as a supplementary measure. Wind power and photovoltaics are projected to account for approximately 70% of the energy mix. The State Grid is expected to achieve full zero-carbonization by 2050.

Under this premise, building energy supply must transition to full electrification and zero-carbon energy sources. This is because, in addition to electricity, buildings in China currently rely on coal and natural gas for space heating, cooking, domestic hot water, and steam. Some projects also utilize gas-fired absorption chillers for cooling purposes. Compared with developed countries, the electrification rate of building energy consumption in China remains relatively low; however, it has been steadily increasing since the beginning of this century, rising from 18% in 2002 to 43% in 2022. Since 2018, has surpassed that of Germany and the United Kingdom. In 2023, carbon emissions from building operations in China are estimated to reach approximately 2.27 billion tons, of which 1.35 billion tons result from electricity consumption and 920 million tons stem from direct fossil fuel combustion. Consequently, in the future, the portion of fossil energy used for heating and other non-electric applications will need to be replaced by zero-carbon electricity, while the remaining fossil energy demand will be substituted with zero-carbon alternatives such as renewable energy, industrial waste heat recovery, and other forms of natural energy.

3 Technical Pathways for Carbon Emission Reduction in China's Building Sector

Building winter space heating energy consumption constitutes the largest proportion of building energy consumption in China. In the northern region alone, district heating accounts for 19% of the total energy consumption of buildings. Nevertheless, a significant portion of energy consumption is still attributed to space heating in urban and rural residential, commercial, and public buildings nationwide. Notably, the heating demand for buildings in areas south of the Yangtze River has been increasing annually.

The northern region of China falls within both the cold and severe cold climate zones. Towns located in these two climatic zones are predominantly served by district heating systems. By the end of 2023, the total floor area served by district heating systems nationwide had reached 17.3 billion square meters, accounting for 24.2% of the country's total construction area. The heat sources for district heating in northern China primarily consist of waste heat from combined heat and power (CHP) plants, coal-fired boilers, and gas-fired boilers. In 2023, fossil energy consumption by China's district heating system accounted for 19% of the total annual building energy consumption, largely attributable to coal-fired and gas-fired boilers.

In the future, district heating systems will expand the scale of waste heat utilization from combined heat and power (CHP) plants, promote industrial waste heat recovery, geothermal energy utilization, and large-scale heat pump systems to harness various forms of waste heat and natural energy sources, and gradually phase out coal-fired and gas-fired boilers. The “*Beijing Carbon Peaking Implementation Plan*” issued by the Beijing Municipal Government in October 2022, explicitly prohibits the construction or expansion of independent gas heating systems. For areas in the northern region not covered by district heating systems, such as rural residences and newly constructed urban buildings, low-temperature air-source heat pumps will be utilized for heating purposes.

The national standard “*Low Ambient Temperature Air Source Heat Pump (Chilling Water) Unit (GB/T 25127)*”, released in 2022, explicitly stipulates that low-temperature air source heat pumps (ASHP) must maintain stable operation even when outdoor air temperatures drop to -25°C . Currently, numerous urban and rural households in cold regions of China have adopted low-temperature ASHP as a replacement for household gas boilers or coal stoves for heating purposes. In fact, since 2016, local governments have provided financial subsidies to farmers who switch from coal stoves to ASHP for space heating. It can be anticipated that low-temperature ASHP with further enhanced heating efficiency will likely be deployed on a large scale in severe cold climate zones in the near future.

China's Yangtze River Basin falls within the hot-summer and cold-winter climate zone, with a population of approximately 600 million. It is the most economically active region in China. As the economy continues to develop, the demand for space heating in this climate zone is steadily increasing. Currently, residential and public buildings predominantly rely on ASHP (split air conditioners) and gas boilers for

space heating purposes. Given that winter temperatures in this climate zone are highly conducive to the operation of ASHP, their penetration rate in residential homes is currently substantial. Looking ahead, it is anticipated that all buildings within this climate zone will transition to ASHP-based heating systems, phasing out gas boilers entirely.

If the district heating system is to be developed in this region, it should only be implemented when free heat sources such as industrial waste heat are available. Otherwise, not only would the initial investment and operating costs be significantly higher, but the operational energy consumption and carbon emissions would also far exceed those of commonly used systems, such as ASHP (split air conditioners) or multi units system (VRF). This is because the district heating system requires continuous operation, and the water pumps used for transmitting and distributing hot water consume substantial amounts of energy. In contrast, split air conditioners or VRF system can operate independently based on residents' needs, consuming less energy while meeting individual preferences. Additionally, localized electric heating solutions may satisfy individual thermal requirements with lower electricity consumption. Therefore, developing furniture-style and wearable personalized heating facilities represents an excellent direction for future development.

The construction and management of residential or public buildings in accordance with industrial park standards represent a distinctive feature of urban development in China. For building parks, it is essential to develop distributed renewable energy sources such as rooftop photovoltaic power generation, tap into the extensive energy storage resources within building areas, establish a DC microgrid system, and achieve a "photovoltaic-storage-DC-flexible" building energy system that is both grid-friendly and supports flexible energy utilization. This approach will effectively underpin the development of a new zero-carbon power system.

Building energy supply will transition to full electrification and zero-carbon energy sources. This implies that heating, cooling, domestic hot water, cooking, steam generation, and other energy demands within buildings will no longer rely on the direct combustion of fossil fuels such as coal or natural gas. Instead, heating, cooling, and domestic hot water will be supplied by various low-grade zero-carbon energy sources. In cases where low-grade zero-carbon energy is unavailable, electric-driven heat pumps will be utilized to extract the required thermal energy. Given that the temperature difference between space cooling and space heating requirements and ambient temperature is typically less than 30° C, and domestic hot water temperatures will not exceed 60° C, these demands can be met using low-grade energy sources. Such energy can be effectively harnessed from lower-temperature industrial and residential waste heat, solar energy, geothermal energy, or even directly from outdoor air wet bulb temperatures, dew point temperatures, effective sky temperatures, groundwater, deep lake water, and other natural cold sources. Herein, this type of low-grade energy is referred to as "natural energy."

Cooking will be entirely transitioned from direct gas combustion to electric cookers, presenting a significant challenge to traditional Chinese cooking methods. Despite the widespread adoption of electric cookers in Chinese households, the replacement of

gas stoves with electric alternatives has progressed slowly due to the requirement for quick stir-frying over an open flame in traditional Chinese cuisine. Consequently, it is imperative to research and enhance electric cookers to better accommodate Chinese cooking techniques. In recent years, the “electric flame stove” has been developed, utilizing low-temperature plasma technology to simulate the flame effect of conventional gas stoves. This innovation ensures cooking quality while enhancing safety and reducing air pollution. However, due to its high cost and the absence of relevant national standards, it has not yet achieved widespread adoption.

Traditionally, domestic hot water in China has primarily been supplied by gas water heaters and electric water heaters, with some contributions from solar water heaters. In recent years, ASHP water heaters have gradually gained popularity as a replacement for gas and electric water heaters. In 2023, ASHP water heaters constituted between 10% and 15% of the household water heater market in China, with an average annual growth rate exceeding 10%. The penetration rate in regions south of the Yangtze River is higher than in northern regions. Under normal operating conditions, the coefficient of performance (COP) of ASHP water heaters can reach over 3. Low-temperature models can operate normally at -25°C , making them suitable for use in cold areas; however, their application in severe cold areas remains limited.

ASHP steam generators have been increasingly adopted in commercial and public buildings, such as hotels and hospitals, across China as a replacement for gas boilers or electric heaters. These generators feature adjustable steam pressure and can achieve a coefficient of performance (COP) ranging from 3.0 to 4.0. However, there remains significant potential for further increasing their penetration rate.

At present, the difficulty is that the heat supply of ASHP water heater or steam generator drops greatly in the severe cold weather in northern winter. Solutions need to be sought from many aspects such as improvement of heat pump cycle and energy storage.

Currently, one of the primary challenges is the significant reduction in heat supply from ASHP water heaters or steam generators during severe cold weather in northern winters. Solutions must be explored from multiple perspectives, including the optimization of heat pump cycles and the integration of energy storage systems.

4 Carbon Emission Reduction Technologies and Applications in China's Building Sector

4.1 Carbon reduction technologies for space heating

In recent years, among the heat sources utilized in district heating systems in northern China, the proportion of district heating utilizing waste heat from combined heat and power (CHP) in power plants has been increasing. From 2013 to 2020, the share of CHP increased from 42% to 55%, while the share of coal as a heat source decreased from 42% to 13%.

To fully utilize the waste heat from power plants, Fu *et al.* (2008)^[4] proposed replacing the traditional water-water plate heat exchanger between the primary network

(heat source side) and the secondary network (user side) with an Absorption Heat Pump (AHP). This approach can lower the return water temperature of the primary network below that of the secondary side. Such an AHP, which can be driven by hot water from the power plant and is also referred to as an Absorption Heat Exchanger (AHE), significantly increases the temperature difference between the supply and return water in the primary network (Figure 3)^[5]. This expansion enhances the effective utilization of waste heat from power plants, thereby eliminating some coal-fired or gas-fired boilers used for supplementary heating in urban district heating networks and effectively reducing carbon emissions. With this method, not only can the waste heat from power plants be fully utilized, but other low-grade industrial waste heat and renewable energy can also be harnessed to achieve low-carbon or zero-carbon heating. Furthermore, due to the large temperature difference between the primary network's supply and return water, the flow rate of hot water and the energy consumption of pumps are reduced, enabling long-distance heat transfer.

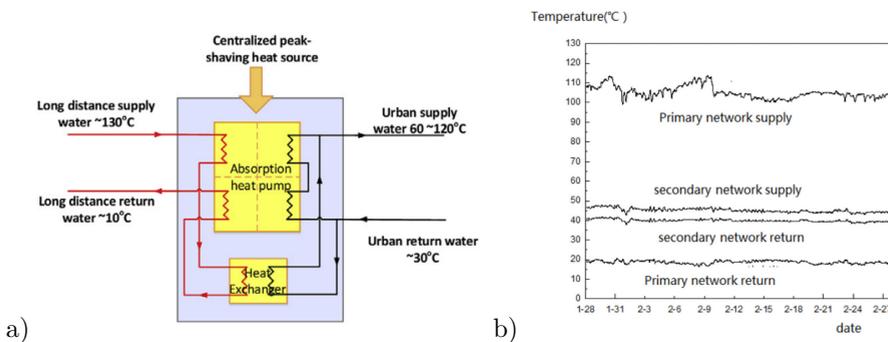


Figure 3: The heat exchange stations with the absorption heat pump^[5]

a) Schematic diagram of energy station designs with peak-shaving heat source.

b) The measured operating temperatures of the primary and secondary networks in an actual project.

By 2021, this method had achieved low-carbon heating for a building area of 100 million square meters in northern China^[5]. Reference [5] describes a case study of an urban centralized heating system utilizing absorption heat exchanger (AHE) technology in Taiyuan City, China. This project represents the first successful implementation in China of long-distance heat transmission based on a large temperature difference pipeline system, which conveys waste heat from a thermal power plant located 37 km away to the main urban heating network. The supply and return water temperatures from the long-distance transmission network are 130° C and 37° C, respectively. By 2021, the system provided heating for approximately 66 million m² of building floor area, with 60% of the heat substations retrofitted with AHE technology. Since the project's commissioning in 2016, it has replaced 41 million m² of heating previously supplied by scattered coal-fired boilers and led to the shutdown of a central city power plant equipped with four 300 MWe units. Consequently, annual coal consumption for heating has been reduced by 3.66 million tons, resulting in the elimination of 13,000 tons of air pollutant emissions, including nitrogen oxides (NO_x), sulfur dioxide (SO₂),

and particulate matter (PM₁₀), as well as a reduction of 9.5 million tons of carbon dioxide (CO₂) emissions per year.

Li and Xia *et al.* (2019)^[6] proposed a Combined Heat and Water (CHW) system solution that integrates a seawater desalination transportation system with a waste heat heating system^[6]. In this approach, desalinated water serves as a heat carrier to transport thermal energy from CHP power plants to urban district heating systems. Unlike the traditional urban district heating system, the CHW system does not require the return of backwater to the heat source.

This system utilizes the waste heat from cogeneration power plants (including nuclear power plants) located near the sea for seawater desalination. The obtained desalinated water is then further heated to approximately 95° C using the waste heat and transmitted over long distances to the target city. First, the thermal energy of the hot desalinated water is transferred to the primary pipe network of the urban district heating system, which is designed with a supply/return water temperature of 90/30° C, *via* a heat exchanger. Considering a heat exchange temperature difference of 5° C, the outlet temperature of the desalinated water from the heat exchanger can reach 35° C. Subsequently, an electric heat pump is employed to further extract heat from the 35° C desalinated water for use in the district heating system, reducing the temperature of the desalinated water to below 10° C for transportation to the urban sanitation system. If the desalinated water is intended for direct drinking purposes, its temperature will be maintained within the range of 10–20° C.

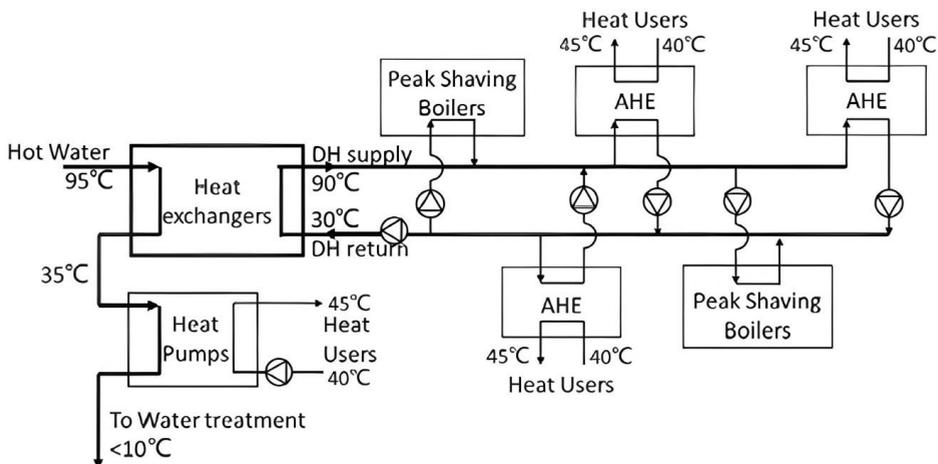


Figure 4: Schematic diagram of heat separation process of CHW system^[6]

In this system, while the return water temperature of the secondary network must reach 40° C to ensure users' heating requirements, the application of the aforementioned Absorption Heat Exchanger (AHE) enables the return water temperature of the district heating primary network to reach 30° C, as illustrated in Figure 4.

In China, this technology has been implemented in four projects, covering a heating floor area exceeding 10 million square meters. Currently, eight additional projects are under planning and design.

In recent years, a novel form of geothermal energy—Hot Dry Rock (HDR)—has garnered attention and technological advancements in the heating sector of northern China. A double-pipe heat exchanger is embedded within a 1000–2000 m deep heat exchange borehole to facilitate heat exchange between circulating water and rock formations, yielding hot water with temperatures typically below 40° C. By employing electric heat pumps, the grade of extracted heat can be enhanced to a certain extent, thereby meeting space heating demands. To date, the district heating system utilizing HDR has been implemented in practical engineering projects across various regions in China, including Shaanxi Province, Gansu Province, Shanxi Province, and Beijing Municipality. The total floor area served by HDR heating system has reached 30 million square meters, with prospects for further significant development in the future.

4.2 Carbon reduction technologies for space cooling

With the advancement of economic development, the energy demand for space cooling continues to rise. Relying solely on passive building design cannot ensure that occupants achieve their required thermal comfort during hot summers. Cooling is often achieved through electric or gas-based refrigeration systems. However, it is feasible to reduce indoor temperatures below the outdoor air temperature by utilizing novel natural cold energy sources. Natural cold energy sources encompass low outdoor air wet-bulb or dew-point temperatures, effective sky radiation temperatures, groundwater, deep lake water, or seawater, all of which are characterized by temperatures lower than the desired indoor air temperature. Nevertheless, in traditional air conditioning systems, these temperature-level cold sources are frequently underutilized for space cooling.

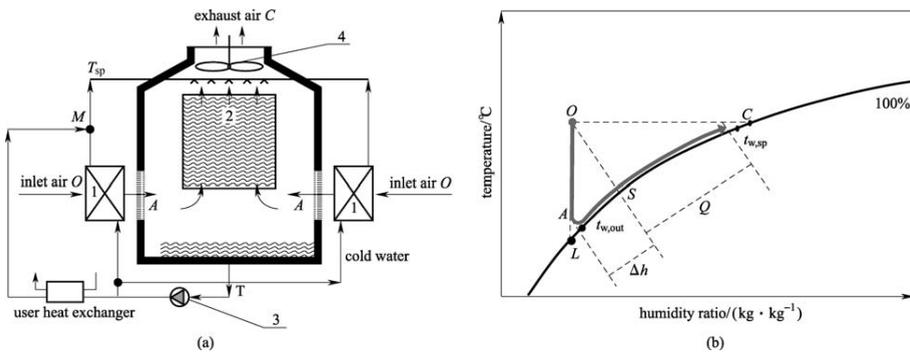


Figure 5: Structure of the indirect evaporative chiller^[7]

To fully utilize natural cold energy, Xie (2010)^[7] and Jiang (2010)^[8] *et al.* proposed a novel indirect evaporative chiller (IEC) that prepares low-temperature chilled water *via* indirect evaporative cooling instead of relying on electric chillers for cooling systems (Figure 5). This unit effectively harnesses natural cold energy and approximately reversibly utilizes dry air to prepare chilled water with the dew point temperature as the limiting temperature. Unlike direct evaporation technology, which brings water temperature close to the wet-bulb temperature, IEC achieves water temperatures lower than the wet-bulb temperature and approaching the dew point temperature (Figure 6), offering significant advantages in hot and arid climate regions. In such climates, it can even entirely replace electric refrigeration systems to achieve natural summer cooling^[9]. Additionally, IEC features an anti-freeze function during winter to ensure safe evaporative cooling operation without freezing. This represents one of the key approaches to achieving year-round low-carbon natural cooling. Currently, IEC is widely applied in various settings, including data center cooling, public building cooling, and industrial cooling processes.

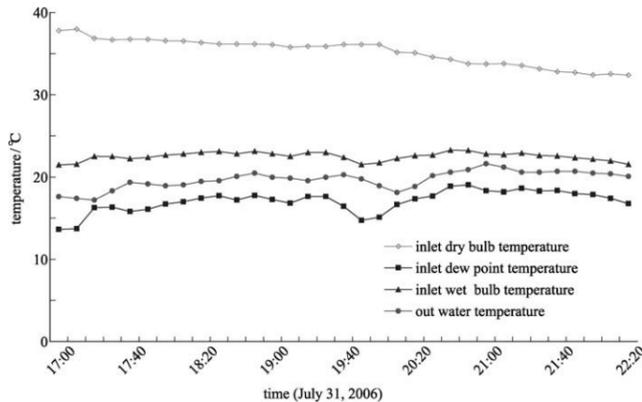


Figure 6: Tested out water temperature of indirect evaporative chiller ^[7]

Over the past decade, in Xinjiang, China, a region with a hot and dry climate in summer, IEC has been utilized in buildings exceeding 3 million square meters floor area. Reference [26] describes a case study of IEC (Indirect Evaporative Cooling) applied in an ophthalmology hospital located in Urumqi, Xinjiang, China. The total air-conditioned floor area of the hospital is 17,231.4 m². During the summer season, the local outdoor wet-bulb temperature typically remains below 18.3° C, with a dew-point temperature below 14° C. The project implemented a cooling system combining floor radiant cooling and a dedicated outdoor air system. A 560 kW IEC chiller supplied 16° C chilled water for the radiant floor cooling, maintaining the floor surface temperature at approximately 20° C, while six IEC outdoor air handling units were used to condition the fresh air. As a result, the indoor temperature was consistently maintained around 26° C. This case demonstrates the feasibility of achieving near-zero carbon cooling in summer solely through the application of IEC technology.

Shen and Li (2016)^{[10][11]} proposed embedding pipes within the exterior wall or double-skin façade of buildings, through which cooling tower water or water from other natural cool source could be circulated. This approach effectively mitigates heat transfer from the outdoor environment to the indoor space *via* the envelope during summer, thereby reducing the building's cooling load and significantly decreasing air-conditioning energy consumption (see Figure 7). In winter, low-grade heat sources can be utilized for space heating. For instance, in the case of a double-layer pipe-embedded exterior wall, water at 12° C can be circulated through the outer pipe, while water at 22° C can be circulated through the inner pipe, eliminating the need for additional space heating facilities and ensuring indoor thermal comfort during winter^[12].

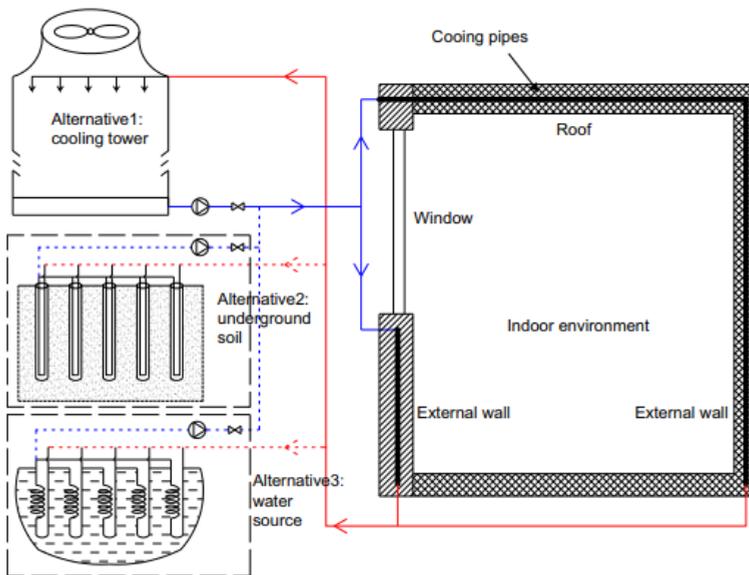


Figure 7: Schematic diagram of the pipe-embedded wall ^[10]

Zhai *et al.*(2017) ^[13] proposed a radiative cooling film that effectively utilizes the effective sky temperature for building cooling. This 50-micron-thick metamaterial film consists of randomly distributed silica microspheres (6% by volume) and is backed by a 200-nanometer-thick silver coating. It exhibits an infrared emissivity greater than 0.93 across the entire atmospheric window (8–13 microns) and reflects 96% of solar radiation. Consequently, even under direct solar radiation, this material achieves a radiative cooling power of 93 W/m². At night, it solely emits heat to the sky, maintaining a cooling state throughout the day with an average daily cooling power of 110 W/m². Currently, in China, this material has been successfully applied to the outer surfaces of boarding bridges, terminal building roofs, oil depots, and other facilities, and has been widely promoted in grain depot cooling applications. It significantly enhances the thermal environment within these facilities while effectively reducing air conditioning energy consumption. This material is suitable for buildings

with predominant cooling requirements, as well as buildings with large roof areas, such as those located in subtropical and tropical climate zones, ice and snow venues, and cold storage facilities, offering broad prospects for development.

5 Potential Directions for the Future Development of Technology

To achieve the zero-carbon goal, it is imperative to minimize the energy demand of buildings to the greatest extent possible, thereby enabling the limited renewable energy resources to meet this portion of the energy demand. Passive energy-saving building design methods must continue to be prioritized. Advanced passive low-carbon building design necessitates close collaboration between architects and HVAC engineers. Moreover, the development of next-generation HVAC systems represents a new direction for innovation. The implemented technologies should consider human behavioral patterns and emphasize delivering services for indoor environmental goals in specific spatial and temporal contexts.

In traditional air-conditioning design, the thermal environment of the entire space is typically maintained as uniform and stable as possible, ideally approaching $PMV = 0$. Despite the fact that such a stable thermal environment entails higher energy consumption, it does not necessarily enhance occupant satisfaction due to inherent individual differences among humans. In response to this phenomenon, two interrelated emerging research hotspots and technological development trends have emerged in recent years:

5.1 Personal Comfort System (PCS) / Personal Environment Control System (PECS)

Most of the cooling or heating provided by traditional air-conditioning systems is consumed in intermediate heat transfer media, such as air or indoor surfaces, while the proportion of energy directly acting on the human body remains very small. From the perspective of fulfilling personnel comfort requirements, this represents a highly energy-intensive approach. Personal Comfort Systems (PCS) aim to deliver individual-scale “precise thermal services” by providing cooling or heating directly to the human body, thereby reducing the stringent demands on the background environment. In scenarios where multiple occupants are present and conventional air-conditioning systems fail to accommodate individual preferences, PCS enables the creation of a relaxed background thermal environment while allowing individuals to customize their own thermal conditions. UC Berkeley was the first to propose the concept of PCS and conducted research on its comfort and energy-saving effects^{[18][19]}. Currently, PCS has been recognized as an effective strategy for reducing air-conditioning energy consumption and enhancing occupant comfort^[20].

When the ambient air temperature is 30°C, the contact cooling seat developed by the Tsinghua University team can enable subjects to perceive thermal neutrality (i.e., a sensation that is neither cold nor hot) when the surface temperature of the chair backrest and cushion is maintained at 26° C^[14]. A waistcoat incorporating phase change materials with a phase transition temperature of 27°C can maintain the subject's thermal neutrality at an ambient air temperature of 30° C^[15]. A key characteristic of

these Personal Comfort Systems (PCS) in direct contact with the human body is their ability to utilize high-temperature cold sources ranging from 26 to 27° C. Similarly, a leg warmer utilizing graphene for electrical heating of the calf can provide thermal neutrality in an indoor environment of approximately 15° C.

Hoyt employed the energy simulation software EnergyPlus to investigate the typical building energy consumption of a standard office building under varying indoor temperature settings across different climate zones in the United States [21]. The simulation results indicated that expanding the annual indoor temperature setpoint range from 21.1° C – 22.2° C to 18° C – 28° C could lead to energy savings ranging from 32% to 73%. To assess the energy-saving potential of contact cooling seats, a comparable simulation methodology is applied to a real-world three-story office building located in Beijing. The building has a cooling demand floor area of 9,614 m² during summer, and its envelope design complies with the requirements specified in the “Design Standard for Energy Efficiency of Public Buildings” (GB50189-2016). When the indoor air conditioning setpoint was increased from 26° C to 30° C during the summer season, the total cooling energy consumption was projected to decrease by 77%, primarily due to reductions in both the operating hours and cooling load of the air conditioning system.

The extensive energy consumption data collected through field investigations by the research team from Tsinghua University demonstrate that the average electricity consumption for air conditioning in Beijing’s office buildings during the summer season is approximately 40 kWh/m². By implementing contact cooling seats with a power consumption of 3 W per seat and increasing the ambient air conditioning setpoint temperature to 30° C, the total cooling-related electricity consumption during summer can be reduced to 9.7 kWh/m².

Taking a 20 m² personal office in Beijing as a practical example, the indoor temperature can reach approximately 15° C during clear daytime hours in winter. By utilizing a leg warmer, if an individual remains in the room for 800 hours during the winter season, the total power consumption amounts to 3.7 kWh/m², while the sensation of a cool head and warm feet achieves higher levels of thermal comfort. Conversely, if a heat pump with an average energy efficiency ratio (COP = 4) is employed to heat the entire office space to 20° C, the power consumption would need to reach at least 12.5 kWh/m².

However, considerable effort is required to achieve effective PCS/PECS, as the development of this miniaturized thermal environment control technology encounters greater challenges compared to traditional full-space air conditioning technology. The primary obstacle lies in the absence of mature microenvironment regulation technology.

Although safe local electric heating technology has reached a high level of maturity, several questions remain: Where should the heating be applied? What should the temperature control settings be? Should the heating be continuous or intermittent? Should it operate at a constant temperature or variable temperature? How can the lowest power consumption and longest battery life of wearable heating PCS be

achieved? These are all issues worthy of investigation, though they primarily focus on the demand side.

It is even more difficult to realize local “micro-refrigeration” technology. It is necessary to develop a new type of refrigeration equipment. The heat flow only needs to be less than 70W/square meter, and the cold surface temperature is maintained at 26 27° C, so as to transfer the heat generated by the human body to the ambient air at 30° C. If this kind of “micro-refrigeration” equipment with small temperature difference and small heat flow can be developed, theoretically speaking, its energy efficiency ratio should be much higher than that of commonly used air-conditioning and refrigeration equipment with large temperature difference and large heat flow. At present, the “micro-refrigeration” technologies that are possible to achieve this goal are all related to the research and development of new materials, but there are still some problems, such as too low energy efficiency, too low surface temperature, or still not commercially available, which requires great efforts to carry out research. In addition, it is necessary to study the lower limit of safe and healthy temperature for local cooling of human body, which is quite different from heated PCS.

The realization of local “micro- refrigeration” technology poses an even greater challenge, necessitating the development of a novel type of refrigeration equipment. Such equipment should maintain a heat flow of less than 70 W/m² while keeping the cold surface temperature within the range of 26 to 27° C, thereby transferring the heat generated by the human body to ambient air at 30° C. If this kind of “micro- refrigeration” equipment with a small temperature difference and low heat flow can be successfully developed, its theoretical energy efficiency ratio (EER) would significantly surpass that of conventional air-conditioning system and chiller, which typically operate with large temperature differences and high heat flows. Currently, the “micro-refrigeration” technologies capable of achieving this goal are closely tied to the research and development of new materials; however, several issues remain unresolved, such as insufficiently high energy efficiency, excessively low surface temperatures, or lack of commercial availability, all of which require substantial effort for further investigation. Additionally, it is essential to explore the lower limit of safe and healthy temperatures for localized human body cooling, which differs considerably from heating PCS.

Therefore, to address the challenges associated with PCS equipment, it is necessary to engage in interdisciplinary collaboration with fields such as physiology, psychology, new materials, and renewable energy in order to achieve the intended objectives.

5.2 Intelligent Control of Indoor Environment Based on Artificial Intelligence

The future air-conditioning system should provide “precise thermal services” for indoor occupants, and certain personalized thermal environment conditioning devices or so-called PCSs will also deliver localized cooling or heating near the human body to fulfill thermal comfort requirements. Most users are not experts in thermal environmental. While individuals can subjectively perceive whether they feel cold or hot, they lack the ability to accurately determine the specific thermal environment they truly require and are unfamiliar with how to adjust it appropriately. In this context, correctly identifying individual needs becomes critically important. Currently, re-

search in this domain is still in its infancy. Although numerous smart home products are available on the market and appear to offer comprehensive functionalities, many of these features are impractical and fail to align with the genuine requirements of occupants. Furthermore, due to limitations in sensor placement, these systems cannot adequately reflect the actual conditions of each occupant's activity area. Additionally, the absence of support from human thermal comfort theory means that the pursuit of constant temperature and humidity levels cannot satisfy the differentiated needs of individual occupants.

Indoor environment control based on artificial intelligence should first be capable of identifying the activity areas of occupants, thereby providing appropriate thermal conditions, air quality, lighting, and acoustic environments tailored to these areas. Secondly, by leveraging data-driven recognition models and self-learning methodologies, it should be able to understand the behavioral characteristics and real-time requirements of specific occupants according to their habits within the area, thus creating an optimal indoor environment that meets their individual needs.

The identification of indoor occupants' behavioral characteristics encompasses: movement or stationary spaces, presence or absence of perceived control, types of activities (work, study, exercise, leisure), needs (thermal comfort, ergonomics, health, sleep quality), and physiological traits (gender, age groups such as children and the elderly, physical condition), among others. Recognition targets include physiological parameters^{[22][23]}, facial expressions^[24], postures^[25], verbal cues, clothing, and similar indicators. For example, Wu *et al.* (2023) demonstrated that the identification of facial skin temperature *via* digital vision technology serves as a relatively reliable indicator for assessing the thermal sensation of indoor occupants^[16]. Based on this finding, they developed a methodology to drive the PCS system for environmental regulation according to real-time thermal sensation identification (Figure 8)^[17].

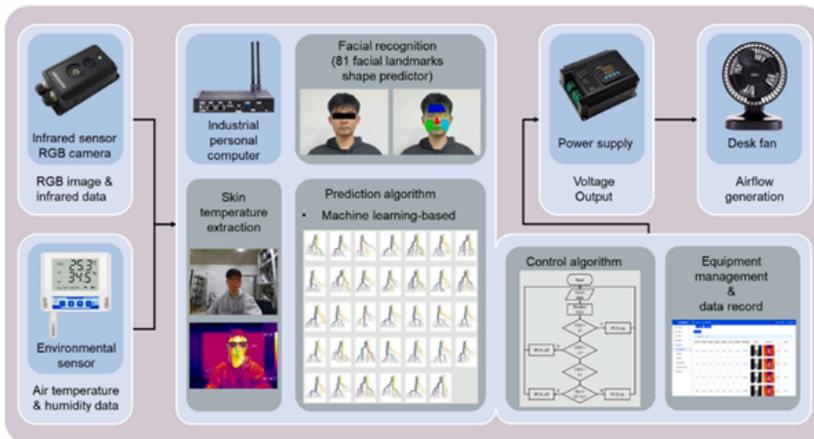


Figure 8: Automatic personal comfort system architecture^[17]

Since the same individual exhibits varying activity intensities when seated quietly *versus* performing housework, with differing thermal environment requirements in each case, identifying users' thermal needs through posture recognition is considered a feasible approach. During sleep, variations in body temperature and other physiological states occur across different sleep stages, and specific thermal environment conditions are required to ensure sleep quality. However, individuals cannot manually adjust their air conditioning equipment during sleep. Moreover, children, the elderly, and younger adults exhibit significantly different thermal environment preferences, meaning that each family member may possess unique thermal requirements. Consequently, individual demand identification represents a critical foundational research area for achieving AI-driven personalized indoor environment control, necessitating substantial effort and resources for investigation.

6 Conclusion

The establishment of China's "dual carbon" goals has introduced significant new challenges to the field of built environmental control, while simultaneously presenting new opportunities for development. The advancement of various low-carbon and energy-efficient technologies that enhance indoor environmental quality necessitates collaboration among researchers, engineers, technicians, and industry stakeholders to address key issues in fundamental scientific research and applied technologies. Only through the integration of cutting-edge achievements in information technology, material science, artificial intelligence, life sciences, and healthcare can the goal of "carbon neutrality" in the construction sector be realized. This will effectively drive technological progress and industrial upgrading in this domain, fostering greater development through innovation.

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