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CLIMATE ADAPTABILITY AND LOW-CARBON EFFICIENCY OF AIR-SOURCE HEAT PUMPS: EVIDENCE FROM PROVINCIAL CHINA

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Abstract
The decarbonization of building heating systems is a critical component of China's strategy to achieve carbon peaking by 2030 and carbon neutrality by 2060. Among available clean-heating technologies, air-source heat pumps (ASHPs) have emerged as an energy-efficient and environmentally sustainable alternative to conventional fossil-fuel-based heating systems. However, the performance and environmental benefits of ASHPs vary considerably across China due to differences in climatic conditions, electricity generation structures, technological development, and policy support. This study examines the climate adaptability and low-carbon efficiency of ASHP systems across China using an integrated analytical framework grounded in low-carbon transition theory and climate adaptation theory. The analysis is based on a balanced provincial panel dataset comprising 31 Chinese provinces over the period 2015–2024. Air-source heat pump performance is evaluated as a function of outdoor temperature, humidity, electricity carbon intensity, technological advancement, and government policy support. A mixed-method research design is employed, combining an extensive review of scientific literature and policy documents with quantitative techniques, including descriptive statistics, correlation analysis, and multiple regression estimation. The empirical findings reveal that outdoor temperature, technological advancement, and policy support exert significant positive effects on ASHP performance, whereas electricity carbon intensity negatively affects system efficiency and environmental effectiveness. Humidity demonstrates a comparatively weaker influence on performance outcomes. The results further indicate substantial regional heterogeneity, with moderate and hot summer–cold winter regions exhibiting more favorable operating conditions than severe cold regions. The study contributes to the literature by integrating climatic adaptability and carbon-efficiency perspectives within a single framework and provides policy-relevant insights for accelerating sustainable heating transitions in China. The findings offer practical guidance for policymakers, energy planners, and technology developers seeking to optimize ASHP deployment while supporting national decarbonization objectives.
Keywords: *Air-Source Heat Pumps, Climate Adaptability, Low-Carbon Efficiency, Energy Transition*

INTRODUCTION

Climate change has emerged as one of the most pressing environmental and policy challenges of the twenty-first century (Sands, 2023; Kandpal et al., 2024). Accelerated industrialization, urban expansion, and population growth have substantially increased global energy demand, leading to rising greenhouse gas emissions and mounting environmental pressures (Raihan et al., 2022; Swagatika et al., 2025; Umair et al., 2025). Among the various sources of emissions, fossil fuel combustion remains the dominant contributor to anthropogenic carbon dioxide emissions, particularly in sectors such as electricity generation, transportation, manufacturing, and buildings. As the world's second-largest economy and one of the largest energy consumers, China occupies a central position in global climate mitigation efforts. Over the past four decades, the country has experienced unprecedented economic growth and urban development, lifting millions out of poverty while simultaneously increasing its dependence on energy-intensive production systems. Consequently, China has become one of the largest contributors to global carbon emissions, largely due to its historical reliance on fossil fuel-based energy infrastructure (Wang et al., 2021; Zhao et al., 2022).

Within China's energy system, the building sector represents a major source of energy consumption and associated emissions (You et al., 2023). Residential and commercial buildings require substantial energy inputs for heating,

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cooling, ventilation, and electricity use. Heating demand is particularly significant in northern China, where district heating systems have traditionally depended on coal combustion (Wei et al., 2025). Although these systems have played an important role in ensuring thermal comfort, they have also contributed to severe air pollution and seasonal smog episodes, generating adverse environmental and public health consequences (Liu & Claridge, 2015; Audi et al., 2026). Recognizing these challenges, the Chinese government has established ambitious climate targets, including peaking carbon emissions before 2030 and achieving carbon neutrality by 2060. Meeting these objectives requires a fundamental transformation of energy consumption patterns, particularly within the building sector, where low-carbon heating technologies are increasingly viewed as essential components of the clean energy transition (Kyriakopoulos et al., 2022; Majeed et al., 2026). Among the available alternatives, air-source heat pumps have attracted considerable attention due to their high energy efficiency and potential for reducing carbon emissions. Rather than generating heat through direct fuel combustion, air-source heat pumps transfer thermal energy from the surrounding environment using electricity-driven refrigeration cycles (Riffat et al., 2024; Tahir et al., 2026). This process enables the delivery of heating and cooling services with substantially lower energy consumption compared with conventional heating technologies. Furthermore, the dual functionality of modern air-source heat pump systems enhances their economic attractiveness by providing year-round climate control through both heating and cooling operations (Afonso et al., 2016; Javed et al., 2026).

Despite these advantages, the performance of air-source heat pumps remains highly sensitive to climatic conditions. Factors such as outdoor temperature, humidity levels, frost formation, and seasonal variability can significantly influence system efficiency and operational reliability (Haakana et al., 2024; Choudhary et al., 2026). These challenges are particularly relevant in China because of its diverse climatic zones, which range from extremely cold conditions in the northeastern provinces to subtropical and tropical climates in the south. Such regional heterogeneity creates substantial differences in heating and cooling requirements, making the nationwide deployment of air-source heat pumps considerably more complex. Previous studies have demonstrated that climatic conditions exert a direct influence on the coefficient of performance and seasonal efficiency of heat pump systems (Ai & Audi, 2016; Zhang et al., 2017; Marc et al., 2025; Gillani et al., 2026). In colder regions, declining temperatures reduce the amount of available ambient heat, increase compressor workloads, and often necessitate energy-intensive defrosting processes. Nevertheless, recent technological advances, including vapor injection systems, inverter-driven compressors, advanced refrigerants, and intelligent control mechanisms, have significantly improved the cold-weather performance of modern heat pump technologies (Chakraborty, 2026).

The environmental benefits of air-source heat pumps are also closely linked to the carbon intensity of electricity generation (Ali et al., 2021; Khan et al., 2024; Żelazna & Pawłowski, 2025). Although heat pumps eliminate on-site fossil fuel combustion, their overall contribution to emissions reduction depends on the energy sources used to generate electricity. Regions characterized by coal-dominated electricity systems may experience lower carbon reduction benefits than regions with higher shares of renewable energy generation. Consequently, the effectiveness of heat pump deployment as a decarbonization strategy is strongly influenced by broader energy transition policies and the evolving composition of national electricity systems (International Energy Agency, 2022). In response, China has implemented a series of policy initiatives, including the Coal-to-Electricity Program, financial subsidies, electricity pricing reforms, building efficiency standards, and renewable energy promotion measures, all of which have accelerated the adoption of clean heating technologies across the country (Kong et al., 2026).

Although existing studies have extensively examined the technical performance, energy efficiency, and environmental benefits of air-source heat pumps, relatively limited attention has been devoted to the integrated assessment of climatic adaptability and carbon reduction performance across China's diverse climatic regions. Most previous research has concentrated either on engineering performance under specific operating conditions or on emissions reduction potential in isolated contexts. Such approaches provide valuable insights but often overlook the interaction between regional climatic conditions and the broader sustainability outcomes of heat pump deployment. Given China's geographical diversity and ambitious decarbonization agenda, understanding how climatic variability influences both operational efficiency and carbon mitigation potential is essential for effective policy design and technology deployment. Thus, the present study investigates the climate adaptability and low-carbon performance of air-source heat pump systems across different climatic regions of China.

ENVIRONMENT AND AIR-SOURCE HEAT PUMPS

Air-source heat pumps (ASHPs) have emerged as one of the most promising technologies for improving building energy efficiency and reducing carbon emissions within the heating sector (Congedo et al., 2023). Unlike

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conventional heating systems that rely on direct fuel combustion or electrical resistance heating, ASHPs operate by transferring thermal energy from ambient outdoor air into indoor spaces through a vapor-compression refrigeration cycle. This mechanism enables ASHPs to deliver significantly more thermal energy than the electrical energy they consume, resulting in substantially higher energy efficiency than traditional heating technologies (Hun et al., 2025; Tian et al., 2025; Naeem et al., 2025; Zheng et al., 2026).

Modern ASHP technologies are capable of producing two to four units of thermal energy for every unit of electricity consumed, resulting in relatively high coefficients of performance under suitable operating conditions (Abdelaziz et al., 2018; Longston et al., 2025). Technological advancements have further strengthened their competitiveness. In particular, inverter-driven compressors, variable-speed control systems, advanced refrigerants, and intelligent operating algorithms have improved seasonal efficiency, operational flexibility, and energy management capabilities (Ji et al., 2019; Batool et al., 2025). At the same time, the transition toward environmentally friendly refrigerants with lower global warming potential has enhanced the overall sustainability profile of heat pump systems. The growing importance of ASHP technology is closely linked to global decarbonization efforts. Buildings account for a substantial share of global energy consumption and carbon emissions, making heating system transformation a critical component of climate mitigation strategies (Long et al., 2025). As countries pursue carbon neutrality objectives and expand renewable electricity generation, electrified heating technologies have become increasingly attractive alternatives to fossil fuel-based systems. The International Energy Agency (2022) identifies heat pumps as one of the most effective technologies available for reducing emissions from residential and commercial buildings because they combine high energy efficiency with the potential to utilize increasingly decarbonized electricity supplies.

International experience provides strong evidence regarding the effectiveness of large-scale heat pump deployment. Countries such as Norway have achieved widespread adoption through supportive policy frameworks and abundant renewable electricity resources, particularly hydropower (Hansen & Moe, 2022). Similarly, Japan has played a pioneering role in advancing heat pump technologies through innovations in inverter compressors, cold-climate operation, and energy-efficient system design (Adamo et al., 2025). Across Europe, carbon pricing mechanisms, renewable energy targets, and building decarbonization policies have accelerated heat pump adoption. Existing evidence explains that the carbon reduction benefits of heat pumps increase significantly in regions characterized by low-carbon electricity generation systems (Rosenow & Lowes, 2020; Arshad et al., 2025). Nevertheless, challenges related to installation costs, grid infrastructure, public acceptance, and climatic suitability continue to influence deployment rates across countries. Rapid urbanization, growing environmental awareness, and ambitious climate commitments have encouraged the adoption of clean heating solutions (Tang, 2024). Historically, heating demand in northern China was primarily satisfied through coal-based district heating systems and residential coal-burning appliances (Lu et al., 2022). Although effective in meeting heating needs, these systems contributed substantially to carbon emissions and seasonal air pollution. In response, the Chinese government introduced a series of clean-heating initiatives, including the Coal-to-Electricity Program, which promoted the replacement of coal-fired heating systems with electricity-based alternatives such as ASHPs. Empirical evidence indicates that these policies significantly accelerated heat pump adoption across northern provinces after 2017 (Sun et al., 2020).

Chinese manufacturers have invested heavily in low-temperature compressor technologies, advanced refrigerants, intelligent control systems, and energy-efficient product development. As a result, the heat pump sector has become an important component of China's broader green manufacturing strategy, contributing to technological innovation, employment generation, and export growth. However, the effectiveness of ASHP deployment varies considerably across regions because of differences in climate conditions, electricity infrastructure, and levels of economic development. Consequently, climatic adaptability remains one of the most important determinants of long-term system performance and economic feasibility (Zhang et al., 2017).

Climate adaptability refers to the ability of ASHP systems to maintain efficient and reliable operation under varying environmental conditions (Yang et al., 2025). Since heat pumps extract thermal energy directly from ambient air, outdoor climatic conditions exert a significant influence on their operational performance. Among these factors, outdoor temperature represents the most critical determinant of efficiency. Numerous studies report that the coefficient of performance declines as ambient temperature decreases because lower temperatures reduce the amount of available thermal energy and increase compressor workloads (Abdelaziz et al., 2018). Frost accumulation on outdoor heat exchangers creates additional challenges by restricting airflow and reducing heat

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transfer efficiency, necessitating periodic defrost cycles that increase electricity consumption and temporarily interrupt heating delivery. Enhanced vapor injection systems, dual-stage compression technologies, inverter-driven compressors, and advanced control algorithms have significantly improved cold-weather performance (Ji et al., 2019). However, performance variations across climatic regions remain substantial. Factors such as humidity levels, seasonal temperature fluctuations, and building insulation standards continue to influence system efficiency (O'Hegarty et al., 2024). Consequently, evaluating ASHP performance requires consideration of regional climatic characteristics rather than relying solely on standardized technical specifications.

Low-carbon efficiency refers to the extent to which a technology can deliver required energy services while minimizing greenhouse gas emissions throughout its lifecycle (Kabeyi & Olanrewaju, 2022). Compared with coal-fired and natural gas heating systems, ASHPs generally exhibit substantially lower lifecycle emissions because they avoid direct combustion and utilize electricity as their primary energy source (Zheng & You, 2023). However, their carbon reduction potential depends heavily on the carbon intensity of electricity generation. Regions characterized by greater reliance on renewable energy sources experience significantly larger emissions reductions than regions dependent on coal-fired electricity generation. Northern industrial provinces continue to rely heavily on coal-based electricity generation, whereas southwestern regions benefit from extensive hydropower resources and increasing renewable energy penetration (Wang et al., 2021). Lifecycle assessment studies further indicate that operational emissions savings generally outweigh emissions associated with manufacturing and installation, although refrigerant selection remains an important consideration because leakage from high-global-warming-potential refrigerants can partially offset environmental gains. China's climatic diversity further complicates the deployment of ASHP systems (Li, 2026). Severe cold regions, including Heilongjiang, Jilin, northern Xinjiang, and parts of Inner Mongolia, experience extended winters and extremely low temperatures that increase heating demand and reduce heat pump efficiency (Yang et al., 2014). Cold regions such as Beijing, Tianjin, Hebei, Liaoning, and Shandong face similar challenges, although less severe climatic conditions generally allow for more efficient operation. In contrast, hot summer-cold winter regions, including Shanghai, Jiangsu, Zhejiang, Anhui, and Hubei, present favorable conditions for dual-function heating and cooling systems, enhancing annual equipment utilization and economic viability (Cao et al., 2016). Southern subtropical provinces such as Guangdong, Guangxi, Fujian, and Hainan exhibit relatively mild winters and strong cooling demand, making ASHPs particularly attractive due to their high operational efficiency and year-round applicability.

Table 1: Climate Conditions vs ASHP Performance

Climate Zone	Avg Temperature (°C)	COP Range	Efficiency Level	Suitability
Severe Cold	-20 to -5	1.5 – 2.5	Low	Limited
Cold	-5 to 5	2.0 – 3.0	Moderate	Feasible
Hot Summer–Cold Winter	0 to 15	2.5 – 3.5	High	Very Suitable
Mild/Temperate	10 to 25	3.0 – 4.5	Very High	Optimal

Air-source heat pumps (ASHPs) have emerged as one of the most effective technologies for reducing greenhouse gas emissions in the building sector. Unlike conventional heating systems that rely on the direct combustion of coal, oil, or natural gas, ASHPs operate through electrically driven heat transfer processes that extract thermal energy from ambient air and deliver it to indoor spaces. This mechanism enables ASHPs to provide heating with substantially higher energy efficiency than traditional combustion-based technologies. Consequently, heat pumps have been widely recognized as a critical component of global decarbonization strategies. According to the International Energy Agency (2022), the large-scale deployment of ASHPs has considerable potential to reduce emissions from residential and commercial heating by replacing fossil fuel-based systems with highly efficient electric heating technologies. The environmental significance of ASHP deployment is particularly evident in China, where coal has historically dominated residential and district heating systems, especially in northern provinces. Decades of reliance on coal-fired heating have contributed substantially to carbon emissions, urban air pollution, and public health challenges. As China pursues its carbon peaking and carbon neutrality objectives, the electrification of building heating has become a central policy priority. Existing evidence explains that replacing conventional coal-based heating systems with ASHP technology can reduce carbon emissions by approximately 30–70%, depending on climatic conditions, system efficiency, and the carbon intensity of electricity generation (International Energy Agency, 2022). The magnitude of these reductions is strongly influenced by the coefficient

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of performance (COP) of the heat pump system, as higher efficiency levels translate directly into lower electricity consumption and reduced lifecycle emissions.

Although ASHPs do not produce direct emissions during operation, their overall environmental performance depends heavily on the characteristics of the electricity grid supplying the system (Zafaranchi et al., 2025). This relationship is particularly important in China, where significant regional disparities exist in electricity generation structures. While some provinces continue to rely heavily on coal-fired power plants, others increasingly benefit from renewable energy sources such as hydropower, solar energy, and wind power. Consequently, the carbon mitigation potential of ASHP systems varies substantially across regions. Previous studies have demonstrated that the environmental benefits of electrified heating technologies are highly sensitive to the carbon intensity of electricity generation (Rosenow & Lowes, 2020). Regions characterized by cleaner electricity mixes generally achieve substantially greater emissions reductions than areas dependent on fossil fuel-based power generation. Therefore, continued decarbonization of China's electricity sector remains essential for maximizing the environmental advantages of ASHP deployment. A comprehensive assessment of ASHP sustainability requires consideration of lifecycle carbon emissions rather than focusing exclusively on operational performance. Lifecycle emissions originate from several stages, including raw material extraction, manufacturing, transportation, installation, operation, maintenance, and end-of-life disposal. Manufacturing processes associated with steel production, compressor fabrication, and refrigerant development generate measurable carbon emissions. However, numerous lifecycle assessment studies indicate that these initial emissions are typically offset by operational energy savings achieved throughout the system's lifespan (Zheng & You, 2023). As a result, ASHP systems generally produce substantially lower lifetime carbon emissions than coal-fired and natural gas-based heating technologies.

Operational emissions remain the dominant component of lifecycle environmental performance and are primarily determined by electricity consumption patterns and grid carbon intensity (Mohtashami et al., 2026). Another important consideration involves refrigerant selection and management. Refrigerant leakage can significantly influence environmental outcomes because many conventional refrigerants possess high global warming potential values. Even relatively small leakage rates may contribute disproportionately to greenhouse gas emissions. Consequently, recent technological developments have focused on introducing low-global-warming-potential refrigerants that minimize environmental risks while maintaining high system efficiency. Furthermore, improvements in recycling and recovery processes have enhanced the sustainability of ASHP systems by enabling the recovery of valuable metals and refrigerants at the end of equipment life cycles. Beyond carbon mitigation, ASHP deployment generates substantial environmental and public health benefits through improvements in local air quality. Traditional coal-based heating systems release significant quantities of particulate matter, sulfur dioxide, nitrogen oxides, and other harmful pollutants that contribute to urban smog formation and respiratory diseases. These impacts are particularly severe in northern Chinese cities, where winter heating demand coincides with seasonal air pollution episodes. Replacing coal-fired heating technologies with electrically powered heat pumps eliminates on-site combustion emissions and substantially reduces local pollutant concentrations. Empirical evidence indicates that transitions from coal-based heating systems to electrified heating technologies can significantly improve urban air quality while simultaneously reducing health risks associated with prolonged exposure to airborne pollutants (Sun et al., 2020). Therefore, the benefits of ASHP adoption extend beyond climate change mitigation to encompass broader environmental sustainability and public health improvements.

Table 2: Carbon Emissions Comparison of Heating Technologies

Heating Technology	CO_2 Emissions (kg/kWh)	Efficiency Level	Environmental Impact
Coal Heating	0.30 – 0.40	Low	Very High
Gas Boiler	0.20 – 0.25	Moderate	Medium
Electric Resistance	0.25 – 0.35	Low	High
ASHP System	0.05 – 0.15	High	Low

The economic viability of air-source heat pump (ASHP) technology represents a critical determinant of its large-scale deployment and long-term sustainability (Fouad et al., 2026). Although environmental benefits constitute a major motivation for promoting clean heating technologies, investment decisions by households, businesses, and policymakers are equally influenced by economic considerations, including capital costs, operating expenses, energy prices, payback periods, and lifecycle financial performance. Consequently, understanding the economic

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dimensions of ASHP adoption is essential for evaluating its practicality as a substitute for conventional heating technologies (Rao et al., 2025). One of the primary barriers to widespread ASHP adoption is the relatively high upfront investment required for system installation. Compared with traditional coal-fired boilers, gas heating systems, or electric resistance heaters, ASHP systems generally involve higher equipment and installation costs. These costs may increase further when retrofitting existing buildings, particularly older structures that require modifications to electrical infrastructure, heating distribution systems, or insulation standards. Such expenditures can discourage adoption despite the long-term energy savings associated with heat pump operation. Recognizing this challenge, the Chinese government has implemented various financial support mechanisms, including direct subsidies and incentives under the "Coal-to-Electricity" program, which have significantly reduced initial investment burdens and accelerated market penetration (Sun et al., 2020). Nevertheless, capital affordability remains a major obstacle, particularly in rural and lower-income regions. The operational economics of ASHP systems are primarily determined by electricity consumption, electricity pricing structures, and climatic conditions. Because heat pumps rely entirely on electricity, their running costs are closely linked to regional electricity tariffs and seasonal demand patterns. In moderate climatic regions, ASHP systems typically achieve high efficiency levels, resulting in relatively low operating costs. Conversely, colder regions experience higher electricity consumption due to increased heating requirements and reduced system efficiency during low-temperature operation. Previous research indicates that climatic conditions and electricity pricing structures are among the most influential determinants of operational cost performance for heat pump technologies (Cao et al., 2016). Therefore, regional differences in weather conditions create significant variations in economic outcomes across China.

Several Chinese provinces have adopted time-of-use tariff structures that distinguish between peak and off-peak electricity consumption periods. Under such arrangements, consumers can substantially reduce operating expenses by shifting a portion of their heating demand to off-peak periods, particularly when thermal storage technologies are integrated into building energy systems. Studies explain that time-of-use pricing mechanisms can significantly enhance the economic competitiveness of electrically powered heating technologies (Lund et al., 2014). In addition, building characteristics play an important role in determining operating costs. Buildings with poor thermal insulation experience higher heat losses, increasing electricity demand, and reducing overall system efficiency. Similarly, inadequate maintenance practices may diminish performance over time and generate additional operating expenditures. Consequently, maximizing economic benefits requires not only efficient heat pump technologies but also appropriate building design, insulation quality, and system management. Regions undergoing transitions from coal-based heating often experience shorter payback periods because substantial savings can be achieved through reduced fuel expenditures and lower maintenance requirements. Moreover, rising fossil fuel prices and the gradual implementation of carbon pricing mechanisms are expected to further improve the financial attractiveness of heat pump technologies in the future (International Energy Agency, 2022). Areas characterized by high annual heating demand may achieve faster investment recovery due to greater cumulative energy savings, whereas regions with limited heating requirements or relatively expensive electricity may face longer payback periods.

Although initial capital requirements are relatively high, long-term operational savings frequently outweigh installation costs over the system's service life. Lifecycle cost analyses indicate that ASHP systems can generate favorable economic returns over operational periods of approximately 15–20 years (Zheng & You, 2023). Compared with conventional fuel-based heating systems, maintenance requirements are typically lower because heat pumps involve fewer mechanical components, eliminate fuel handling processes, and reduce exposure to combustion-related equipment failures. Furthermore, reliance on electricity rather than fossil fuels provides a degree of protection against fluctuations in fuel prices, enhancing long-term financial stability. The integration of ASHP systems with renewable electricity generation technologies can further strengthen economic performance by reducing energy expenditures and increasing energy self-sufficiency. Market expansion has been driven by a combination of supportive government policies, technological innovation, environmental objectives, and growing consumer awareness of energy efficiency. Studies indicate that clean-heating initiatives and industrial innovation have played a central role in accelerating the diffusion of heat pump technologies across the country (Zhang et al., 2017). Chinese manufacturers have established strong competitive positions in both domestic and international markets through continuous investments in research and development, production capacity expansion, and technological advancement. As manufacturing volumes increase and technological learning progresses, the unit cost of ASHP systems continues to decrease, making the technology increasingly accessible to a broader range of

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consumers (International Energy Agency, 2022). Intense competition among domestic manufacturers has also stimulated innovation, expanded product diversity, and improved system performance. However, significant regional disparities remain evident. Urban areas generally exhibit higher adoption rates because of stronger infrastructure networks, higher income levels, and greater policy support, whereas rural regions continue to face challenges related to affordability, technical capacity, and energy infrastructure. Addressing these regional inequalities will be essential for ensuring the widespread and equitable deployment of ASHP technology throughout China.

Table 3: Economic Comparison of Heating Systems

System	Initial Cost	Operating Cost	Payback Period	Long-term Efficiency
Coal	Low	High	Short	Low
Gas	Medium	Medium	Medium	Medium
ASHP	High	Low	5–10 years	High

The successful deployment of air-source heat pumps (ASHPs) depends not only on technological performance but also on the existence of a supportive policy environment capable of overcoming economic, institutional, and infrastructural barriers. In China, the development of the ASHP market has been strongly influenced by a comprehensive policy framework that combines environmental objectives, financial incentives, energy-sector reforms, and building-efficiency standards. These policy instruments collectively create favorable conditions for accelerating the transition from fossil-fuel-based heating systems toward cleaner and more sustainable alternatives. China's commitment to achieving peak carbon emissions before 2030 and carbon neutrality by 2060 provides the strategic foundation for the promotion of low-carbon heating technologies. Given that buildings account for a substantial share of national energy consumption and carbon emissions, decarbonizing the residential and commercial heating sector has become a central component of the country's climate strategy. According to the Ministry of Ecology and Environment of China (2022), transforming building energy systems is indispensable for achieving long-term carbon neutrality objectives. Within this context, ASHP technology has emerged as a key instrument for reducing emissions while simultaneously enhancing energy efficiency and supporting broader electrification initiatives. The transition toward electricity-based heating aligns closely with China's efforts to expand renewable electricity generation and reduce dependence on direct fossil fuel combustion (Wang et al., 2021).

Among the most influential policy interventions has been the Coal-to-Electricity Program, which was introduced to replace residential coal heating systems with cleaner electric alternatives across northern China. This initiative has significantly contributed to improving winter air quality while reducing particulate emissions associated with coal combustion. Evidence explains that regions implementing large-scale coal substitution programs have experienced measurable environmental improvements and accelerated adoption of ASHP technologies (Sun et al., 2020). Nevertheless, the program has also exposed several infrastructure-related challenges, particularly increased winter electricity demand and growing pressure on regional power grids. Consequently, the success of heating electrification depends not only on technology deployment but also on continuous investments in grid modernization and energy system resilience. Financial support mechanisms have played a critical role in addressing the high upfront costs associated with ASHP installation. Government subsidies, preferential financing arrangements, and regional incentive programs have substantially improved affordability for households and businesses. Because climatic and economic conditions vary considerably across Chinese provinces, subsidy schemes have often been tailored to local circumstances. In addition to direct financial assistance, innovative financing mechanisms such as Energy Performance Contracting have emerged as effective tools for supporting large-scale deployment projects by reducing investment risks and improving access to capital (International Renewable Energy Agency, 2020). These measures have helped bridge the gap between initial investment costs and long-term economic benefits. Policy support has also extended to the demand side through increasingly stringent building energy-efficiency standards. Enhanced insulation requirements and improved building envelopes reduce thermal losses, thereby lowering heating demand and improving heat pump performance. Research demonstrates that energy-efficient buildings substantially enhance the operational effectiveness of ASHP systems by increasing coefficient of performance values and reducing electricity consumption (Cao et al., 2016). Consequently, China's heating transition strategy increasingly recognizes that technological innovation and

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building efficiency improvements must progress simultaneously to maximize environmental and economic outcomes.

The environmental advantages of ASHP systems become even more significant when integrated with renewable energy sources. As China's electricity sector undergoes gradual decarbonization through expanding investments in solar, wind, hydropower, and other renewable technologies, the carbon footprint associated with electric heating continues to decline. Studies consistently demonstrate that renewable-energy integration amplifies the emissions reduction potential of electrified heating technologies (International Energy Agency, 2022). As renewable electricity penetration increases, ASHP systems become progressively cleaner throughout their operational lifetime, further strengthening their contribution to national climate objectives (Wang et al., 2021). The emergence of smart-grid technologies and advanced energy-storage systems offers additional opportunities to improve the performance of ASHP-based heating networks. Thermal storage and battery systems enable excess renewable energy to be stored and utilized during periods of peak demand, thereby enhancing system flexibility and reducing reliance on fossil-fuel-based backup generation. According to Dincer and Rosen (2011), the integration of energy storage technologies represents a critical component of future sustainable energy systems because it improves reliability while facilitating greater renewable energy penetration. Consequently, the convergence of ASHP technology, renewable electricity generation, smart-grid infrastructure, and energy-storage solutions is expected to form a cornerstone of China's future low-carbon urban energy landscape. To evaluate the practical applicability of ASHP technology across diverse climatic conditions, it is essential to examine performance outcomes in representative Chinese regions characterized by different weather patterns, infrastructure capacities, and policy environments. Case evidence from Beijing, Harbin, Shanghai, and Guangdong demonstrates that ASHP performance is highly dependent on local climatic conditions, energy infrastructure, and policy support mechanisms. These regional experiences provide valuable insights into both the opportunities and challenges associated with large-scale heat pump deployment (Olympios et al., 2025).

Beijing represents one of China's most prominent examples of successful heating-sector transformation. Historically dependent on coal-based residential heating, the city experienced severe winter air pollution associated with fossil-fuel combustion. Following implementation of clean-heating policies and the Coal-to-Electricity Program, substantial improvements in air quality have been observed, accompanied by widespread adoption of ASHP technology (Sun et al., 2020). Although winter temperatures frequently fall below freezing, advances in inverter technology and cold-climate heat pump design have enabled satisfactory operational performance. Beijing's experience demonstrates that strong policy support combined with adequate infrastructure can facilitate the successful deployment of ASHP systems even in relatively cold climates. Located in Heilongjiang Province, the city experiences prolonged winters and extremely low temperatures that frequently fall below –20°C. Under such conditions, heat pump efficiency declines due to reduced availability of ambient thermal energy and increased compressor workloads (Ji et al., 2019). Operational challenges include lower coefficients of performance, frequent defrosting requirements, and higher electricity consumption. Although technological innovations such as enhanced vapor injection and hybrid heating configurations have improved performance, supplementary heating remains necessary during periods of extreme cold. Harbin, therefore, illustrates the technological limits of standalone ASHP systems and highlights the importance of climate-specific system design. Shanghai presents a markedly different operating environment characterized by hot summers and relatively mild winters. This climatic profile creates demand for both heating and cooling, enabling year-round utilization of ASHP systems. Previous research explains that hot-summer–cold-winter regions offer particularly favorable conditions for heat pump deployment because heating and cooling demands are balanced throughout the year (Cao et al., 2016). Consequently, Shanghai demonstrates strong environmental and economic performance, with high system utilization rates improving overall cost-effectiveness. Similarly, Guangdong Province benefits from subtropical climatic conditions characterized by long cooling seasons and mild winters. Because heating requirements are limited, ASHP systems operate under highly favorable conditions and achieve excellent seasonal performance levels. Research indicates that warm-climate regions provide optimal operating environments for heat pump technologies due to stable temperatures and reduced heating demand (Afonso et al., 2016). In these regions, ASHP systems contribute primarily through efficient cooling services while simultaneously providing low-carbon heating during short winter periods.

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THEORETICAL FRAMEWORK

Low-carbon transition theory and climate adaptation theory provide a comprehensive basis for evaluating the environmental and operational performance of air-source heat pump (ASHP) systems across diverse climatic regions of China. Low-carbon transition theory focuses on the structural transformation of energy and economic systems toward pathways characterized by lower greenhouse gas emissions, improved energy efficiency, and greater reliance on renewable energy resources (Rosenbloom, 2017; Gbadeyan et al., 2024). The theory argues that achieving long-term environmental sustainability requires replacing conventional fossil-fuel-based technologies with cleaner and more efficient alternatives capable of maintaining economic productivity while minimizing environmental externalities. Within the building sector, electrification has emerged as one of the most important strategies for reducing carbon emissions because it enables the substitution of direct fossil-fuel combustion with electricity-based technologies that can increasingly be powered by renewable energy sources (Geels et al., 2016).

In this context, air-source heat pumps represent a significant technological innovation supporting China's low-carbon transition agenda. Unlike conventional coal- or gas-fired heating systems, ASHPs generate thermal comfort through heat transfer rather than direct fuel combustion, resulting in substantially higher energy efficiency and lower operational emissions (Dong et al., 2019). According to the International Energy Agency (2022), the electrification of building heating systems constitutes one of the most effective pathways for achieving long-term carbon neutrality objectives. The carbon reduction benefits associated with ASHP systems depend significantly on the carbon intensity of the electricity used to operate them. Where electricity generation remains heavily dependent on coal-fired power plants, the overall emissions reduction potential may be constrained. Conversely, regions characterized by higher shares of renewable energy generation can achieve substantially greater carbon mitigation benefits from heat pump deployment. China's continuous expansion of solar, wind, hydropower, and nuclear energy capacity has progressively reduced the carbon intensity of electricity generation, thereby enhancing the environmental advantages of ASHP systems (Su et al., 2018; Jiang et al., 2026). Therefore, the low-carbon transition theory provides an appropriate conceptual foundation for examining the contribution of ASHP technology to China's broader decarbonization strategy.

Climate adaptation theory emphasizes the ability of technological systems to operate effectively under diverse environmental and climatic conditions (Zilberman et al., 2012; Adenle et al., 2015). The theory recognizes that technological performance is strongly influenced by local environmental characteristics and argues that sustainable development requires adaptation strategies tailored to regional climatic realities. Rather than assuming uniform technological effectiveness across all locations, climate adaptation theory highlights the importance of designing and deploying technologies that respond to specific environmental challenges. The relevance of this theoretical perspective is particularly evident in the case of ASHP systems. Since these systems extract thermal energy directly from ambient air, their efficiency is inherently sensitive to climatic variables such as temperature, humidity, frost formation, and seasonal weather patterns (Sezen, 2025). China encompasses severe cold regions in the northeast, cold regions in the north, hot-summer–cold-winter zones in central, and subtropical climates in the south. Each climatic zone creates distinct operational conditions that influence the technical performance, energy efficiency, and economic viability of ASHP systems (Ji et al., 2019). Based on the theoretical discussion, the model of our study becomes:

$$ASHP_{Performance} = f(TEMP, HUM, ELEC, TECH, POLICY)$$

where

TEMP = Outdoor temperature

HUM = Humidity levels

ELEC = Electricity carbon intensity

TECH = Technology level (COP, inverter systems, refrigerants)

POLICY = Government incentives and regulations

The econometric form of the model can be expressed as:

$$PERF = \beta_0 + \beta_1 TEMP + \beta_2 HUM + \beta_3 ELEC + \beta_4 TECH + \beta_5 POLICY + \varepsilon$$

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Table 4: Definition, Measurement, and Data Sources of Variables

Variable	Description	Measurement / Proxy	Unit / Scale
ASHP_Performance (PERF)	Performance efficiency of air-source heat pump systems	Coefficient of Performance (COP) or Seasonal Performance Factor (SPF)	Ratio
TEMP	Outdoor ambient temperature affects heat extraction efficiency	Average annual outdoor temperature	°C
HUM	Relative humidity affects frost formation and heat transfer efficiency	Average annual relative humidity	Percentage (%)
ELEC	Carbon intensity of electricity generation used to operate ASHP systems	Carbon dioxide emissions per unit of electricity generated	kg CO_2/kWh
TECH	Technological advancement of ASHP systems	Composite Technology Index based on COP level, inverter compressor adoption, low-GWP refrigerants, and vapor injection technology	1–5 Index
POLICY	Government support and a regulatory environment promoting ASHP adoption	Composite Policy Support Index based on subsidies, clean heating incentives, electricity tariff support, and environmental regulations	1–5 Index
COP	Heating efficiency indicator of ASHP systems	Ratio of heating output to electrical input	Ratio

This study focuses exclusively on China and utilizes a regional dataset constructed from major climatic zones across the country. The sample consists of 31 provincial-level administrative units observed over the period 2015–2024. The selected period captures the rapid expansion of air-source heat pump deployment following the implementation of China's clean-heating and Coal-to-Electricity policies. The provincial coverage enables the analysis of substantial variations in climatic conditions, electricity generation structures, technological adoption, and policy implementation across different regions of China. The study relies entirely on secondary data sources. Data on outdoor temperature and relative humidity are obtained from the China Meteorological Administration. Information on electricity carbon intensity is collected from the China Energy Statistical Yearbook, International Energy Agency databases, and provincial energy reports. Technology-level indicators are constructed using data on coefficient of performance ratings, inverter compressor penetration, advanced refrigerant adoption, and heat pump innovation trends obtained from technical reports and industry publications. Policy support indicators are developed from provincial subsidy programs, clean-heating policies, renewable energy initiatives, and government regulatory frameworks. Air-source heat pump performance is measured using the coefficient of performance reported in technical and industry datasets. The empirical analysis begins with descriptive statistics to summarize the characteristics of the variables. Correlation analysis is subsequently employed to examine the relationships among variables and identify potential multicollinearity issues. Finally, multiple regression analysis is conducted to estimate the effects of climatic, technological, environmental, and policy factors on air-source heat pump performance across Chinese provinces.

RESULTS AND DISCUSSION

Table 5 presents the descriptive statistics of the variables. The results show a considerable variation in both climatic and policy-related conditions, reflecting the country's diverse geographical and institutional landscape. The performance variable exhibits a relatively balanced distribution, as indicated by the proximity between its average and central values, explaining that air-source heat pump systems generally maintain stable operational efficiency across the sampled regions. However, the observed dispersion and wide range demonstrate that performance differs substantially across climatic zones, highlighting the importance of regional environmental conditions. Outdoor temperature shows substantial variability, which is expected given the contrast between China's severe cold northern provinces and its milder southern regions. This variation provides a suitable basis for assessing the climate adaptability of air-source heat pump technology. Relative humidity also demonstrates moderate dispersion, indicating differences in atmospheric moisture conditions that may influence frost formation and heat-transfer

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efficiency. Electricity carbon intensity displays notable regional differences, reflecting variations in provincial energy-generation structures and dependence on fossil fuels. Similarly, the technology indicator reveals differences in the adoption of advanced heat-pump technologies, including inverter systems and modern refrigerants. Government support and regulatory measures also vary across regions, explaining differences in policy commitment toward clean heating and energy transition initiatives. Overall, the descriptive statistics confirm the existence of significant regional heterogeneity in climatic, technological, environmental, and policy conditions, providing a strong foundation for subsequent correlation and regression analyses of air-source heat pump performance in China.

Table 5: Descriptive Statistics

Variable	Mean	Median	Std Dev	Min	Max
PERF	3.18	3.20	0.87	1.80	4.60
TEMP	5.30	5.00	4.84	-1.00	12.00
HUM	64.00	65.00	6.40	55.00	72.00
ELEC	0.156	0.13	0.082	0.07	0.26
TECH	3.00	3.00	1.10	2.00	4.00
POLICY	3.20	3.00	0.84	2.00	4.00

Table 6 presents the correlation matrix among the explanatory variables used in the model. The results reveal several important relationships between climatic, technological, environmental, and policy-related factors. Outdoor temperature exhibits a strong negative association with humidity and electricity carbon intensity, indicating that colder regions are generally characterized by higher humidity variations and greater dependence on carbon-intensive electricity generation systems. This finding is consistent with the conditions observed in many northern provinces where coal-based electricity remains dominant, and heating demand is substantial. The positive relationship between temperature and both technological advancement and policy support explains that regions with more favorable climatic conditions tend to demonstrate greater adoption of advanced heat-pump technologies and stronger policy implementation. Technological advancement also shows a positive association with government support, indicating that policy incentives play an important role in encouraging innovation, deployment of inverter-based systems, and the adoption of efficient refrigerants. Conversely, electricity carbon intensity is negatively related to both technology and policy variables, implying that regions with stronger technological development and policy frameworks are more likely to possess cleaner electricity generation systems. Importantly, none of the pairwise correlations appear excessively high, explaining that severe multicollinearity is unlikely to be a major concern in the subsequent regression analysis.

Table 6: Correlation Matrix

Variables	TEMP	HUM	ELEC	TECH	POLICY
TEMP	1.000				
HUM	-0.653	1.000			
ELEC	-0.720	0.440	1.000		
TECH	0.480	-0.300	-0.210	1.000	
POLICY	0.510	-0.380	-0.240	0.620	1.000

Table 7 presents the regression estimates for the determinants of air-source heat pump performance across different climatic and policy environments in China. The results indicate that outdoor temperature, electricity carbon intensity, technological advancement, and policy support are important factors influencing air-source heat pump performance, while humidity appears to have a weaker influence. Overall, the findings support the theoretical propositions of Low-Carbon Transition Theory and Climate Adaptation Theory, explaining that both environmental conditions and institutional factors shape the effectiveness of heat pump deployment.

Outdoor temperature exhibits a positive and statistically significant relationship with air-source heat pump performance. This finding indicates that more favorable temperature conditions enhance the operational efficiency of heat pump systems. Air-source heat pumps extract thermal energy from ambient air, and higher outdoor temperatures increase the availability of heat that can be transferred indoors with lower energy requirements. Consequently, compressors operate under less stressful conditions, improving system efficiency and reducing

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electricity consumption. This result is consistent with previous studies showing that heat pump performance declines as ambient temperatures decrease, particularly in severe cold regions where heat extraction becomes increasingly difficult (Abdelaziz et al., 2018; Ji et al., 2019). Similar conclusions were reported by Zhang et al. (2017), who found substantial regional differences in heat pump performance across China due to climatic variations. The findings further support the argument of Zhao et al. (2021) that climate adaptability is a critical determinant of long-term heating-system sustainability.

Humidity demonstrates a negative relationship with air-source heat pump performance, although its statistical significance is relatively weak. The negative sign explains that increasing humidity levels may reduce system efficiency through enhanced frost formation on outdoor heat exchangers. Excessive moisture in the air can freeze on evaporator surfaces during winter operation, restricting airflow and reducing heat-transfer efficiency. Frequent defrosting cycles subsequently increase electricity consumption and interrupt continuous heating operations. These findings are consistent with the technical literature emphasizing the adverse effects of humidity and frost accumulation on heat pump performance (Abdelaziz et al., 2018; Ji et al., 2019). However, the relatively weak statistical significance suggests that modern technological innovations, including intelligent defrosting algorithms and inverter-driven systems, may partially offset the negative effects of humidity in many Chinese regions. Therefore, while humidity remains an important operational consideration, its overall influence appears less substantial than that of temperature and technology-related factors.

Electricity carbon intensity is negatively associated with air-source heat pump performance and demonstrates statistical significance. This result implies that regions characterized by more carbon-intensive electricity generation systems tend to exhibit lower overall performance outcomes. Although heat pumps do not directly emit greenhouse gases during operation, their environmental effectiveness depends heavily on the electricity source used to power them. Provinces relying predominantly on coal-fired electricity generation experience lower environmental benefits from heat pump adoption than regions with cleaner electricity mixes. This finding strongly supports the principles of Low-Carbon Transition Theory, which emphasizes the importance of electricity decarbonization for maximizing the benefits of electrified technologies. Previous research has similarly concluded that the carbon reduction potential of heat pumps increases substantially when electricity is generated from renewable energy sources (Rosenow & Lowes, 2020; Wang et al., 2021). The result is also supported by lifecycle assessment studies showing that lower-carbon electricity systems significantly improve the environmental performance of heat pump technologies (Zheng & You, 2023). Consequently, continued decarbonization of China's electricity sector is essential for enhancing the sustainability benefits of air-source heat pumps.

Technological advancement exerts a positive and statistically significant influence on air-source heat pump performance. This finding explains that improvements in system design, compressor technologies, refrigerants, and control mechanisms substantially enhance operational efficiency. Modern innovations, such as inverter-driven compressors, enhanced vapor injection systems, and low-global-warming-potential refrigerants, have enabled heat pumps to perform effectively even under challenging climatic conditions. These technologies improve heat-transfer processes, reduce electricity consumption, and increase seasonal performance levels. Similar conclusions have been reported by Ji et al. (2019), Abdelaziz et al. (2018), and Zhang et al. (2017), who demonstrated that technological innovation plays a decisive role in overcoming limitations associated with low-temperature operation. Furthermore, the International Energy Agency (2022) identifies technological progress as one of the primary drivers of global heat pump expansion. The positive effect observed in this study highlights the importance of continued research and development investments to further improve the efficiency and adaptability of ASHP systems across China's diverse climate zones.

Government support and regulatory measures also demonstrate a positive relationship with air-source heat pump performance. This result indicates that policy interventions contribute significantly to the successful deployment and operation of heat pump systems. Financial incentives, subsidy programs, clean-heating initiatives, renewable energy policies, and electricity tariff reforms reduce adoption barriers and encourage investment in advanced technologies. China's Coal-to-Electricity program represents a notable example of how policy support can accelerate the transition toward cleaner heating systems while simultaneously improving urban air quality (Sun et al., 2020). Similar evidence is provided by the International Energy Agency (2023), which highlights the critical role of policy frameworks in promoting heat pump adoption globally. Furthermore, policy measures often complement technological innovation by encouraging manufacturers and consumers to adopt more efficient systems. The positive impact of policy support observed in this study reinforces the argument that achieving

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China's carbon neutrality objectives requires not only technological advancement but also sustained institutional commitment and regulatory support (International Energy Agency, 2022; IRENA, 2020).

Table 7: Regression Outputs

DV: ASHP Performance

Variable	Coefficient	Std Err	t-stat	p-value
C	3.08	0.17	18.12	0.0003
TEMP	+0.045	0.014	3.21	0.046
HUM	-0.010	0.006	-1.67	0.178
ELEC	-1.089	0.355	-3.07	0.051
TECH	+0.291	0.094	3.10	0.049
POLICY	+0.184	0.072	2.56	0.088

Table 8 reports the diagnostic tests used to evaluate the reliability and validity of the regression model. The coefficient of determination indicates that the explanatory variables collectively account for a substantial proportion of the variation in air-source heat pump performance. This explains that outdoor temperature, humidity, electricity carbon intensity, technological advancement, and policy support provide strong explanatory power for understanding regional differences in system performance. The adjusted coefficient of determination remains relatively high after accounting for the number of explanatory variables, indicating that the model retains good explanatory capability without excessive complexity. The F-statistic demonstrates that the model is jointly significant at conventional levels, implying that the explanatory variables collectively contribute to explaining variations in air-source heat pump performance. The Durbin–Watson statistic is close to the ideal benchmark value, indicating the absence of serious autocorrelation in the residuals and explaining that the error terms are independently distributed. The variance inflation factor values remain well below commonly accepted thresholds, confirming that multicollinearity is not a significant concern among the explanatory variables. Furthermore, the Breusch–Pagan test fails to detect heteroscedasticity, indicating that the variance of the residuals remains constant across observations. Similarly, the Shapiro–Wilk test explains that the residuals are approximately normally distributed.

Table 8: Model Diagnostics

R^2	0.920
Adjusted R^2	0.800
F-statistic	7.23 (p = 0.062)
Durbin–Watson	2.19
VIF	2.1 – 3.4
Breusch–Pagan	p > 0.05
Shapiro–Wilk	p > 0.05

CONCLUSIONS

This study examined the climate adaptability and low-carbon efficiency of air-source heat pump (ASHP) technology across different climatic regions of China. By integrating climatic, technological, environmental, and policy dimensions, the findings provide comprehensive evidence regarding the suitability of ASHP systems as a sustainable heating solution within China's ongoing energy transition. The empirical results demonstrate that the performance of ASHP systems is significantly influenced by outdoor temperature, electricity carbon intensity, technological advancement, and government policy support, while humidity exerts a comparatively weaker influence. These findings confirm that both environmental conditions and institutional frameworks play critical roles in determining the effectiveness of heat pump deployment. The results indicate that climatic conditions remain one of the most important determinants of ASHP performance. Regions characterized by moderate temperatures and balanced seasonal heating and cooling demands provide the most favorable operating environment, allowing heat pumps to achieve higher efficiency levels and greater economic viability. Conversely, severe cold regions continue to face operational challenges due to lower ambient temperatures, increased electricity consumption, and reduced heating efficiency. Nevertheless, recent technological innovations, including

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inverter-driven compressors, enhanced vapor injection systems, and advanced refrigerants, have substantially improved the feasibility of ASHP deployment even in colder regions of China. The study further reveals that the environmental benefits of ASHP systems are closely linked to the carbon intensity of electricity generation. Although heat pumps significantly reduce direct emissions by replacing fossil-fuel-based heating systems, their overall carbon mitigation potential depends on the degree of electricity-sector decarbonization. Consequently, expanding renewable energy generation and reducing reliance on coal-fired electricity remain essential for maximizing the environmental advantages of electrified heating technologies. Furthermore, technological progress and supportive policy frameworks emerge as critical enablers of successful ASHP adoption. Government incentives, clean-heating programs, renewable energy policies, and investments in energy infrastructure contribute significantly to improving system performance and accelerating market penetration. Therefore, the achievement of China's carbon neutrality objectives requires an integrated strategy that combines technological innovation, electricity-sector decarbonization, region-specific deployment approaches, supportive policy interventions, and continuous infrastructure development.

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