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Lifecycle carbon footprints of buildings and sustainability pathways in China

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Abstract

The Paris Agreement, with a 2 °C temperature increase baseline and a 1.5 °C target temperature increase, imposes challenges to the sustainability of buildings. However, as an end-user or end-of-the-art, the building sector overlaps with other sectors, such as industry and transportation in building materials manufacturing (such as steel, concrete, cement, *etc.*) and electricity use (such as building-to-vehicle charging), imposing difficulties in lifecycle carbon footprint quantification in buildings. In this study, the lifecycle carbon footprint of buildings and sustainability pathways in China are provided. Tools and platforms for lifecycle carbon footprint quantification in buildings are reviewed. A global database for lifecycle carbon footprint quantification in buildings is reviewed and compared, together with an analysis of the advantages and disadvantages. Furthermore, decarbonization technologies in the building operation stage are comprehensively reviewed, including the decarbonization potential, technology readiness level (TRL), techno-economic performance, and current technical status. Pathways on carbon neutrality in building sectors in China are provided. The results indicate that inconsistencies in global databases, unclear definitions of lifecycle carbon emissions, and inaccurate models of building energy consumption are the main challenges for accurate lifecycle carbon analysis in buildings. Various carbon neutrality transformation technologies can be classified into ultralow energy building and near zero-energy building technologies and into efficient heat pump and smart metering technologies. Pathways for low-carbon transition in building sectors include building energy saving (330 million tCO_2 with 22%), renewable energy supply (299 million tCO_2 with

20%), building electrification and power sector decarbonization (450 million tCO_2 with 30%), and carbon capture, utilization and storage (CCUS) technology (420 million tCO_2 with 28%). These research results can pave the way for upcoming studies on the lifecycle carbon footprint in buildings and sustainability pathways in China.

Keywords: Carbon footprint, renewable energy, building energy engineering, lifecycle analysis, carbon neutrality

INTRODUCTION

Green energy, green energy finance, and green governance are necessary for sustainable development goals[1]. End-of-life electric vehicle battery treatment for new battery manufacturing can reduce total carbon emissions by 32% by 2060[2]. Carbon footprint (CF) analysis has attracted the interest of researchers worldwide through life cycle assessment (LCA), input-output analysis (IOA), and the Intergovernmental Panel on Climate Change (IPCC) accounting method[3]. Cross-scale models are important for carbon quantification[4,5]. Globally, carbon neutrality requires energy efficiency, renewability, and carbon trading with advanced energy policies[6]. With increasing carbon emissions worldwide, the building sector accounts for approximately 40% of total carbon emissions globally[7]. Decarbonization in the building sector aligns well with the global carbon neutrality target. However, building decarbonization has many challenges throughout its lifetime.

The lifecycle carbon footprint of buildings and sustainability pathways include several different steps. The carbon footprint of lifecycle buildings has attracted widespread interest. Cheng *et al.* studied the embodied environmental impacts of buildings[8]. Based on the normalized environmental impact factors, mineral resource consumption, timber consumption, and fossil fuel consumption account for more than 80% of the life cycle embodied environmental impacts. The cradle-to-grave lifecycle carbon footprint of district buildings has been quantified, together with building integrated photovoltaic (BIPV) decarbonization analysis[9]. Furthermore, the lifecycle carbon footprint of the battery circular economy with renewables, buildings, and electric vehicles clearly identifies the main areas involved in the low-carbon transition[10]. Huang *et al.* studied the life cycle carbon emissions of buildings, together with carbon reduction strategies[11]. Carbon footprint analysis can promote decision-making in advanced building energy technologies[12].

Sustainability pathways mainly include energy savings, renewable energy supplies, and low-carbon building zero carbon buildings. Energy savings and renewable energy supplies are regarded as the main strategies for low-carbon buildings. In terms of energy savings, researchers have focused mainly on phase change materials[13], smart building envelopes[14], superinsulating aerogels[15,16], energy-efficient heating, ventilation and air conditioners (HVACs)[17], and so on. In terms of the renewable energy supply, hydrogen, as a clean energy source, can provide both power and thermal energy[18,19]. A combined thermal/power and cooling energy supply with waste heat recovery from fuel cell electric vehicles can be a reliable and sustainable energy source for building energy supplies[20]. Smart cities with sustainable airport energy ecosystems[19] can provide energy for sustainable buildings. Building energy savings and renewable supplies are two roadmaps for low-carbon buildings[21]. Due to the limited available space for renewable installations, researchers have focused on integrated solar photovoltaic/thermal systems[22], solar energy utilization efficiency improvement[23], and design/operation parameter optimization[24].

For zero-carbon buildings, the main challenges are considerable energy consumption in HVAC systems and future climate change. Low-global warming potential (GWP) refrigerants in HVAC can mitigate carbon emissions[25]. Climate adaptation with respect to energy resilience has been systematically reviewed, including urban morphology, mobility-based interactive energy sharing in regional districts, smart microgrids with vehicle-to-everything (V2X), and flexible energy buildings[26]. Zhou *et al.* studied climate-adaptive resilience in district buildings through distributed renewables, electric vehicles, and microgrids[27]. The research results indicate the challenges imposed by climate change on zero-carbon buildings. Peer-to-peer energy trading among building prosumers can enhance renewable self-consumption and reduce grid import pressure[28].

For building sustainability transitions in China, many researchers have focused on passive[29] and active technologies[30], cross-scale modeling[5], and advanced policies[31]. Liu *et al.* studied zero-carbon building retrofitting with low-carbon technologies. Research results indicate that increasing the use of low-carbon technologies can increase economic benefits from 42% to 66%[32]. Cabeza and Chàfer[33] reviewed both passive and active technologies for zero-energy buildings. In terms of advanced policies, Zhang *et al.* studied carbon-neutral building promotion policies, including reducing fossil energy consumption, improving building energy efficiency, utilizing renewable energy, and implementing zero energy/emission policies[31]. Li *et al.* studied and designed a financial incentive policy to promote zero carbon buildings[34]. From the perspective of cross-scale modeling, Zhou *et al.* studied decarbonization quantification approaches based on a cross-scale model[5]. Research results indicate that across China, the most promising technology will be industry, buildings and appliances, and transportation in mainland China (with decarbonization amounts of 37.5, 21.2, and 9.9 hundred million tons, respectively).

Based on the above literature review, the following scientific gaps can be summarized:

(1) The lifecycle carbon footprint of buildings is often uncertain and inaccurate. There are various tools and platforms for lifecycle carbon footprint quantification in buildings, but the advantages and disadvantages of these tools are not clear.

(2) Decarbonization pathway explorations and predictions in the building sector are not clear, and comparisons of different CST pathways in China have not been provided.

(3) Classifications of various decarbonization technologies in the building sector have not been provided. Furthermore, decarbonization potential levels, technical readiness level (TRL), techno-economic performance and current technical status have not been provided.

This study aims to address the abovementioned gaps. The objectives of this study are summarized below:

(1) Tools and platforms for quantifying the lifecycle carbon footprint of buildings are comprehensively reviewed, together with comparisons of their advantages/disadvantages and suitable application scenarios for each platform.

(2) The lifecycle carbon footprint of buildings under historical and current states in China are provided, together with sustainability transition pathways in China.

(3) Decarbonization technologies in building operation stages are comprehensively reviewed, including decarbonization potential levels, technical readiness level (TRL), techno-economic performance and current technical status.

The significance of this study is the following: (1) suitable tools and platform selections for lifecycle carbon footprint quantification to avoid calculation errors; (2) frontier guidelines on CST pathways in China with advanced technologies and policies; and (3) decarbonization technologies and their potential in building operation stages, together with their practical suitability in various scenarios.

The paper is organized as follows. The research methodology is described in Section "METHODOLOGY", Section "SYSTEMATIC LITERATURE REVIEW ON THE LIFECYCLE CARBON FOOTPRINT OF BUILDINGS" provides a systematic literature review on the lifecycle carbon footprint of buildings. The results and discussion are presented in Section "RESULTS AND DISCUSSION". Finally, conclusions are presented in Section "CONCLUSIONS".

METHODOLOGY

The research methodology for determining the lifecycle carbon footprint of buildings and sustainability pathways is shown in Figure 1. The method chosen for this study is based on bibliometric and citation analyses. Multiple technoeconomic-environmental performance metrics are applied for assessment. First, the lifecycle carbon footprint in buildings is comprehensively reviewed, including the concept definition and energy boundary, lifecycle zero-carbon buildings, tools and platforms for building carbon quantification. Afterwards, carbon-neutral pathways in building sectors are explored, including different decarbonization pathway explorations and predictions, decarbonization technologies and technical readiness levels. Finally, an outlook and recommendations are provided.

SYSTEMATIC LITERATURE REVIEW ON THE LIFECYCLE CARBON FOOTPRINT OF BUILDINGS

Zero-energy building concept definition and energy boundary

Zero-energy buildings (ZEBs) generally refer to total energy consumption equal to the total renewable energy supply. However, depending on the energy system boundary and time span, there is no agreement on the exact definition of ZEBs. Figure 2 shows an integrated building energy system with different energy boundaries. ZEBs refer to the total energy inputs (renewable energy and grid import energy) equal to the total energy outputs (energy consumption and grid export energy). Table 1 summarizes the global definition of zero-energy buildings. Some researchers define both import/export and load/generation balances for net zero energy buildings[35]. Some researchers argue that not only the operational stage but also the energy during construction and component delivery need to be included in ZEBs[36]. Furthermore, considering the dynamic performance degradation of integrated components (such as renewable systems, storages, and power transmission loss), ZEBs require the dynamic update of integrated capacity[37,38].

Lifecycle of zero-carbon buildings

Lifecycle zero-carbon buildings are based on current buildings designed under national building regulations without renewables or innovative building materials. Figure 3[42] shows the life cycle carbon emissions of the buildings in the four stages of the different modules. Note that the operational use stage includes use, maintenance, repair, replacement, refurbishment, operational energy, and water use, as shown in Figure 3A. Based on the case study, the carbon emissions from operation and raw materials account for approximately 56.2% and 41.3%, respectively (as shown in Figure 3B. However, the specific proportions may be slightly different, depending on the local climate conditions, building type, *etc.* Stage-based roadmaps for zero-energy buildings, including low-energy, ultralow energy, prosumer, and thermal/electrical storage-based buildings, are shown in Figure 3C. Moschetti *et al.* studied the pathway transitions from zero-energy to zero-emission buildings[43]. These studies indicate that renewable energy can only cover operational energy/carbon, while the embodied energy of materials imposes great challenges. Mytafides *et al.* studied the transition into a zero-energy building of a university building with various alternative methods[44].

Table 1. Summary of zero-energy buildings

Studies	Systems	Definition	Method	Results
Zhou *et al.*[18]	Renewable-building-battery & hydrogen system	The ZEB-ZEV system considers the energy interaction interface with the power grid	Numerical simulation	Dynamic degradation will gradually break the energy balance of the ZEB-ZEV system
Sartori *et al.*[35]	Net Zero Energy Building	Import/export balance and the load/generation balance	Net ZEB definitions	Energy interaction between buildings and grids with indicators for building energy design
Hernandez and Kenny[36]	Life cycle zero energy buildings	Operation of the building and energy use related to the construction and delivery are included in LCA carbon of buildings	Literature review	Both embodied energy of building components and energy use in operation are within the boundary in life cycle zero energy buildings
Zhou[37]	Low-energy districts	Energy sharing districts for high energy utilization	Literature review	System design, planning, operation and optimization are essential for high energy utilization
Zhou and Zhou[38]	Zero-energy buildings	Hydrogen fuel cell and electrochemical battery for energy supply in energy flexible buildings	Numerical simulation	Low-grade heat recovery for power-H_2-power conversion can contribute to low-energy buildings
Marszal *et al.*[39]	ZEB	metrics, balancing period, energy use types, renewable energy supply options, energy infrastructure and energy efficiency	Literature review	Consistent ZEB definition and robust energy calculation methodology are needed
Shirinbakhsh and Harvey[40]	Zero energy building in different dimensions	net-zero energy, net-zero energy-cost, and net-zero emission buildings	Global analysis	Definition of net-zero site-energy buildings, net-zero source-energy buildings, net-zero energy-cost buildings, and net-zero emission buildings have different impacts on greenhouse gas emissions
Song and Zhou[41]	A zero-energy district	The zero-energy district	Numerical simulation	The zero-energy district with different controls on thermal and electrical systems will lead to different operating costs

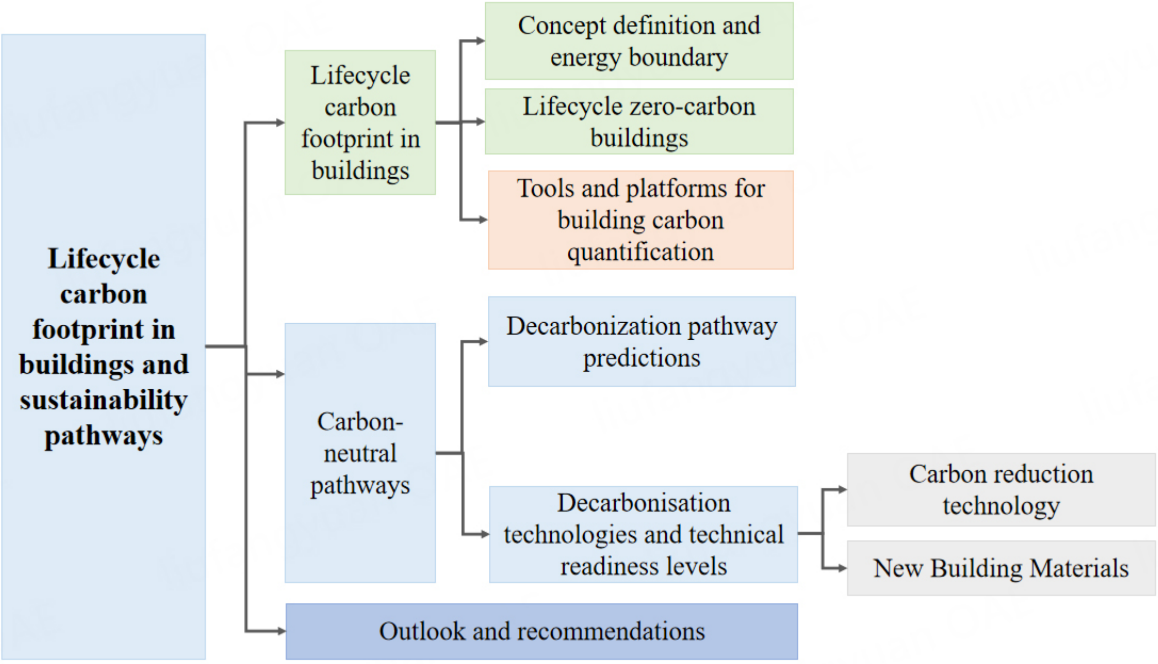

Figure 1. An overview of the research methodology.

Building carbon quantification tools and platforms

Lifecycle carbon analysis in buildings is complex due to inconsistencies in global databases, unclear definitions of carbon emissions in transport, inaccurate models of building energy consumption, *etc.*

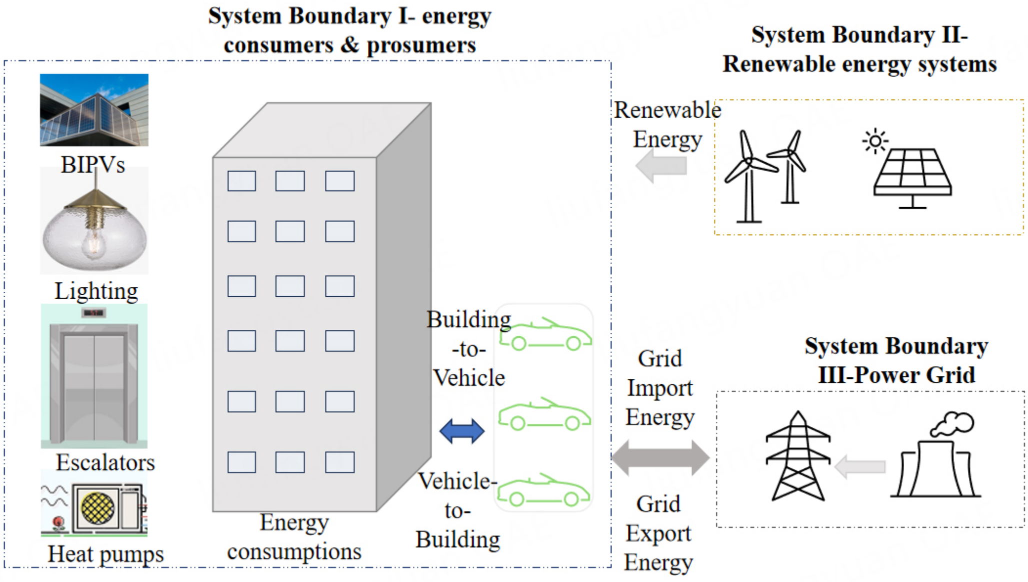

Figure 2. Energy boundary of integrated building energy systems.

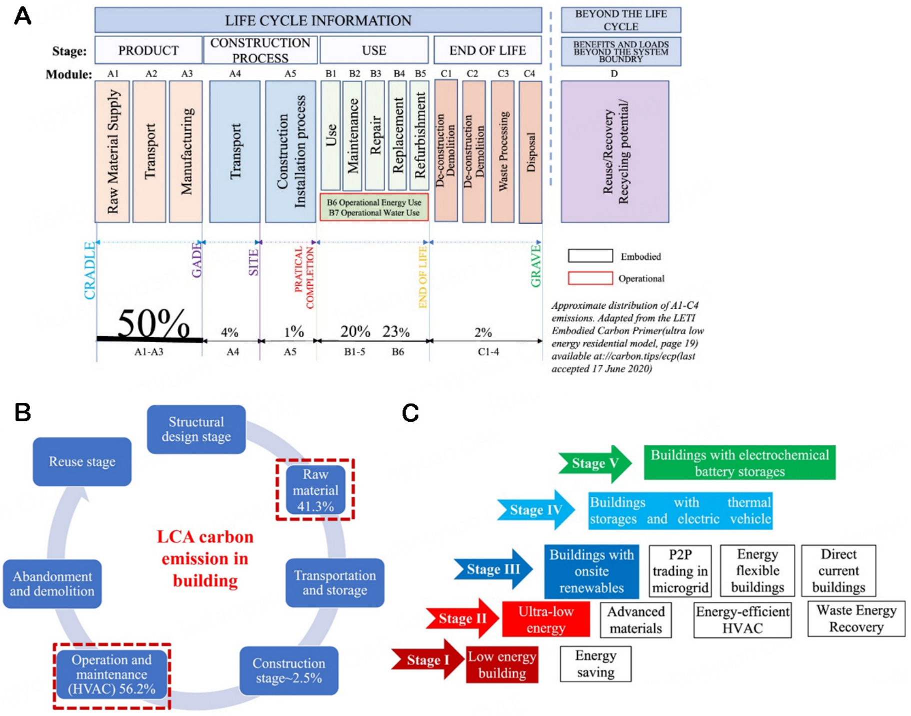

Figure 3. Overall framework of lifecycle carbon emissions in buildings: (A) cradle-to-grave lifecycle information; (B) lifecycle assessment (LCA) of carbon emissions; and (C) stage-based roadmaps for zero-energy buildings[42].

Considering the complexity of carbon quantification in buildings, researchers worldwide are attempting to accurately quantify LCA carbon emissions. Research directions mainly include database comparison[45], complete database establishment[46], new approach development[46,47], building information models[48,49,50], accurate model development in building energy simulations[51,52,53], and onsite renewable supply[53,54].

Building carbon quantification tools and platforms are summarized in Table 2[55-59]. As shown in Table 2, most researchers use BIM for carbon emission quantification. Other platforms include TRNSYS, EcoTect, EnergyPlus, and EcoInvent. The Ecoinvent database contains more than 2,500 background processes with easy data exchange[60]. Furthermore, the characteristics and shortcomings of various building carbon quantification tools and platforms are provided in Table 3[61-70]. Researchers can select the appropriate database for carbon quantification in different scenarios.

RESULTS AND DISCUSSION

Decarbonization pathway predictions

For lifecycle carbon footprint prediction, most researchers use BIM with implemented databases during the design stage[71]. The TRNSYS platform with embodied energy in materials can also be adopted for LCA carbon intensity[9,11].

Figure 4 shows the carbon emission evolution and decarbonization potentials for different scenarios in 2060[72]. Carbon emission evolution and decarbonization potentials lack solutions. The carbon emission evolution in Figure 4A shows the real-time carbon emissions under different scenarios. Specifically, compared with the benchmark scenario, the reduction potentials are 330 million tCO_2 (22%) by building energy savings, 299 million tCO_2 (20%) via renewable energy supplies, 450 million tCO_2 (30%) by building electrification and power sector decarbonization, and 420 million tCO_2 (28%) via carbon capture, utilization and storage (CCUS) technology, as shown in Figure 4B.

The technology readiness of new technologies for low-carbon buildings is listed in Table 4. In terms of decarbonization, the high potential of decarbonization includes radiative/radiant cooling technology, superthermal insulation technology, onsite wind turbines, BIPVs and onsite solar-wind systems. Technologies with high TRLs include onsite wind turbines, BIPVs and onsite solar-wind systems, and their economic performance is high.

Decarbonization technologies and technical readiness levels

Carbon reduction technology for building operation and maintenance

The heat transfer process of buildings is complex, and there are various cooling/heating loads, such as the thermal conductivity of building envelopes, personnel, lighting, equipment, solar radiation, and household hot water. The energy consumption of buildings is influenced by various factors, such as their shape, orientation, insulation, ventilation and lighting, and equipment selection. Passive buildings include superinsulated building envelopes, radiative cooling, and nanocoating. By adopting special designs, sealing structures, and materials with good insulation properties for window frames, roofs, and exterior walls, heat loss and energy consumption can be reduced, which is crucial for carbon neutrality in the construction industry. Active building energy-saving technologies include energy recovery, intelligent control, and photovoltaic/photothermal technologies. Automatic regulation and optimization of indoor and outdoor environments can be achieved through energy conversion and regulation systems, reducing energy consumption and environmental pollution, which is also an indispensable part of building energy conservation and emission reduction.

(1) Ultralow energy buildings and near-zero energy building technologies

(1.1) Advanced dehumidification technologies

Table 2. Summary of carbon quantification tools and platforms

Studies	Tools and platforms	Systems	Method	Results
Eleftheriadis *et al.*[55]	BIM	Building Structures	Structural design optimization	Design optimization on reinforced concrete (RC) buildings is important for LCA carbon performance
Li *et al.*[56]	BIM	Prefabricated buildings	Lifecycle carbon accounting and comparison	For residential prefabricated buildings, average annual carbon emission per unit area at approximately 105.88 $kgCO_2/(m^2.a)$, which is much lower than the cast-in-place building at approximately 130.79 $kgCO_2/(m^2.a)$
Li *et al.*[57]	BIM	prefabricated concrete buildings	Lifecycle carbon accounting and comparison	Regulations and emission reduction policies
Pan *et al.*[9]	TRNSYS	A small-scale building district	Dynamic simulation	26.5%, 24.4%, and 22.5% decrease in carbon emission can be achieved in hotel, office, and residential buildings through building Integrated Photovoltaics (BIPVs)
Peng[58]	Ecotect and BIM	Entire life cycle of the building	Simulation	operational, construction, and demolition stages generate 85.4%, 12.6%, and 2% of the total CO_2 emissions
Schwartz *et al.*[59]	EnergyPlus	office building	Multiobjective optimization and decision-making	Different design solutions can be obtained under decision-making design procedures

Table 3. Analysis of various building carbon quantification tools and platforms

Types	Sources	Characteristics	Shortcomings
European databases	GaBi database[61]	Integrity, usability and dedicated resources; more than 1,000 processes for construction materials	-
	Ecoinvent[62]	Consistency and transparency with 100 out of its 4,000 processes open licenses; freely consult it online and download	-
	European reference lifecycle database 3.1[63]	Free of charge; online consultation	limited data number
	PlasticsEurope Eco-Profiles[64]	Raw material extraction, emissions to air and water, and waste generated are included, and transport derived from production, vehicle maintenance, and the replacement of batteries and tyres	-
American databases	Athena database[65]	Data for construction materials, energy, transport, construction and demolition processes, maintenance, repairing, and waste disposal, considering differences in transport, energy mix and recycled material rates	Access licence is needed
	U.S. life cycle inventory database[66]	Input and output flows of energy and materials with detailed flow charts	Unclear energy sources with simple assumption on 100% fossil fuel; Only consultation online
Spanish	Base carbone[67]	free online database with only gas emissions	No methodology in the database
	BEDEC database[68]	Data for embodied energy, CO_2 emissions, and waste disposal with economic and environmental information.	Not clear definition on transformation into a construction product or its transport to the building site; no visible link for consultation
	CPM LCA database[69]	Three assessment methodologies with manufacturing processes	complication for applications in building process due to the very specific production stages; no update for certain elements
	ProBas[70]	Complete database with more than 7000 unitary processes with 700 construction materials	Forbidden in German
China	Chinese life cycle database	Incomplete database	Ecoinvent database and European life cycle database act as supplementary

In terms of new dehumidification technologies, such as metal-organic frameworks (MOFs)[4], excellent performance in terms of moisture absorption and dehumidification can be observed. MOFs are lattice structures composed of metal ions and organic ligands, and their controllable pore structure allows them to adapt to different humid environments. However, performance stability and cost are still core issues that

Table 4. Technology readiness of new technologies for low-carbon buildings

Technologies	Decarbonization levels	Technical Readiness Level (TRL)	Techno-economic performance	Current technical stage
New dehumidification technology	Medium	5	General	Research and development
Radiative/radiant cooling technology	High	6	General	Experimental demonstration
Super thermal insulation technology	High	8	Good	Promotion and applications
Intelligent building exterior walls	Low	7	Poor	Experimental demonstration
Onsite wind turbines	High	9	Good	Frontier research
BIPVs	High	9	Good	Promotion and applications
Onsite solar-wind systems	High	9	Good	Promotion and applications
Digital twin technology	Medium	5	General	Experimental demonstration
Waste heat recovery and utilization technology	Medium	6	Good	Experimental demonstration
Internet of Things	Medium	7	General	Experimental demonstration
Ground/water-source heat pumps	Medium	8	General	Promotion and applications
Sky radiative cooling	Medium	6	General	Experimental demonstration

Results in the table are based on scientific research from researchers in academia and professional reports from engineers in industry.

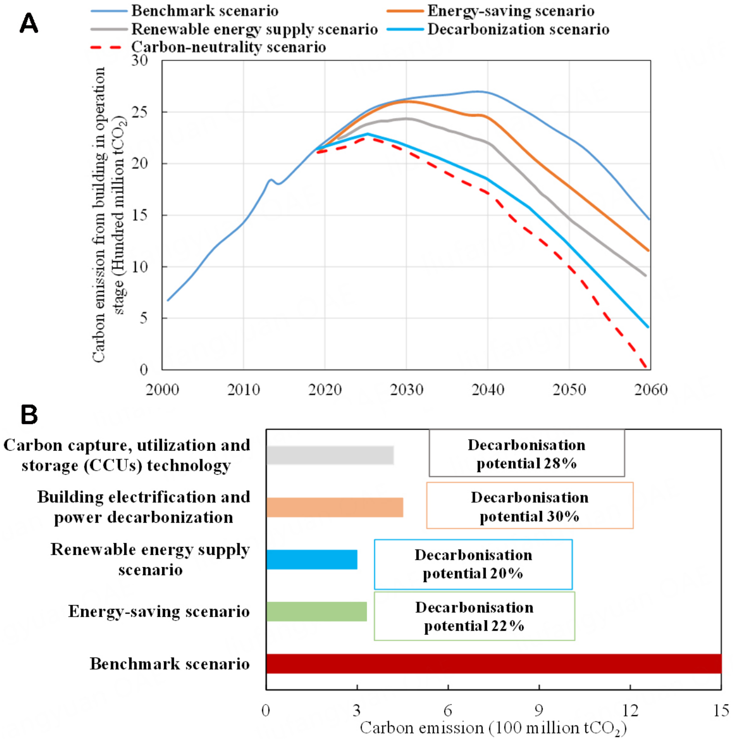

Figure 4. 2060 carbon neutrality in building sectors in China: (A) carbon emission evolution[5]; (B) decarbonization potentials for the carbon neutrality scenario[72].

need to be urgently addressed, and further improvement of material stability is needed to cope with high-humidity environments and reduce preparation costs to promote commercialization. In addition to MOFs, there are other new dehumidification technologies, such as ionic liquids[73] and polymer materials[73,74], which have shown different advantages and potential in humidity control. The progress of these technologies lies in their high efficiency and controllability, enabling them to adapt to diverse humidity requirements and play a role in industrial, commercial, and household environments. However, these emerging technologies also face challenges in practical application and commercialization, requiring environmental adaptability, sustainability, safety, and standardization.

(1.2) Radiant air-conditioning technology

Compared with traditional convective air conditioning systems, radiative air conditioning has many advantages, including high comfort, low energy consumption, good air quality, and effective prevention of COVID-19 transmission[75]. Radiant air conditioning is suitable for large open areas, with an investment payback period of 4-8 years[76]. The problem of surface condensation is the main technical problem that restricts the widespread application of radiant air conditioning. This will increase the water supply temperature and require an auxiliary refrigeration system with high energy consumption. Therefore, developing an anticondensation technology for radiant air conditioning (such as infrared thermal insulation technology) is the core issue for ensuring ultralow radiative surface temperatures and solving condensation problems in which the use of radiant air conditioning technology needs to be addressed.

(1.3) Superinsulating technology for building envelope structures

There are a large number of old buildings with poor thermal insulation performance, resulting in buildings with over 40% urban electricity and approximately 20% carbon emissions. Therefore, enhancing building insulation is important for reducing building energy consumption and carbon emissions, with a carbon reduction potential of up to 25% for buildings in cold northern regions. Traditional building insulation materials have a high level of technological maturity (TRL 9) and a short economic recovery period of only approximately 2-6 years. However, there are problems with insufficient insulation performance and inconsistent design standards. Therefore, the development of new thermal insulation materials (such as superinsulated aerogel glass[77] and microencapsulated phase change walls[13]) with safety, thermal insulation, economic, environmental performance, and durability is urgently needed for building thermal insulation. In terms of policies to improve building insulation performance and reduce building energy consumption and carbon emissions, effective methods mainly include strengthening technical research and development support, strengthening financial subsidies, promoting the research and application of high-performance insulation materials, improving insulation standards and evaluation systems, and increasing the acceptance of new insulation materials by residents.

(1.4) Smart building envelopes

The term “smart exterior walls” refers to the use of advanced technology and intelligent systems to enable building exterior walls with more functions and intelligent characteristics[78]. Smart exterior walls can achieve functions such as environmental monitoring, energy management, and safety protection by integrating various sensors and control systems. At the same time, smart exterior walls can also achieve dynamic shading, ventilation control, and dynamic climate-adaptive insulation through intelligent control and variable structural materials while improving the comfort of residents, reducing unnecessary heat loss or gain, and improving overall energy efficiency. At present, the technological maturity of building smart exterior walls is approximately 8, and the investment return period is approximately 8-20 years. The main issues limiting the development of smart exterior walls in buildings include high initial construction costs and difficulty in technical implementation. Advanced sensors, control systems, and new materials often require significant investment, which may hinder some developers or homeowners from adopting these technologies. In addition, the design and installation of smart exterior walls often require interdisciplinary professional knowledge, and there is a lack of sufficient technical talent and experienced construction teams in the market. In addition, the maintenance and upgrading of smart exterior wall systems also require professional knowledge, which may increase long-term operating costs. A lack of policy support and market awareness is also a problem that constrains the development of smart exterior walls. In terms of policy, strengthening technological research and development support, establishing special funds, and cultivating interdisciplinary talent are effective means to promote the development of smart exterior wall technology and accelerate the large-scale application of smart exterior walls.

(1.5) Building integrated micro wind technology

Wind power-supported building technology refers to the integration of wind power generation equipment in buildings, which utilizes the wind energy around the building to generate electricity and achieve self-sufficiency in the building[79]. Wind power-supported building technology is an effective technical means to reduce building energy consumption and carbon emissions in wind resource-rich areas, such as Xinjiang and Inner Mongolia. The maturity of wind power building integration technology is approximately 8, and it can now be applied to various types of buildings, including residential, commercial, and public buildings. The existing wind power equipment has problems such as high power generation volatility, high initial investment costs, large space occupation, and impacts on urban ecology and aesthetics. The main development direction of wind power building integration technology is to develop highly efficient wind power equipment, reduce the cost of wind power equipment, and use energy storage systems, demand-side management, and other methods to improve the wind power self-consumption ratio in buildings. In terms of policies, special funds will be established to promote the research and development of efficient integrated wind power building systems, supporting energy storage systems, and building energy control systems. New types of wind power conversion equipment will be developed to improve the energy and carbon reduction performance of existing wind power equipment. Market promotion and publicity will be strengthened, and financial subsidies will be established to enhance the enthusiasm of building owners for using wind power equipment.

(1.6) Building integrated photovoltaic (BIPV) technology

Building integrated photovoltaic (BIPV) technology combines photovoltaic panels with buildings[80] and uses them as part of exterior walls, roofs, or sunshades to achieve a self-sufficient energy supply for buildings. This technology can improve the clean energy utilization efficiency of buildings, especially in areas with strong solar radiation, such as Yunnan and the Qinghai-Tibet Plateau. It can reduce energy consumption by up to 20% and carbon emissions by 15%, while also providing exterior design and indoor lighting effects for buildings. The technological maturity of BIPV is approximately 9, and the current challenges include high technical costs (initial investment cost of approximately 1,500 yuan per kilowatt), inconsistent technical standards, *etc.* It is necessary to strengthen the research and development of low-cost photovoltaic conversion technology and standard formulation and promote the popularization and application of this technology. In addition, the grid connection of distributed energy will have a certain impact on the security and stability of the power grid. How to achieve safe grid connections for distributed energy is a bottleneck that restricts the large-scale implementation of BIPVs. In terms of renewable energy trading and sharing, China lacks a clear trading and sharing system, and the enthusiasm for participation in renewable energy trading and sharing among buildings, photovoltaic owners, and power users is still questionable. Therefore, the government can increase support and encouragement for the grid connection of distributed photovoltaic systems; mobilize the enthusiasm of buildings, photovoltaic owners, and power users through policies, funds, and other means; promote grid connections and the trading and sharing of renewable energy; promote the popularization and application of clean energy; and achieve the goal of sustainable development.

(2) Near zero carbon transformation technology for public infrastructure

(2.1) Complementary wind-solar technology

Complementary wind-solar technology is a set of power generation technologies applied to building energy systems. This technology supplies the electricity generated by photovoltaic panel arrays and wind turbines to various electrical equipment in buildings through transformers or inverters and stores the remaining electricity in energy storage batteries. The complementary technology of wind and solar energy has been widely used in various large-scale wind and solar power plants and energy storage stations, but its application in buildings has hindered further development due to its complexity. The complexity of wind-solar complementary technology lies in the following two points: (1) The coupling operation of solar power generation, wind power generation, rectifiers, inverters, building electrical equipment, and energy storage batteries is difficult, and the building demand does not match the power generation curve; (2) The renovation of wind complementary power generation systems in existing buildings is difficult, and onsite wind power generation renovation is also challenging. Additionally, there are safety issues with energy storage batteries. In addition, the cost of wind-solar complementary technology is still relatively high. The levelized cost of electricity (LCOE) is 0.32-0.76 yuan/kWh for BIPVs (including inverters), 0.35-0.6 yuan/kWh for small wind turbines (including rectifiers), and approximately 0.21-0.56 yuan/kWh for battery energy storage. Considering that the penetration rate of renewable energy in wind-solar complementary systems is only approximately 50%, the LCOE of wind-solar complementary technology will be as high as 1 yuan/kWh or more. If it can be reduced to below the average electricity price (approximately 0.6 yuan/kWh), wind-solar complementary technology will achieve positive economic benefits on the premise of significant carbon reduction benefits.

(2.2) Digital-twin technology

According to the definition in the White Paper on Digital Architecture 2021, digital architecture is based on the concept of digital twins and comprehensively utilizes advanced technologies, such as 5G, BIM, and the Internet of Things. It is committed to achieving digitalization and intelligence of the entire building process, all elements, and all participants, thereby building a new platform ecosystem for projects, enterprises, and industries.

Although certain achievements have been made, the digitalization process of China's construction industry is still relatively lagging behind, facing challenges such as a lack of information exchange and cross-disciplinary coordination. Digital architecture and its core technologies, such as BIM, can promote the circulation, sharing, and utilization of data, information, and resources throughout the entire construction process through information sharing, professional collaboration, and other capabilities. This effectively aggregates the main entities of various links in the industrial chain, achieving synergistic capabilities and specialties throughout the entire industrial chain.

In the future, with the continuous maturity of technology and the increase in market demand, the application of digital twin technology in the construction industry will lead to a broader development space, providing strong support for carbon reduction and comprehensive transformation and upgrading of the construction industry.

(3) Efficient heat pump and smart metering technology

(3.1) Waste heat utilization technology

Waste heat recovery technology aims to recover and utilize the heat energy lost during the operation of buildings and reuse this waste heat to generate hot water, thereby improving energy efficiency[81]. Waste heat recovery technology in buildings mainly involves the recovery of waste heat from HVAC systems, hot water systems, and so on. Its main equipment includes air source heat pumps, water source heat pumps, and heat exchangers. The problem with waste heat recovery technology is that the initial investment cost is high, and the recovery efficiency is low. At present, the initial investment cost of air source heat pumps is approximately 300-600 yuan/m^2[82], and the initial investment cost of water source heat pumps is approximately 200-400 yuan/m^2[83], which is much greater than that of general indoor heating technologies (such as underfloor heating). Therefore, using heat pumps to achieve active waste heat recovery lacks economic feasibility. As the only choice for passive waste heat recovery, heat exchangers have been rapidly developed in recent years. The efficiency of air heat exchangers used in air conditioning systems is 40%-75% (depending on indoor and outdoor temperatures), while the efficiency of fluid heat exchangers used in air conditioning and hot water systems is 80%-90%. Therefore, advanced air and fluid heat exchangers require efficiencies of 75% and 90% or above, respectively.

(3.2) Internet of things technology

The Internet of Things technology refers to the connection between various object features and device perception information and the internet based on information sensing and communication facilities following custom communication protocols. Through information dissemination media, information exchange and communication between objects and devices are carried out to achieve integrated monitoring, positioning, and control of objects and devices in multiple regions. The combination of Internet of Things technology and building space heat metering has made significant progress this year, aiming to achieve customized heating for buildings in terms of space and demand.

Household heat metering technology is currently the mainstream metering technology in China[84] and mainly includes remote wireless meter reading technology and remote wired meter reading technology. Remote wireless meter reading technology is a popular direction that combines Internet of Things technology with Bluetooth technology, ZigBee technology, infrared technology, GPRS technology, *etc.* The Internet of Things technology integrates the information of building heat users, building area heating management centers, and heating companies to form an intelligent control IoT network system, which allows the control center to quickly and effectively obtain, collect, and analyze the energy consumption data of building heat users, providing technical support for further predicting user heat loads. At present, companies (such as Siemens in Germany and Danfoss in Denmark) have combined internet technology with heat metering technologies, such as the K-coefficient heat calculation method and the M-BUS meter reading method, forming a mature intelligent heat metering monitoring system.

At present, China's household heat metering technology based on the Internet of Things technology is still in the partial demonstration stage, and further efforts are needed in the construction of the industrial information IoT, standardization of data centers, and refinement of household heating.

(3.3) Ground source/water source heat pump technology

The maturity of ground source heat pump and water source heat pump technology is high, with a TRL index above 8[85]. However, their investment cost is high (1,000-2,000 yuan per square meter), operation and maintenance are difficult, the economic payback period is as high as 15-20 years, and climate and regional adaptability are limited. They are usually only suitable for buildings in hot summer and cold winter climate zones with large temperature differences throughout the four seasons. Therefore, future development should focus on the miniaturization, simplification, and universality of heat pumps. The government can use tax incentives, financial subsidies, and regulations to incentivize the large-scale standardized application of heat pump technology.

(3.4) Outer space radiative cooling technology

Space radiation refrigeration technology is suitable for tropical regions with clear weather and good air quality (such as Guangdong, Yunnan, *etc.*)[86], which can reduce building cooling loads by approximately 20% and achieve high economic benefits. The recovery period is only approximately 3-8 years. However, the maturity of space radiation cooling technology is only approximately 5, and poor stability, low cooling capacity, and insufficient lifespan are bottleneck problems that restrict the large-scale application of space radiation cooling. Therefore, the development of low-cost, high visible light reflectivity, high infrared emissivity, and high radiation cooling materials (such as aerogels and hydrogels) and the use of fiber reinforcement, polymer reinforcement, and other technologies to enhance the mechanical properties and lifespan of materials are the main directions for the development of space radiation cooling technology. Future policies can adopt the establishment of special funds, the cultivation of interdisciplinary talent, and the strengthening of international cooperation to promote the research and development of new generation space radiation cooling materials.

Low-carbon building materials implied carbon reduction technology

Table 5[91] shows the low-carbon building materials and their decarbonization levels, technical readiness levels (TRLs), and techno-economic performance, together with their current development status. They are based on scientific research from researchers in academia and professional reports from engineers in industry. Details on each technology are provided in the following subsections.

(1) Nano aerogel insulation materials

Nano aerogel insulation material is an efficient insulation material with a micropore structure[87]. This principle is based on the structural characteristics of aerogels, which are composed of a three-dimensional network of highly porous and ultrafine pores. These micropores are much smaller than the diameter of human hair, effectively blocking the conduction and convective heat transfer of gas molecules and thus providing excellent insulation. In recent years, significant progress has been made in the research and application of this material in the field of insulation. Through nanotechnology, the pore structure and surface properties of aerogels can be regulated, further enhancing their thermal insulation performance. Moreover, nano aerogel insulation materials are lightweight, soft, and easy to process, making them widely used in various fields, such as architecture, clothing, and aerospace. In the future, with the continuous

Table 5. Low-carbon building materials

Technologies	Decarbonization levels	Technical readiness level (TRL)	Techno-economic performance	Current technical stage
Nano aerogel insulation material[87]	High	7	General	Experimental demonstration
Phase change materials[88]	High	6	Good	Experimental demonstration
Nanoporous hydrogel material[89]	Medium	5	General	Research and development
Nanofilm technology[90]	Medium	8	Good	Promotion and applications

development of nanotechnology and materials science, nano aerogel thermal insulation materials are expected to become more efficient and environmentally friendly thermal insulation materials, making important contributions to energy conservation and emission reduction.

(2) Microcapsule phase change materials

Microcapsule phase change materials are innovative materials widely used in the field of construction[88]. By encapsulating phase change materials through microcapsule technology, precise control of the phase change process and controllable release of energy can be achieved.

In the field of construction, microencapsulated phase change materials are widely used in intelligent temperature control materials. It can regulate the internal temperature of buildings and save energy through the phase change heat absorption characteristics of phase change materials. When the indoor temperature exceeds the set value, phase change materials absorb heat, causing the temperature of the room to decrease. When the indoor temperature drops below the set value, phase change materials release stored heat, providing additional heating effects. This intelligent temperature control material can provide a more comfortable indoor environment and effectively reduce energy consumption.

Microcapsule phase change materials can also be applied to building facade materials, providing heat control and energy conservation functions. By applying microencapsulated phase change materials to the exterior facades of buildings, it is possible to absorb and release solar radiation heat, thereby reducing the indoor heat load, reducing the burden on air conditioning systems, and improving the energy efficiency of buildings.

In addition, microencapsulated phase change materials can also be used to improve building materials, and enhance their insulation performance and heat load management capabilities. By applying microencapsulated phase change materials to walls, roofs, and other areas, heat conduction can be effectively reduced, the insulation performance of buildings can be improved, and the goals of energy conservation and environmental protection can be achieved.

In summary, the application of microencapsulated phase change materials in the field of construction is highly important. This approach can achieve intelligent temperature regulation, heating control, and energy conservation functions, improve indoor environmental comfort, reduce energy consumption, and improve the energy efficiency of buildings. With the continuous development of technology, the application prospects of microencapsulated phase change materials in the field of construction will be even broader.

(3) Nanoporous hydrogel materials

Nanoporous hydrogel materials are materials with a three-dimensional hydrophilic network structure and a water content of more than 60%[89]. Its unique water absorption and flexibility give it the potential to be widely used in sensing, strain responsiveness, drug delivery, moisture absorption, evaporation, and other fields. Hydrogel materials have attracted much attention due to their water absorption ability and have diverse application prospects. Future development directions include regulating the chemical composition or solvent composition of the hydrogel and providing the hydrogel with more functions, such as controlled release, intelligent sensing, *etc.* At the same time, building a double network structure and accurately designing molecular chains and other means will also be important ways to improve the performance of hydrogels to enhance their mechanical and functional properties. In recent years, researchers have been committed to improving the performance and diversity of hydrogel materials, and exploring their new applications in fields such as medicine, biosensing, and environmental governance. With the continuous progress of technology in the future, hydrogel materials are expected to become more intelligent and multifunctional materials, providing reliable solutions for various fields.

(4) Nanofilm technology

At present, nanotechnology has a wide range of applications in new building materials and is highly important for reducing hidden carbon emissions in buildings[90]. Nanofilm technology achieves precise control of light by designing the structure of nanopores in composite materials. First, through the application of nanofilms, building materials can improve insulation performance, reduce indoor temperature fluctuations, reduce dependence on air conditioning, and thus reduce energy consumption. This helps to reduce energy consumption, indirectly reducing carbon emissions related to energy production and use. Second, nanofilm technology can make building materials more transparent, allowing more natural light to illuminate the interior and reducing the need for artificial lighting. This not only improves the thermal comfort of buildings but also reduces electricity consumption, further reducing carbon emissions. In addition, nanofilms can effectively block ultraviolet radiation, reduce sun damage to indoor furniture, floors, and other items, extend their service life, reduce resource waste, and reduce the carbon footprint of remanufactured materials. At the same time, the nanofilm itself has good weather resistance and scratch resistance and long service life and can reduce the splashing of glass fragments when glass is broken, improve safety, and achieve carbon reduction by reducing the number of membrane replacements.

Overall, the application of nanofilm technology in new building materials can effectively reduce building energy consumption and carbon emissions by improving insulation performance and increasing transparency, providing practical technical support for sustainable building and carbon neutrality goals.

Decarbonization practices in China

Decarbonization practices of buildings have been widely studied in China. Figure 5 demonstrates the Evolution of zero energy building standards in China[91]. These evolutions will help promote the transition from low-energy toward zero-energy buildings.

Based on the above analysis, decarbonization practices in China have been studied in academia. Generally, researchers mainly focus on two aspects. In terms of advanced technologies, Li *et al.* studied carbon reduction in commercial buildings at the provincial level in China and indicated that the total reduction in China's commercial buildings was 1.38 $GtCO_2$ from 2001-2016[92]. Carbon emissions in China from 1994 to

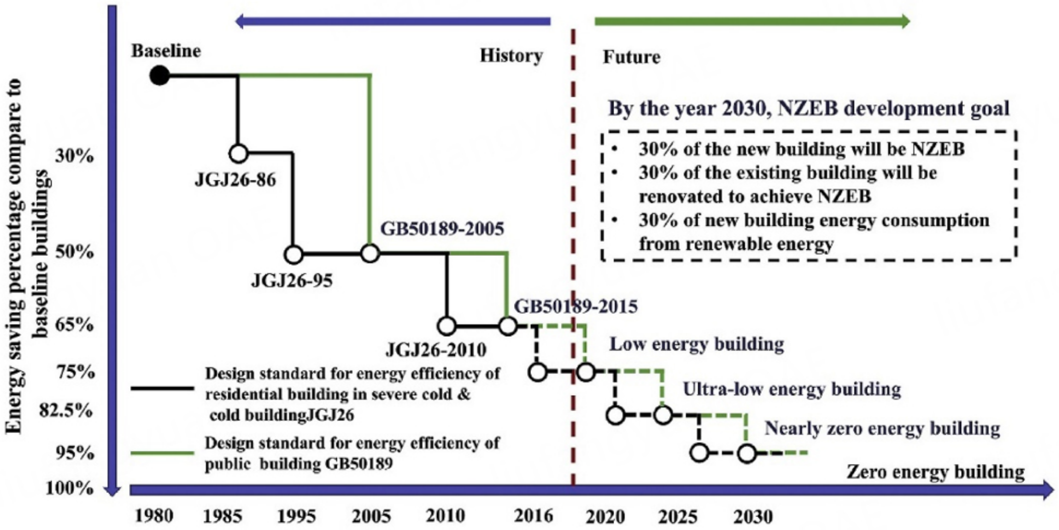

Figure 5. Evolution of zero energy building standards in China[91].

2012 indicate that total construction emissions annually increased by 6.9%, while the emission intensity annually decreased by 4.7%[93]. Zhou *et al.* analyzed decarbonization in building sectors in China and indicated that systems and practices were effective in minimizing building energy use[94]. By analyzing historical carbon emissions and mitigation tendencies, Ma *et al.* concluded that for the 2030 emission peak goal of residential buildings, a benchmark of 1.258 $BtCO_2$ is necessary[95]. Based on a bottom-up model, Yang *et al.* studied combined strategies for controlling floor space, energy consumption, and energy structure to reduce carbon emissions in buildings[96]. Zhang and Wang[97] developed lifecycle assessment and control measures for lifecycle carbon emission reductions. Research results indicate that by using a reinforced concrete block masonry structure, carbon emissions can be reduced by 38-112 $kgCO_2/m^2$.

In addition to advanced technologies, national policies have also been studied for building sector decarbonization. Wang *et al.* studied greenhouse gas emission mitigation policies with balanced costs and benefits for stakeholders[98]. Lin and Liu[99] studied carbon reduction policy and concluded that population migration played a major role in carbon emissions.

CONCLUSIONS

In this study, the lifecycle carbon footprint of buildings and sustainability pathways in China were explored. First, a systematic literature review on the lifecycle carbon footprint in buildings was conducted, including the concept definition and energy boundary. Tools and platforms for lifecycle carbon footprint quantification in buildings are reviewed. A global database for lifecycle carbon footprint quantification in buildings is reviewed and compared, together with an analysis of the advantages and disadvantages. Furthermore, decarbonization technologies in the building operation stage are comprehensively reviewed, including the decarbonization potential, technical readiness level (TRL), techno-economic performance, and current technical status. Pathways on carbon neutrality in building sectors in China are provided. The results indicate that lifecycle carbon analysis in buildings is complex and challenging due to inconsistencies in global databases, unclear definitions of carbon emissions in transport, inaccurate models of building energy consumption, *etc.* For carbon neutrality transformation, the main technologies include ultralow energy buildings and near zero energy building technologies (e.g., advanced dehumidification technologies, radiant air conditioning technology, superthermal insulation technology, building integrated solar-wind technology, *etc.*), net zero carbon transformation technology (e.g., complementary wind-solar technology and digital twin technology, *etc.*), and efficient heat pump and smart metering technologies (e.g., waste heat utilization technology, Internet of Things Technology, ground source/water source heat pump technology, outer space radiative cooling technology, *etc.*). Furthermore, new building materials for embodied carbon reduction technologies, such as nano aerogel insulation materials, microcapsule phase change materials, nanoporous hydrogel materials, and nanofilm technology, are promising but still in their infancy. Finally, carbon reduction potentials are 330 million tCO_2 (22%) by building energy savings, 299 million tCO_2 (20%) via renewable energy supplies, 450 million tCO_2 (30%) by building electrification and power sector decarbonization, and 420 million tCO_2 (28%) via carbon capture, utilization and storage (CCUS) technology.

However, the research limitations of this study include the following: (1) the impact of parameter uncertainty on lifecycle decarbonization in the building sector has not been analyzed; and (2) climate-adaptive CST pathways have not been studied across different climates in China. Future studies will focus on parameter uncertainty related to lifecycle decarbonization in the building sector and climate-adaptive sustainability transitions in different climate regions in China. Furthermore, based on the footprint impacts of green energy, green energy finance and green governance, net zero energy building evaluation[100,101], and the carbon footprint of the construction industry[102], future studies can work continuously to improve the results or methods.

DECLARATIONS

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Authors' contributions

Conceptualization, methodology, software, formal analysis, investigation, resources, data curation, writing - original draft, writing - review & editing, formal analysis, visualization, supervision, project administration, funding acquisition: Zhou Y
Conceptualization, methodology, software, formal analysis, investigation, resources: Yu X
Conceptualization, methodology, software, formal analysis, investigation, resources: Zhang X

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Availability of data and materials

The data that were used are confidential.

Conflicts of interest

Zhou Y is an Editorial Board member of the journal *Carbon Footprints*, while the other authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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