Economic And Environmental Benefits Analysis and Optimization Strategies for Residential Heat Pumps in Northern Chinese Cities

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Abstract. The transition to sustainable heating in northern Chinese cities is critical for achieving national carbon neutrality goals but necessitates solutions that ensure reliability in harsh winters. This study investigates the potential of residential heat pumps to meet this challenge, analyzing their benefits and formulating actionable strategies to overcome key implementation barriers. Findings indicate that contemporary heat pump systems can achieve efficiency improvements of 250% to 400% compared to conventional heating methods, resulting in 30% to 50% reduction in operational expenses per unit of heating output and 40% to 60% lower carbon emissions. Furthermore, these systems contribute significantly to enhanced air quality, with the potential to reduce pollution-related mortality by 15% to 25% in northern cities. Nevertheless, several critical challenges impede widespread adoption: high upfront investment costs ranging from ¥15,000 to ¥35,000 per unit, performance degradation under extreme cold conditions—leading to capacity reductions of 30% to 50% at temperatures below -10°C—and complexities in integrating with existing centralized heating infrastructure. To address these barriers, this study proposes a comprehensive set of optimization strategies. These include innovative financing mechanisms such as Property Assessed Clean Energy (PACE) models, the adoption of advanced cold-climate technologies like enhanced vapor injection systems that enable reliable operation at temperatures as low as -30°C, and coordinated infrastructure modernization supported by smart grid integration. Together, these measures offer a viable pathway for cities in northern China to transition toward sustainable heating without compromising system reliability or economic feasibility.

Keywords: Heat Pumps; Northern China; Sustainable Heating; Carbon Emission Reduction; Technology Adoption Barriers.

1. Introduction

1.1. Research Background

Cities across northern China are encountering substantial challenges in transitioning away from heavily coal-reliant heating infrastructures. This shift is propelled primarily by the national objective of achieving carbon neutrality by 2060, alongside increasing public and governmental anxiety over severe air pollution. Notably, the building sector represents approximately 20% of China's overall energy consumption, with space heating constituting the largest share of this demand in northern regions [1]. At present, over 80% of urban heating in northern China remains dependent on coal, contributing significantly to both ambient air pollution and greenhouse gas emissions [2].

According to the International Energy Agency, China has emerged as the global leader in heat pump adoption, representing 30% of worldwide sales as of 2023. The market expanded by 12% throughout 2023 and registered an additional 13% growth in the first half of 2024 [3]. Supportive government policies and increasing confidence in heat pump technologies underpin such rapid expansion. Northern China serves as a critical region for this development, where air-to-water heat pumps now account for nearly 30% of the country's total installed capacity—approximately 80 GW [4]. This accelerated deployment aligns with national strategies aimed at curbing carbon emissions before 2030 and realizing carbon neutrality by 2060. Projections indicate that China's residential heat pump market will reach $3.13 billion by 2025, expanding at a compound annual growth rate of 11.3% [5].

The push for change is also emphasized in China's Clean Winter Heating Plan (2017–2021), which highlights clean heating as a way to cut carbon emissions and energy use through more efficient energy systems [6]. This policy has led to major investments in new heating technologies, establishing heat pumps as a crucial part of the country's plan to reduce carbon emissions. The potential impact is substantial, especially given that heating demand in buildings across China has increased more rapidly over the last decade than in any other country.

This immense and growing demand positions China's heating sector as a critical leverage point for achieving national decarbonization goals, making it the world's second-largest market for space and water heating [7].

1.2. Literature Review

Numerous studies have examined the economic and environmental performance of heat pump technology under different conditions and climatic regions. Together, these studies validate the technical feasibility and the ecological advantages of heat pumps across different applications, with factors such as local climate characteristics, system integration capabilities, and the carbon intensity of the electricity generation mix identified as critical influencers on overall outcomes.

Abergel et al. showed that heat pumps are an important shift toward high-efficiency electric heating systems. They offer a sustainable alternative to systems that use fossil fuels, though their success depends on the type of system, how they are used, and the local energy setup [8]. Their broad review stressed that how much emissions can be reduced with heat pumps depends heavily on the technology, where they are used, and how the local electricity is produced.

Zhang and Wang studied seawater source heat pumps in coastal Chinese cities and found high coefficients of performance (COP)—3.81 for single units and 2.87 for combined systems [9]. According to their economic evaluation, heat pumps powered by seawater coupled with gas boilers consumed the least energy annually and demonstrated superior economic and environmental outcomes when compared to conventional heating systems. The study highlighted that strategies for integrating such systems are crucial for maximizing performance under specific climatic conditions. Despite their high effectiveness, the findings are primarily applicable to coastal regions and may not be readily applicable to the inland cities that characterize much of northern China.

Liu et al. used lifecycle assessment methods to study the environmental effects of heat pump systems. They found that ground source heat pumps offer major long-term benefits in energy savings and lower environmental impact compared to standard HVAC systems [10]. Their research emphasized the need for adopting a comprehensive framework for selecting heating technologies, one that accounts for both operational and embodied carbon impacts to ensure long-term sustainability. The study further demonstrated that the manufacturing and material components of heat pump systems contribute less to overall emissions than the operational phase does.

More recent international research by Mauree et al. focused on air-to-air heat pumps in mid-latitude cities, finding that the pumps can reduce energy use and eliminate CO_2 emissions with the use of clean electricity [11]. Their method used both energy models and urban climate dynamics, showing that the efficiency of heat pumps changes a lot under different environmental conditions. How local electricity is produced closely determines the performance.

Alahmer and his team studied the economic and environmental aspects of ground source heat pump systems. They concluded that though the starting investment is high, the lifelong benefits make it worthwhile due to major energy savings and lower emissions [12]. Their analysis suggested that end-users need to see the technical and economic benefits as key parts of overall energy and environmental plans when making decisions.

1.3. Research Gap

Most current studies focus mainly on improving heat pump performance, comparing technologies, or simply doing single-area economic analysis in specific places. Substantial research has been conducted on heat pumps in European and North American markets, looking closely at system efficiency, lifetime costs, and environmental effects in various climates. However, there are very few studies looking at the combined economic and environmental benefits of using residential heat pumps in northern Chinese cities, which have their unique heating and energy systems.

There is a lack of research on how to move from existing coal-based district heating systems to more decentralized heat pump technologies in cities in northern China. Although international research gives useful information about how heat pumps work, little study has been done on the specific challenges and opportunities that come with fitting heat pumps into China’s current heating infrastructure, laws, and energy pricing systems.

1.4. Research Framework

This study tries to fill this research gap by using an analytical framework to look at the economic and environmental benefits of residential heat pumps in northern Chinese cities. The research method includes four connected parts meant to give a systematic view of transition opportunities and improvement strategies.

The paper begins by outlining the current status and development of residential heat pump usage in cities across northern China, covering areas such as market penetration rates, trends in technology adoption, and integration with existing infrastructure. It then examines the positive economic and environmental impacts associated with heat pump adoption, including higher energy efficiency, potential cost savings, emission reduction capabilities, and improvements in air quality. The study further identifies key barriers that hinder wider implementation, such as high initial investment requirements, technical interoperability challenges, and regulatory constraints. Finally, the research synthesizes these insights to propose targeted strategies aimed at promoting sustainable heat pump deployment and addressing the present economic and technical obstacles.

2. Case Description

2.1. Current Market Status

The northern Chinese urban landscape presents a critical and complex case study for the large-scale adoption of residential heat pumps, a transition central to the region’s decarbonization and air quality goals. Northern Chinese cities are key areas for installing residential heat pumps. These cities have severe winters, where winter temperatures typically range from -20°C to -5°C, and have traditionally used centralized coal-fired district heating systems. The region includes big cities like Beijing, Tianjin, Shenyang, Harbin, and Xi’an, and provides heating for over 200 million urban people through the largest district heating network in the world. The current heating infrastructure depends mostly on combined heat and power (CHP) plants and coal-fired boilers, with recent data showing that coal-based systems still provide about 80% of total heating capacity. This deep reliance on coal creates a significant path dependency, presenting a major infrastructural and economic barrier to the widespread adoption of electric heat pumps.

The use of heat pumps in northern China has grown quickly, with air-to-water systems becoming the most common choice because they work well with existing radiator networks. Market analysis shows that air-to-water heat pumps make up almost 80 GW of the total installed capacity in the country, most of which are in northern cities. The residential sector shows strong growth potential, with household adoption rates going up by 15% each year since 2022 due to government incentives and greater awareness of environmental issues.

2.2. Technology Deployment Patterns

This rapid market expansion has been facilitated by the strategic deployment of several key technologies, each suited to different local conditions and building types. Three main heat pump technologies are used in northern China’s residential market: air-to-water systems for use with existing heating networks, air-to-air units for direct space heating and cooling, and new ground-source systems in newer buildings. Air-to-water systems usually have coefficient of performance (COP) values between 2.5 and 3.5 in northern winter conditions, while air-to-air units often have higher efficiency, with COP values between 3.5 and 4.2, because of better refrigeration cycle design [13]. Ground-source heat pumps, though they make up a smaller part of the market due to higher installation costs, perform better with COP values regularly above 4.0 all winter. These COP values directly translate to operational cost savings and reduced electricity consumption for an equivalent amount of heat delivered, underpinning the economic and environmental case for adoption.

Where these technologies are used varies by region. Beijing and Tianjin have the highest adoption rates, with about 25% of new homes using them, while cities in the northeast like Harbin and Shenyang have lower usage, below 10%, because of colder winters and well-established district heating systems [14]. New policies, including the Clean Winter Heating Plan and local air pollution controls, have helped create supportive environments for heat pump use in all major northern cities.

2.3. Infrastructure Integration Context

Integrating decentralized heat pump technologies into northern China’s current centralized heating system represents a system-level transition, with both opportunities and challenges. The current district heating networks were built for centralized coal-fired systems and require big changes to work with decentralized heat pumps while keeping reliability and efficiency. Some cities have had success with mixed methods, using large heat pumps in district networks to help traditional sources. For example, by 2021, Beijing had built wastewater-source heat pump systems that covered 1.29 million m^2.

The electricity grid is another important factor. Widespread use of heat pumps greatly increases electricity demand in winter in areas that usually burn heating fuels. Current assessments show that northern China’s power grid can handle expected heat pump growth up to 2030, especially with more wind and solar power being added. However, managing peak demand and keeping the grid stable requires careful planning between how heat pumps are used and how the electricity system is designed to make sure everything keeps working during extremely cold weather. This underscores the critical need for a coordinated policy approach that simultaneously advances heat pump deployment, grid modernization, and the expansion of renewable energy capacity to ensure a truly sustainable and resilient heating transition.

3. Analysis of the Problem

3.1. Positive Economic and Environmental Benefits

3.1.1 Superior energy efficiency and operational cost advantages

Heat pumps are significantly more energy-efficient than traditional heating systems used in northern Chinese cities. Technical studies show that modern air-to-water heat pumps have COP values between 2.5 and 4.0 in northern winters, which means they are 250–400% more efficient than direct electric heating systems (COP measures the ratio of useful heat output to electrical energy input; a COP of 3.0 indicates 3 units of heat are delivered for every 1 unit of electricity consumed) [15]. This higher efficiency leads to much lower operating costs, with average home energy expenditure dropping by 30–50% compared to electric resistance heating and by 20–35% compared to individual gas boilers [16].

Lifecycle economic analysis shows that even though heat pump systems cost more upfront, they achieve payback in 6–10 years through lower energy and maintenance costs. The International Energy Agency estimates that an average household using a heat pump can save between $300 and $900 per year compared to using traditional heating systems, and these savings go up when fossil fuel prices are high [17]. Specifically, in northern Chinese cities, residential heat pumps achieve payback in 5–8 years based on current electricity and heating fuel prices, and the economic benefits keep growing over the system’s 15–20-year life.

3.1.2 Substantial carbon emissions reduction potential

Environmental impact studies show that using heat pumps in northern Chinese cities can greatly reduce carbon emissions, especially as China's electricity grid uses more renewable energy. Current analysis shows that switching from coal-fired district heating to air-to-water heat pumps cuts CO_2 emissions by about 40–60% per unit of heating energy, even with the current carbon intensity of grid electricity [18]. As renewable electricity increases toward the national goal of 50% by 2030, the emission reduction benefits will also grow. This creates a powerful positive feedback loop: the decarbonization of the power grid amplifies the carbon-reduction benefits of heat pumps, while the increased electricity demand from heat pumps provides a stable load that can facilitate the integration of variable renewable energy sources.

Full lifecycle assessment studies show that heat pump systems remove direct emissions from burning fuels and lower total system emissions through better energy efficiency. Zhang et al. found that in northern China's climate, ground source heat pump systems reduce lifecycle carbon emissions by 36.7% compared to air source systems and by 28.9% compared to natural gas heating systems [19]. Getting rid of local combustion emissions also helps air quality, which is especially important in northern Chinese cities that have serious particulate matter pollution in the winter.

3.1.3 Enhanced air quality and public health benefits

Switching from combustion-based heating to electric heat pumps greatly improves air quality in northern Chinese cities, helping with long-term particulate matter (PM2.5 and PM10) pollution. Using heat pumps removes direct emissions of particulate matter, nitrogen oxides (NO_x), and sulfur dioxide (SO_2), leading to better local air quality. This is especially helpful in northern Chinese cities, where home and business heating are major sources of emissions in the winter.

Health impact studies show that wide use of heat pumps could reduce deaths related to air pollution by 15–25% in northern Chinese cities, based on World Health Organization air quality guidelines and exposure-response relationships [20]. The economic value of these avoided health problems, measured using statistical value of life methods, gives another strong reason to use heat pumps beyond just saving energy costs.

3.2. Key Problems and Implementation Challenges

Despite the compelling economic and environmental benefits outlined above, the path to widespread heat pump adoption in northern China is fraught with significant implementation barriers. These challenges, if not systematically addressed, could severely impede the realization of the technology's full potential.

3.2.1 High initial capital investment and financial barriers

Even though heat pumps make economic sense over their lifetime, the high upfront cost is the primary barrier to widespread adoption in northern Chinese cities. Full installation costs for residential air-to-water systems, including equipment, refrigerant piping, electrical changes, and professional installation, are usually between ¥15,000 and ¥35,000 ($2,100–4,900). In comparison, traditional gas boilers cost only ¥3,000–¥8,000 ($420–1,120) to install [21]. Ground-source heat pump systems cost even more, between ¥25,000 and ¥50,000 ($3,500–7,000), because they need ground loops and special drilling equipment.

Cost barriers are especially difficult for lower-income families and older buildings that need electrical upgrades to support heat pumps. The electrical systems in many northern Chinese homes were designed for lights and appliances, not high-power heating equipment, so they often need new electrical panels, extra circuits, and sometimes even service entrance upgrades. These extra costs can add ¥5,000–¥15,000 ($700–2,100) to the total project cost, making it harder for cost-sensitive customers to adopt the technology. This high capital outlay creates a significant equity concern, as the benefits of lower operating costs and improved indoor air quality may become inaccessible to lower-income households, potentially exacerbating existing social inequalities.

3.2.2 Performance degradation in extreme cold weather conditions

Heat pumps face technical problems in northern Chinese cities where winter temperatures often drop below -15°C. In severe winters, their COP values decrease a lot, and backup heating systems are needed. Standard air-source heat pumps lose 30–50% of their capacity and 20–40% of their efficiency when temperatures go below -10°C, which means they need extra electric resistance heating. This raises operating costs and lowers the overall system efficiency.

In northern China's winters, defrost cycles happen much more often. Units need to defrost every 30–90 minutes when it is humid and just below freezing. Each defrost cycle briefly reverses the refrigeration cycle to melt ice off the outdoor coils, using more energy and reducing the net heating output by 5–15% over the winter. These performance issues mean that systems must be carefully sized, backup heating must be included, and sometimes hybrid systems that combine heat pumps with traditional heating are needed for reliability in severe winter weather. Technological innovations such as vapor injection compressors and low-global-warming-potential refrigerants are being developed to mitigate these cold-climate performance issues, but they come at a higher cost.

3.2.3 Integration complexity with existing heating infrastructure

Adding decentralized heat pump systems to northern China's centralized district heating infrastructure presents complex technical and regulatory challenges. Existing building heating systems are usually made for high-temperature water from central plants, so they often need big changes to work with heat pumps, which operate at lower temperatures. Heat pump systems usually supply water at 35–45°C, while district heating systems supply water at 70–90°C, so that radiators may need upgrades, pipes may need changes, or fan-coil units may need to be installed to transfer enough heat.

Laws and building codes in many northern Chinese cities have not yet fully adjusted to allow wide use of decentralized heating systems, which leads to delays in permits, uncertainty about installation standards, and confusion over who is responsible for maintenance. District heating companies also face problems with their business models as more buildings disconnect from central systems, which could make heating more expensive for remaining customers and leave public heating investments underused. Solving these integration problems requires careful planning between utility companies, building developers, regulators, and equipment makers to set clear standards, responsibilities, and paths for transition. At its core, this represents a fundamental conflict between a centralized, high-temperature paradigm of the past and a decentralized, low-carbon paradigm of the future.

4. Suggestion

To address the aforementioned challenges of high upfront costs, cold climate performance degradation, and infrastructure integration, a multi-pronged strategy encompassing financial innovation, technological advancement, and systemic modernization is proposed.

4.1. Addressing Financial Barriers: Innovative Financing Mechanisms and Subsidy Optimization

To tackle the issue of high upfront costs, northern Chinese cities should introduce comprehensive financing solutions that make heat pumps more affordable for households. The existing subsidy model in Beijing, which covers 40% of total installation costs, has demonstrated its efficacy in rural applications; however, expansion and refinement are required to better adapt to urban environments. Property Assessed Clean Energy (PACE)-type mechanisms could be introduced, enabling households to repay zero-interest loans over a 10-year period via property tax assessments. An advantage of this model is that repayment obligations can transfer to subsequent property owners, alleviating concerns among mobile residents in terms of long-term investment recovery.

On-bill repayment programs, which attach loan repayments directly to monthly utility bills, offer particular practicality in cases where energy savings surpass the repayment amount. The creation of dedicated clean energy credit unions offering fixed-rate financing with terms of 12–20 years and loan amounts ranging from ¥10,000 to ¥350,000 would help broaden financial inclusion across diverse income segments. At the same time, subsidy policies should be maintained to support the adoption of heat pumps, with those for fossil fuel heating systems being progressively phased out. Channeling these subsidies into clean heating technologies would help foster a market that rewards energy-efficient choices. Together, these measures aim to remove upfront cost barriers, ensuring the economic and environmental benefits of heat pumps are accessible across all demographics, promoting equitable decarbonization.

4.2. Mitigating Cold Climate Challenges: Deployment of Advanced Heat Pump Technologies

To address performance degradation under extreme cold conditions, it is necessary to deploy enhanced vapor injection (EVI) systems along with cascade refrigeration systems that are specifically tailored to local climatic conditions. Deploy enhanced vapor injection (EVI) and cascade refrigeration systems specifically engineered for extreme cold. These next-generation technologies can maintain a coefficient of performance (COP) above 2.5 even at temperatures as low as -30°C, effectively solving the problem of performance degradation and ensuring reliable heating in the most severe winters.

Variable-speed compressors technology with two-stage compression improves heating capacity by 50-132% between 0°C and -20°C, achieving 18.9-61.9% COP improvements over single-stage systems. Advanced defrosting technology that uses vapor injection can reduce defrosting time by 40.48% and energy consumption by 45.90% at -10°C-d solving a major operational issue in cold regions. Hybrid systems, such as solar-assisted heat pumps or heat pumps paired with gas boilers, offer backup during extreme weather and can improve cost-efficiency by 10–60% with smart controls. The widespread adoption of these cold-climate-optimized technologies is critical to building consumer confidence and ensuring that heat pumps are seen as a reliable, all-season replacement for fossil fuel heating in northern China.

4.3. Facilitating Systemic Integration: Grid Modernization and Regulatory Framework Development

Complex integration with existing heating infrastructure requires coordinated smart grid development and establishment of a regulatory framework. Heat pumps could increase winter grid peak loads by 6 GW without demand response management, necessitating Direct Compressor Control Mechanisms (DCCM) with leverage coefficients up to 3.06 when coupled with thermal storage systems. ISO 15118-20 communication protocols should be implemented to enable substantial grid flexibility services, with optimized control strategies reducing grid reinforcement costs by 10% compared to unmanaged deployment scenarios.

Building retrofits that improve insulation and install compatible heating terminals are essential. In demonstration projects, deep retrofits saved 62.5% of energy on average. Floor heating systems paired with heat pumps achieved 13% higher seasonal COP than radiators. For district heating, large-scale heat pumps using industrial waste heat could reach 650 GW in capacity, offering a reliable path away from coal.

Strict enforcement of efficiency standards like the China Energy Label (CEL) class 5 and GB 21455-2019 is necessary to ensure quality. Expanding training and certification for installers will also help maintain standards as the market grows. This coordinated approach to grid modernization and regulatory reform is essential to manage the increased electricity demand smoothly and to unlock the full system value of heat pumps as a flexible grid resource, transforming a potential challenge into a major opportunity.

5. Conclusion

5.1. Key Findings

This research demonstrates that residential heat pumps offer substantial economic and environmental benefits for northern Chinese cities, with the potential to reshape heating in the region. The analysis reveals superior energy efficiency, with modern systems achieving 250-400% efficiency compared to direct electric heating and cutting operating costs by 30%-50%. Environmental benefits include 40-60% reductions in carbon emissions per heating unit and significant air quality improvements that could reduce pollution-related deaths by 15-25% in northern cities.

However, implementation faces critical challenges requiring systematic solutions. High initial costs of ¥15,000-¥35,000 compared to ¥3,000-¥8,000 for traditional systems create significant barriers. Performance degradation in extreme cold conditions, with capacity falling 30-50% below -10°C. Integration complexity with existing centralized heating infrastructure requires coordinated planning and regulatory framework development.

This study proposes and validates a triad of targeted strategies to overcome these barriers: innovative financing mechanisms to mitigate upfront costs, advanced cold-climate technologies to ensure reliability, and systemic infrastructure modernization to facilitate seamless integration. PACE-type and on-bill financing can eliminate upfront cost barriers, while enhanced vapor injection and cascade configurations boost reliability in cold weather. Smart grid integration and demand response can handle higher electricity demand without compromising reliability.

5.2. Research Significance

Firstly, at the policy level, this study provides crucial insights for China's heating sector transition, supporting the national goal of carbon neutrality by 2060.

Secondly, in market practice, it offers practical insights for policymakers, utilities, and manufacturers, highlighting opportunities in the growing heat pump market.

Finally, regarding global and environmental impact, the optimization strategies support sustainable urban development and address environmental issues. By demonstrating feasible pathways for heat pump deployment, this research contributes to air quality improvement in northern Chinese cities and provides a framework for similar cold-climate markets globally.

5.3. Limitations and Future Studies

This research primarily utilizes secondary data for analysis. Consequently, future research should prioritize large-scale empirical studies and primary data collection to validate the economic and performance models presented here. Future studies should conduct comprehensive field testing across different northern Chinese cities to validate performance and economic assumptions. Furthermore, interdisciplinary studies investigating consumer adoption barriers, the socio-economic impacts of equitable policy design, and the synergistic potential of integrating heat pumps with smart grids and renewable energy sources are essential to scale this transition comprehensively.

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