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中国北方农村空气源热泵电供暖的区域能源和经济承载力

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摘要: 清洁供暖可以缓解中国北方的污染问题, 低成本和电力供应的安全性是推广清洁供暖的关键。从区域视角建立适用于中国北方农村地区空气源热泵供暖的适宜性评估框架, 通过建立区域能源指标和经济指标, 基于情景分析评估农村地区空气源热泵供暖的区域能源和经济承载力。结果表明, 随着居民供暖需求的增加, 区域能源承载力逐渐降低, 且受区域能源基础设施、家庭规模和生活习惯的影响。在从基本需求到高需求的情景, 供暖运行费用占人均可支配收入的比例小于 10%, 显示出较高的经济承载力; 但在中等到高需求情景下, 设备初投资占人均可支配收入的比例为 10.4%~24.9%, 表明经济承载力较弱。农村居民需要财政补贴, 否则居民可能面临能源贫困, 对空气源热泵供暖系统的接受度也可能降低。

关键词: 区域评估; 能源安全; 经济可承受性; 情景分析; 空气源热泵; 供暖方式

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Regional energy and economic affordability: A study of air source heat pump electric heating in rural areas of northern China

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Abstract: Clean heating can mitigate pollution issues in northern China, and affordable cost and security of power supply are keys to promoting clean heating. Therefore, this paper proposed a suitability evaluation framework for air source heat pump heating in rural areas of northern China from a regional perspective. By establishing regional energy indicators and economic indicators, assess the energy and economic affordability of air source heat pump heating in rural areas based on scenario analysis. The results showed that regional energy

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affordability gradually decreased with the increase in residents' heating demand, which is influenced by the regional energy infrastructure, household size, and living habits. Furthermore, in scenarios ranging from basic to high demand, the proportion of heating operation costs in per capita disposable income is less than 10%, showing a high level of economic affordability. However, under medium to high-demand scenarios, the initial investment accounts for a proportion of 10.4% to 24.9% of the per capita disposable income, indicating weak economic affordability. Rural residents require financial subsidies; otherwise, residents may face energy poverty, and their acceptance of air source heat pump heating systems may also decrease.

Keywords: regional evaluation; energy security; economic affordability; scenario analyses; air source heat pump; heating method

1 Introduction

1.1 Background

The recent decline in air quality and the smog issues faced during winter in northern China have garnered significant public attention. A primary contributor to these problems is the combustion of raw coal to meet winter heating demands^[1-3]. To address the atmospheric challenges during the northern heating seasons, China has introduced several clean heating initiatives, including the “coal-to-electricity” and “coal-to-gas” transformation^[4]. As a result, air source heat pumps (ASHP) have become popular due to their flexible control, high efficiency, and energy-saving potential^[5-6]. In 2017, 2.9 million ASHP units were installed in China^[7], and the trend of using ASHP for heating continues to grow with advancements in clean heating technologies^[8].

1.2 Literature review

Currently, scholars have conducted research on the characteristics of the transition to ASHP heating in northern regions of China from various aspects, including technology and economy, to evaluate the suitability of ASHP heating. The technical performance of ASHP heating equipment can impact its promotion and usage. For instance, Hu et al.^[9], Yang et al.^[10] and Wei et al.^[11] conducted experimental tests and selected heating capacity, coefficient of performance (COP), coefficient of performance of heat pump system (COP_s), coefficient of performance of heat pump unit (COP_u), seasonal coefficient of performance (SCOP) and heating season performance factor (HSPF) as evaluation indicators to study the performance of ASHP heating. They discovered that ASHP can operate steadily in low-temperature environments in northern regions and

meet heating demands. By establishing mathematical models and conducting field tests^[12-14], the authors analyzed the technical characteristics of different heating methods. The results indicated that ASHP exhibits its high efficiency and energy-saving properties. Although ASHP heating technology may encounter issues such as frosting, the development of defrosting technology^[15] and low-temperature enhanced vapor injection technology^[16] has assured ASHP heating in northern regions. More recently, ASHP has been widely used owing to its flexible control, high efficiency, and energy-saving potential^[5-6]. As such, they are regarded as an optimal heating solution for rural areas in northern China^[14].

As the primary energy source for supporting electrification heating in northern regions, the electricity security supply is under pressure to transition to clean heating. Thus, existing research indicates that the electrification of heating systems will cause significant changes in the overall load profile and peak power demand of the electricity grid^[17]. Notably, implementing the “Coal-to-Electricity” clean heating project in northern China increased electricity demand in the building sector by 10.1 billion kW·h in 2020^[18]. Meanwhile, the current rural household energy system of power grid capacity is 2-3 kW, yet the electricity demand for electric heating is expected to be 9-10 kW^[19]. Therefore, the current household grid can hardly meet the power requirements for winter heating and needs to be upgraded.

Energy supply security may become a key constraint on the development of electric heating. In addition, due to the electrification of heating in rural areas, household energy costs may increase. The average operating cost of a clean heating system is double that of traditional coal-fired heating. Additionally,

the annual cost of a clean heating operation (12 hours per day) would account for about 14% of the annual household consumption expenditure in China's northern rural areas^[20]. Scholars conducted experimental tests, field tests, or established mathematical models and adopted initial investment^[9], operating cost^[10], and dynamic investment payback period^[11] as the economic indicators to analyze ASHP heating and compared it with other heating methods' economic performance. The ASHP heating system presented reasonable economic performance with low operation costs under both actual operation and laboratory conditions. However, rural residents' heating energy consumption was affected by their household structure, education level, and economic level. Notably, households with a single generation may have more difficulty in accepting clean energy^[20]. However, rural residents with higher educational levels are more likely to choose clean energy^[21]. In addition, when adopting the heating method, residents consider their economic affordability based on their income level^[21-22]. Barnes et al.^[23] point out that in the UK, the installation cost of heat pumps is much higher than that of gas boilers, and rural households generally have lower incomes, with their primary source of income being agricultural labor. Consequently, the high equipment costs will reduce the competitiveness of electrified heating and lower user acceptance. Thus, these factors affect the social acceptance of ASHP clean heating among rural residents, potentially posing hidden dangers to the sustainable development of clean heating.

Despite the clean heating rate in the northern region exceeding 70%^[24], several practical challenges have emerged during the implementation of clean heating projects. These challenges include energy supply shortages and security issues^[18], overburdened financial subsidies^[25], high heating costs^[20], low user acceptance and the ongoing use of raw coal^[14]. As a result, the clean heating program has proven to be unsustainable and non-replicable. Furthermore, many rural areas must transition to the same type of energy (such as natural gas or electricity) for their heating needs. This "one-size-fits-all" approach to clean heating is not sustainable^[26].

The climate, economy, population distribution

and energy structure vary significantly in the northern regions of China. The large-scale implementation of electrified heating in rural areas will have an impact on regional energy supply and the economic life of residents. However, most of the evaluation indicators and methods of the existing studies focus on the technical and economic suitability of ASHP for heating at the micro-scale. Moreover, there is a lack of regional evaluation indicators from the macro-regional perspective to deeply explore the issue of regional suitability for the large-scale application of ASHP heating. To this end, this paper investigates the impact of ASHP electric heating in rural areas on regional energy consumption and the economic life of rural residents. Notably, this is achieved by analyzing the energy and economic affordability of ASHP heating at the rural macro-regional level.

Compared with previous research, the novelty of this study is as follows.

(1) Focusing on the macro-regional level, the energy and economic suitability of ASHP heating, which is barely paid attention to in current research, is examined.

(2) Established regional energy and economic affordability indicators and an evaluation framework for ASHP heating.

The rural areas of six northern provinces and municipalities in China are the target of the research, based on a field investigation of rural ASHP heating. A scenario analysis was conducted to assess the regional energy and economic affordability of ASHP heating in rural areas of northern China. Combined with the research analysis results, suggestions for future energy planning and sustainable development policy of clean heating in the large-scale application of ASHP heating in northern rural areas are given for the reference of policymakers.

2 Methodology

According to the World Bank, affordability is defined as the ability to purchase a necessary quantity of a product or service without enduring significant financial hardship^[27]. This concept of affordability has been widely applied in various fields, including electricity, water, and energy^[27-29]. Thus, this study has established a research framework to evaluate the

suitability of large-scale ASHP heating applications in rural areas, focusing on both energy and economic affordability.

The evaluation framework for this study, as illustrated in Fig. 1, consists of three key components. Firstly, from a micro perspective, the study identifies specific indicators for assessing ASHP heating. These indicators include individual household heating energy consumption, initial investment costs, and ongoing operation and maintenance costs.

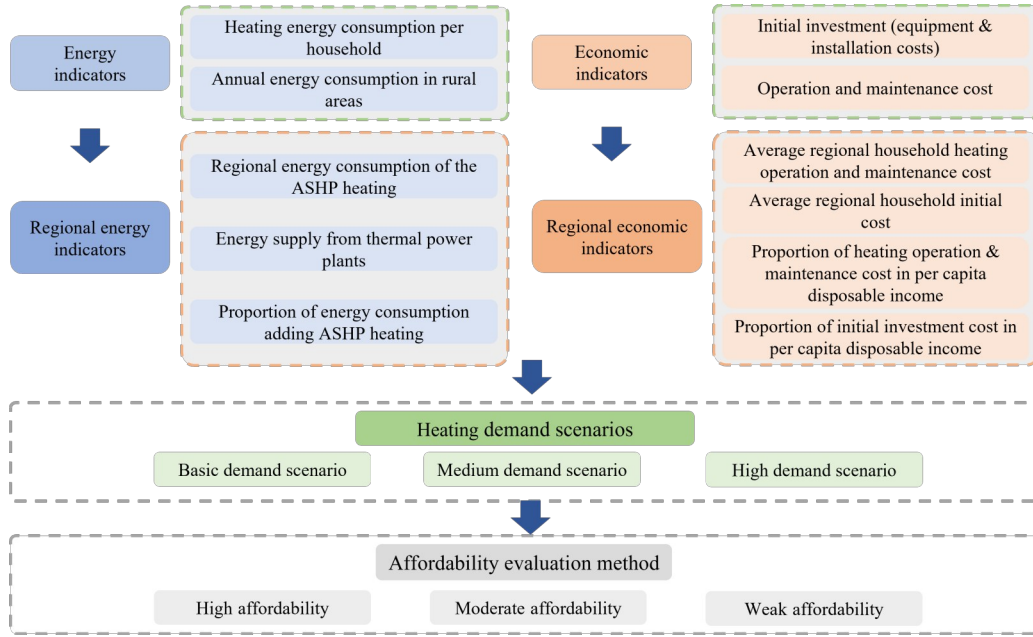


Fig. 1 Research evaluation framework.

2.1 Energy affordability indicator

Implementing electric heating in buildings requires the power grid to have a greater capacity to meet the increased demand for electricity^[19]. However, China's current power generation mix is predominantly coal-fired power plants^[30]. Thus, there are still many challenges and issues in the process of promoting the electrification of heating. This study deduced energy affordability evaluation indicators by the rate of overall power demand to the full power generation potential of a region, as shown in Equations (1) and (2).

$$E_{\text{heating, regional}} = \sum_i \sum_n (\lambda_i \times N_{\text{rural}} \times E_{\text{heating}}(n)) \quad (1)$$

Where, $E_{\text{heating, regional}}$ is the regional electricity consumption of the ASHP heating, billion kW·h; λ_i is the proportion of households of household size in the category i , %; N_{rural} is the total number of households in rural areas, a thousand households; $E_{\text{heating}}(n)$ is the average energy consumption of an

At the macro level, regional energy and economic indicators for ASHP heating have been established.

Building on the characteristics of ASHP heating in rural areas, three heating demand scenarios have been proposed. Finally, the study analyzes the regional energy and economic affordability of ASHP heating in northern China's rural areas by applying a specialized evaluation methodology that considers various heating demand scenarios.

ASHP for heating the n th capacity of a single household, kW·h (refer to Table 1 and Table 2).

$$K_E = \frac{E_{\text{consumption}} + E_{\text{heating, regional}}}{E_{\text{supply}}} \quad (2)$$

Where, K_E is the proportion of annual electricity consumption in rural areas using ASHP for regional heating, %; $E_{\text{consumption}}$ is the annual electricity consumption in rural areas, billion kW·h, and the electricity consumption with ASHP heating not included in $E_{\text{consumption}}$; E_{supply} is the electricity available from thermal power plants in rural areas, billion kW·h.

2.2 Economic affordability indicator

Disposable income is an essential indicator of residents' economic living and reflects the level of economic development and the living standard of residents in a region^[31]. Residents' disposable income is a significant factor influencing heating demand and clean energy choice^[20, 32-35]. Thus, this paper adopts

per capita disposable income (PCDI) to explore the economic affordability of the ASHP heating application in rural areas from the perspective of rural residents. Combined with the ASHP initial investment and operation & maintenance cost, the ratio of per capita initial investment and per capita operation & maintenance cost in PCDI is taken as an economic affordability evaluation indicator, respectively.

The initial investment, operation & maintenance cost for ASHP heating can be calculated by Equations (3) and (4)

$$C_{\text{initial, regional}} = \sum_i \sum_n (\lambda_i \times N_{\text{rural}} \times C_{\text{initial}}(n)) / N_{\text{rural}} \quad (3)$$

Where, $C_{\text{initial, regional}}$ is the initial investment in regional average household heating equipment, CNY; $C_{\text{initial}}(n)$ is the price quoted for the n th capacity ASHP unit in the market, CNY; This includes installation costs, which are 120 CNY per household based on our field investigation.

The maintenance cost of ASHP is assumed to be a fixed factor (2%) of $C_{\text{initial, regional}}$ [36].

$$C_{\text{operation, regional}} = \sum_i \sum_n (\lambda_i \times N_{\text{rural}} \times E_{\text{heating}}(n) \times C) / N_{\text{rural}} \quad (4)$$

Where, $C_{\text{operation, regional}}$ is the average regional household heating operation cost, CNY; C is the electricity price, CNY/kW·h.

The proportion of per capita heating operation & maintenance cost and per capita initial investment in the disposable income of rural residents can be calculated by Equations (5) and (6).

$$K_{\text{operation \& maintenance}} = (C_{\text{operation, regional}} + 2\% \times C_{\text{initial, regional}}) / m / I_{\text{PCDI}} \quad (5)$$

$$K_{\text{initial}} = C_{\text{initial, regional}} / m / I_{\text{PCDI}} \quad (6)$$

Where, the $K_{\text{operation \& maintenance}}$ and K_{initial} are the ratios of per capita heating operation and maintenance cost and per capita initial investment in PCDI, respectively, %. I_{PCDI} is the PCDI of rural residents in each region, CNY. m is the average household size, persons/household (refer to Table 2 and Table 4).

2.3 Affordability evaluation of ASHP heating

Given that coal-fired power still occupies a dominant position in the energy structure, the joint deployment of heat pumps and renewable energy systems requires a specific transition period [8].

Therefore, this study evaluated the ASHP heating application by referring to the annual electricity consumption in rural areas and comparing the total electricity consumption (including ASHP heating) with the full capacity of the thermal power units. In northern China, the regional power grid's deep peak load regulation ranges from 50% to 100% [37]. In this study, the criteria for energy affordability are set at 50% and 100%. We divided the regional energy affordability evaluation criteria into two levels:

(1) High affordability: when the proportion K_E the peaking operation of thermal power units is between 50%-100%, indicating that it can meet the added ASHP heating electricity consumption.

(2) Weak affordability: When the proportion K_E exceeds 100%, indicating that the electricity consumption will exceed the affordability of the thermal power units.

Song et al. [35] calculated the expenditure demand and payment affordability in 35 cities and found that 5% of their disposable income is a reasonable figure for family energy bills. Moreover, fuel poverty in the UK is classified as a household spending more than 10% of its disposable income on energy costs [34, 38]. In this study, 5% and 10% were selected as the benchmark values for evaluating the economic affordability of rural residents to adopt ASHP for heating. Thus, this study divides the regional economic affordability evaluation criteria into three levels:

(1) High affordability: The proportions $K_{\text{operation \& maintenance}}$ and K_{initial} of residents' heating costs are less than 5%.

(2) Moderate affordability: The proportions $K_{\text{operation \& maintenance}}$ and K_{initial} are between 5%-10%. This indicates that the heating economic cost rises slightly but is still within the economic affordability of residents to use ASHP for heating in winter.

(3) Weak affordability: The proportion $K_{\text{operation \& maintenance}}$ and K_{initial} exceeds 10%. Thus, rural households will face the problem of fuel poverty and feel economic pressure to use ASHP for heating in winter.

3 Scenario description and data source

3.1 Scenario description

Unlike urban residents, occupants in rural dwellings potentially present diverse heating demands. For example, rural dwellers may adopt various thermal adaptation behaviors based on their daily activities^[5]. Moreover, occupancy in rural dwellings might change depending on the seasons^[39]. Thus, these factors can eventually affect dwellers' heating demand, energy usage, operation cost, and the actual performance of ASHP heating.

This study assumes two ASHP heating capacity options, including a small-sizing capacity of 1.5 horsepower (P, input electrical power of the ASHP, $1\text{P}=735\text{W}$), households with no more than two occupants (Heating area of 10 m^2 , heating capacity of 3.0 kW , and SCOP of 3.0). A large-sized capacity 5P, households with three or more occupants (Heating area of 120 m^2 , heating capacity of 9.3 kW , and SCOP of 2.8). The SCOP for ASHP heating in this study considers the influence of frosting and low outdoor temperatures on the heating performance. According to our previous research, there are differences in the level of economic development and residents' living habits among different regions, and the number of installed heating equipment also varies^[22]. Families with a single heating device typically install it in the living room or bedroom^[22]. Rural households with higher heating demands and better economic conditions will install heating equipment in multiple rooms to ensure their heating needs are met^[40]. Therefore, we have established two heating patterns for the scenario analyses: continuous heating (24 hours) and intermittent heating (10 hours, 8:00 p. m. to 6:00 a. m.).

To conduct the scenario analyses, this study clarifies the assumptions as follows:

(1) Current thermal power units operate at average load factors of about 58%, and the minimum load factor will drop to less than 30%^[41]. Therefore, this study assumes that the operating load factor of the thermal power unit is 50%.

(2) The Plan for Clean Winter Heating in Northern Areas (2017-2021) was released by the Chinese

government in December 2017 to promote clean winter heating^[26]. Thus, the electricity consumption data for that year could better reflect the energy consumption structure before the implementation of clean heating policies. In this study, the annual electricity consumption in each region is assumed to be the sum of the yearly rural electricity consumption in 2017 and the additional electricity consumed by the applied ASHP heating.

(3) This study assumes all rural dwellings only install and use one ASHP equipment at a time.

Therefore, based on the scenario setting and assumption, three scenarios of ASHP heating are defined as follows:

(1) The basic demand (BD) scenario is that each household in rural areas is equipped with a 1.5P ASHP unit and operates for 10 hours during nighttime (1.5P-10h).

(2) The medium demand (MD) scenario is that small-sized households install a 1.5P ASHP unit, and large-sized households install a 5P ASHP unit. In this scenario, the heating duration is 10 hours during nighttime (1.5P+5P-10h).

(3) The high demand (HD) scenario is the same as the MD scenario, but the heating time duration is 24 hours a day (1.5P+5P-24h).

Based on previous field investigations and considering the dwellers' diverse heating demands in rural areas^[22, 42], this study established BD scenarios, MD scenarios, and HD scenarios to better explore the regional energy and economic affordability of ASHP heating. Notably, the three heating demand scenarios have differences in heating demands. The BD scenario does not consider the influence of household structure, and all households have the same installed capacity, which only meets basic heating demands. However, the MD and HD scenarios consider the impact of household structure in selecting the equipment capacity^[42]. Furthermore, the heating duration reflects the heating demand. Three scenarios of ASHP heating in northern rural areas are illustrated in Table 1.

3.2 Data source

3.2.1 Field investigation

To obtain the household information of dwellers in rural areas and the habits of using ASHP for heat-

Table 1 Definition of heating demand scenarios.

Scenario	Heating capacity	Operation mode
BD scenario	1.5P	10 hours
MD scenario	1.5P+5P	10 hours
HD scenario	1.5P+5P	24 hours

ing, this study conducted a face-to-face questionnaire survey in three northern regions (Shandong, Shanxi and Hebei provinces) in July 2018, July 2019, and December 2021. In total, 205 questionnaires were distributed with a response rate of 86.3%. The questionnaire designed in this study mainly covered three parts: (1) Household information, (2) Building information, and (3) Heating equipment usage.

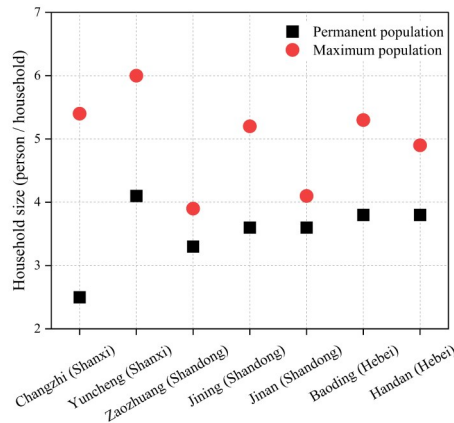
**Fig. 2 Permanent and maximum rural household populations in different cities.**

Fig. 2 shows that the permanent population in each household in rural areas was about 2-4 persons, and the maximum number of persons was about 4-6. Based on the field investigation, most rural residential buildings are 1-2 stories, with single-story structures accounting for approximately 75%. The

average building area is 100-180 m², with a living room area of about 40 m² and a bedroom area of about 20 m². ASHP heating equipment is commonly installed in bedrooms or living rooms, covering a heating area of 20-120 m². Furthermore, around 70% of residents utilize ASHP for heating a single room, while about 30% opt for whole-space heating.

Currently, two main types of ASHP heating equipment are predominantly used in rural areas: air-to-air heat pumps and air-to-water heat pumps [43]. The installed capacity of the equipment was 1.5P, 2P, 3P and 5P units. Although ASHP is the primary heating device for space heating in each region, residents also use electric blankets, air conditioners, and fan heaters for local heating. About 63% of these dwellers adopt the continuous heating mode (24 hours), and approximately 37% of them adopt an intermittent heating pattern (8% of users operated ASHP during daytime and 29% of users operated ASHP at nighttime).

3.2.2 Data collection and processing

This study selected typical regions with heating demands in northern China's cold climate zones [19] (Beijing, Tianjin, Hebei, Shandong, Shanxi and Henan) to explore the energy and economic affordability of ASHP heating in rural areas. The data source covered three parts: (1) Energy-related parameters [44], (2) Economic-related parameters [45-50], (3) Population statistical information [44, 51]. The information on households, total energy supply, and energy consumption of ASHP heating in rural areas is shown in Tables 2 to 4.

Table 2 Rural household information

Region	Household size/ (persons/household)	Total number of households/ (Thousand households)		3 or more persons household/%
		households/ (Thousand households)	1-2 persons household/%	
Beijing	2.52	108.7	51	49
Tianjin	2.72	76.5	37	63
Hebei Province	2.83	1 022.6	39	61
Shandong Province	2.55	1 438.0	44	56
Henan Province	2.98	1 444.3	31	69
Shanxi Province	2.6	489.6	42	58

According to the current market, the initial investment for a 1.5P ASHP unit is 2 500 CNY, while for a 5P unit, it is 15 000 CNY.

The typical dwelling layout in the surveyed rural

areas is shown in Fig. 3. Our field investigation revealed that rural households have a complex household structure and often include multiple members, ranging from single to multi-generational households

Table 3 Total electricity consumption and supply in rural areas

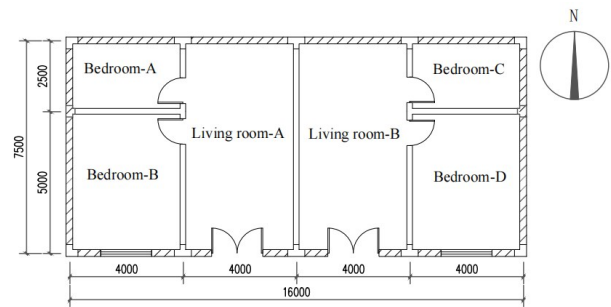
Region	Electricity price/ (CNY/kW·h)	Rural electricity consumption/ (Billion kW·h)	Rural electricity total supply/(Billion kW·h)
Beijing	0.488 3	6.15	12.3
Tianjin	0.490 0	4.03	8.06
Hebei Province	0.520 0	61.52	123.04
Shandong Province	0.576 9	48.85	97.7
Henan Province	0.560 0	32.88	65.76
Shanxi Province	0.477 0	9.93	19.86

Table 4 Per capita disposable income in northern China's rural areas

Region	Per capita disposable income/CNY
Beijing	33 303.7
Tianjin	27 954.5
Hebei Province	18 178.9
Shandong Province	20 793.9
Henan Province	17 533.3
Shanxi Province	15 308.3

[22, 52]. The layout of rural dwellings is designed to meet the housing needs of rural inhabitants^[14], representative of the building layouts in rural areas. How-

ever, the houses are not the same in different regions of northern China. Further information concerning the houses is given in Tables 5 and 6.

**Fig. 3 Typical dwelling layout in rural areas.****Table 5 Basic information regarding the enclosure structure of the typical rural dwelling houses.**

Enclosure Structure	Materials	Heat Transfer Coefficient K/ (W/(m ² ·K))
External walls	Brick wall 240 mm thick (no insulation)	1.633
Exterior window (south)	6 mm single-glazed windows with wooden window frames	4.9
Roof	150 mm reinforced concrete + 80 mm slag + 10 mm cement mortar	2.1
Exterior doors	Wooden exterior door	2.5

Table 6 Basic information regarding the typical rural residential building.

Room	Window-to-wall ratios	Heating areas/m ²		
		Bedrooms A & C	Bedrooms B & D	Livingroom A & B
3.3	0.3	10	20	30

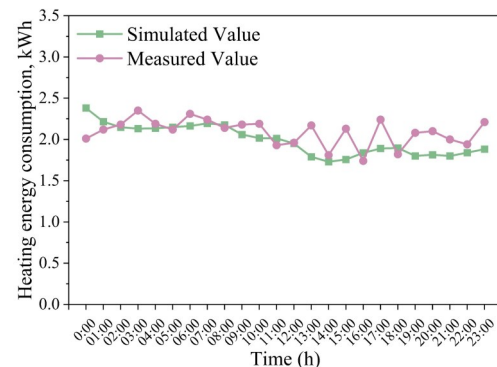
A building energy simulation software (DeST version 3.0) was used to simulate the heating energy consumption of ASHP heating for the rural dwelling model. The energy usage of three demand scenarios was all simulated.

To validate the accuracy of the simulation model, we carried out empirical testing on a rural residence in Hebei that employs an ASHP for its heating demands. The heating schedule followed a continuous heating schedule for 24 hours. Furthermore, the energy usage data from January 15th was chosen for comparative evaluation alongside the simulated data. The average deviation between

the measured and simulated figures was determined using Equation (7).

$$\sigma = \frac{E_{\text{measured}} - E_{\text{simulated}}}{E_{\text{measured}}} \quad (7)$$

Where, σ is the average deviation between the simulated and measured values, %; E_{measured} is the heating energy consumption obtained from the measured, kW·h, and $E_{\text{simulated}}$ is the heating energy consumption obtained from the simulation, kW·h.

**Fig. 4 Simulated and measured results comparison.**

According to Fig. 4, the trend variation of the simulated heating energy consumption aligns with that of the measured values, with an average deviation of approximately 7.83%. The primary source of deviation stems from the use of typical meteorological year data in the simulation model, thereby producing a certain deviation. Notably, these results indicate that the simulation model is reasonable.

Since the outdoor climate of different regions may influence the simulation performance of ASHP heating, the HDD_h (heating degree hours) could reflect different heating demands from the regional perspective^[40]. When calculating the HDD_h , according to the Chinese national design standard *Design S00tandard for energy-efficient of rural residential buildings* (GB/T 50824—2013), the indoor design temperature is 14 °C in rural areas^[53]. Thus, this study selected a typical region for heating energy consumption simulation. Furthermore, the ASHP heating energy consumption in other regions is corrected by using heating degree hours, as demonstrated by Equation (8).

Precisely, the HDD_h is deduced by the heating energy consumption ratio corresponding to the heating degree days ratio.

$$\frac{Q'_n}{Q_n} = \frac{HDD'_h}{HDD_h} \quad (8)$$

Where, Q'_n is the ASHP heating energy consumption of a single household in a typical region, kW·h; Q_n is the ASHP heating energy consumption of a single household in the target region, kW·h; n is the ASHP sizing; HDD_h is the number of heating degree hours in a typical area, °C·h; HDD'_h is the number of heating degree hours in different areas, °C·h. Table 7 summarizes the heating degree hours of six northern regions.

Table 7 Heating degree hours of six northern provinces/municipalities

Region	$HDD_h/(^{\circ}\text{C}\cdot\text{h})$
Beijing	40 192
Tianjin	41 131
Hebei Province	37 288
Shandong Province	31 381
Henan Province	31 228
Shanxi Province	43 042

Table 8 Heating energy consumption in rural households under different heating patterns

Heating energy consumption/(kW·h/household)	Beijing	Tianjin	Hebei	Shandong	Henan	Shanxi
1. 5HP-10	1 243	1 272	1 153	970	966	1 331
1. 5HP-24	1 893	1937	1 756	1 478	1 471	2027
5HP-10	6489	6640	6020	5066	5042	6949
5HP-24	8476	8674	7863	6618	6585	9077

Heating demand scenarios are composed of different heating mode combinations. Additionally, the energy consumption for heating varies among different household structures. As shown in Table 8, under the heating pattern of 1. 5P-10, heating energy consumption in rural areas of each region ranged from 652 to 898 kW·h/household. Notably, the average heating energy consumption is around 780 kW·h/household. In households with 5P ASHP units and operating at night (10 hours), the heating energy consumption was about 5.0 times higher than the heating mode of 1. 5P-10. Furthermore, a large-sized household with a 5P unit (24 hours) was nearly 7.0 times greater than the heating pattern of 1. 5P-10 (average heating energy consumption is about 8000 kW·h/household).

4 Analysis of energy-economic affordability evaluation for ASHP heating

4.1 Energy affordability

As shown in Fig. 5, the increase in heating demand leads to a sharp growth in electricity loads. Under the BD scenario, the annual electricity consumption (including the power consumed by ASHP heating) accounts for about 60% of the available power generated in Beijing, Tianjin, Hebei, Shandong and Henan regions. Moreover, the annual electricity consumption of Shanxi province reached about 72.1% of the available electricity supplied by thermal power units in 2017.

Under the MD scenario, the annual electricity consumption in the rural areas of Beijing, Tianjin, Hebei and Shandong provinces and municipalities

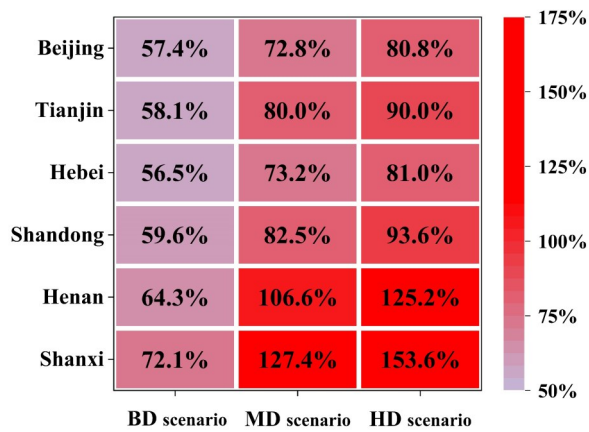


Fig. 5 The annual electricity consumption ratio under different heating demand scenarios

was about 70% to 80% of the thermal power generation capacity in 2017. However, the application of ASHP heating in rural areas of Henan and Shanxi provinces has resulted in annual electricity consumption exceeding 6.6% and 27.4% of the total installed capacities in the two regions, respectively.

Under the HD scenario, the annual electricity consumption in Beijing, Tianjin, Hebei and Shandong was 80.8%, 90%, 81.0% and 93.6% of the maximum electricity generation capacity of thermal power units. Again, the power demand, including ASHP heating, exceeds the full capacity of thermal power units by 25.2% and 53.6% in the Henan and Shanxi regions, respectively.

4.2 Economic affordability

The initial investment to PCDI ratio differs significantly across different demand scenarios, as illustrated in Fig. 6. Under the BD scenario, the proportion of per capita initial investment in PCDI was less than 5% in rural areas of Beijing, Tianjin

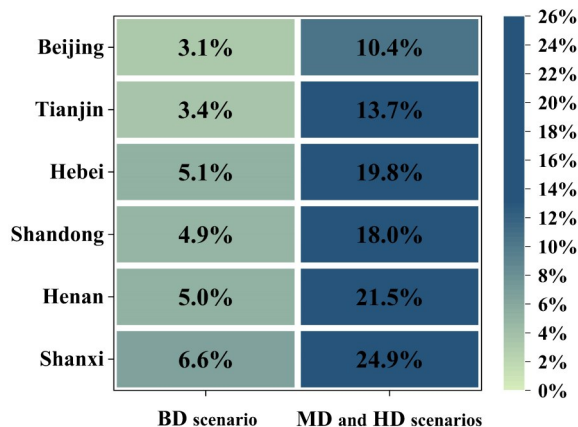


Fig. 6 The initial investment ratio in PCDI for different demand scenarios

and Shandong regions. However, they were slightly higher than 5% in the Hebei and Henan regions. The proportion of initial investments in the Shanxi region was 6.6%. Under the MD and HD scenarios, the ratio of initial investments in six areas ranges from 10.4% to 24.9% in PCDI, all of which exceeded 10%. Both the MD and HD scenarios take into account the impact of household size on heating demand. Therefore, the heating equipment installed by residents under these two scenarios is the same, with the only difference in heating patterns.

Fig. 7 shows the proportion of per capita heating operation and maintenance costs in PCDI from different demand scenarios. Compared with the BD scenario, the price increases about 3-4 times under the MD scenario and about 4-5 times under the HD scenario.

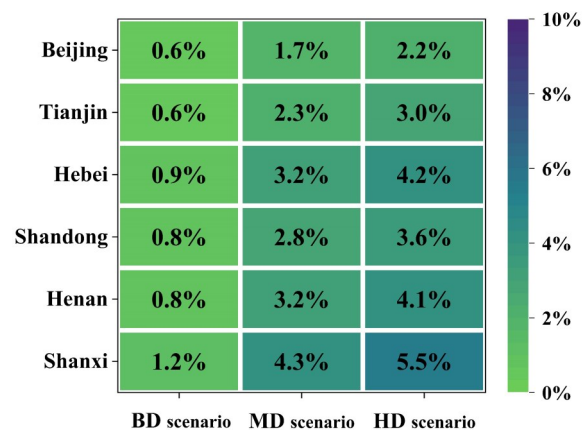


Fig. 7 The operation & maintenance cost ratio in PCDI for different demand scenarios

Under the three heating demand scenarios, the proportion of per capita heating operation and maintenance cost in PCDI in all regions is less than 10%. However, under the HD scenario, the per capita heating operation and maintenance cost in Shanxi had the highest proportion among the six rural regions, reaching about 5.5%.

4.3 ASHP regional clean heating suitability evaluation

4.3.1 Suitability evaluation by energy affordability

The analyses of the energy affordability found that, after ASHP heating was applied, the annual electricity consumption accounts for 56.5%-72.1% of the full power generation capacity of thermal power units in these regions under the BD scenario (see Fig. 5). This indicates high energy affordability

for each area. Furthermore, the power consumed by ASHP heating can be achieved by adjusting the operating load of thermal power units in each region.

For Henan and Shanxi provinces, the annual electricity consumption under the MD scenario was about 106.6% and 127.4% of the current electricity generation capacity, respectively (see Fig. 5). The current power generation capacity in these two regions could hardly satisfy the heating demand in winter and presented weak energy affordability. Unfortunately, these two regions will suffer an energy shortage if the energy supply is mainly based on thermal power plants.

Under the HD scenario, only the Beijing, Tianjin, Hebei and Shandong regions have high energy affordability. However, the annual electricity consumption of the Tianjin and Shandong regions, after ASHP heating in winter, shows that there is only about 10% energy regulation redundancy left. (Accounting for about 90.0% and 93.6%, respectively, see Fig. 5). Notably, the increased electricity consumption by the ASHP for heating has brought regulatory pressure to the regional power supply in these two regions.

Weak energy affordability occurs in both Henan and Shanxi provinces under the MD and HD scenarios. This is especially true in Shanxi province, where the annual electricity consumption under the HD scenario was 1.5 times the power generation capacity. Therefore, the first issue to be solved for ASHP heating in rural areas of Shanxi and Henan was the energy supply. Otherwise, the implementation of clean heating will be affected.

Existing studies^[31] showed that Shanxi and Henan provinces relied primarily on coal usage, and 80% of households in Shanxi province burned fuelwood for heating. Therefore, this might be a challenge in the energy structure of these two regions in transitioning from traditional to clean heating. Furthermore, Henan province had the most significant number of households and a high proportion (69%) of the households with three or more occupants (refer to Table 2). Consequently, this has led to an increased demand for heating in many rural households in Henan, requiring the adoption of MD or HD heating scenarios. Therefore, not only the energy generation

structure but also the household structure can impact the energy affordability of ASHP heating in rural areas.

4.3.2 Suitability evaluation by economic affordability

Fig. 6 shows that under the BD scenario, the proportion of initial investment in these regions within the PCDI ranges from 3.1% to 6.6%. Among them, Hebei and Shanxi exceed 5% but are less than 10%, with moderate economic affordability. In contrast, the proportion in other regions is below 5%, indicating a higher economic affordability. However, under the MD and HD scenarios, this proportion has increased to 10.4%-24.9%, exceeding 10% of PC-DI and presenting weak economic affordability for all regions. High initial costs may make heating equipment unaffordable for many rural households, reducing the acceptance of clean heating and leading people to resort to traditional coal-burning heating instead^[21-22]. Therefore, under the MD and HD scenarios, promoting ASHP heating technology must consider one-time subsidy measures.

In addition to the equipment installation costs, the operating expenses of heating are the decisive factor affecting the sustainability of clean heating. Under the BD scenario, the proportion of heating operation and maintenance costs in PCDI was less than 2%, and each region's economic affordability was high (see Fig. 7). Under the MD scenario, the heating operation and maintenance cost was increased by about 3-4 times compared with the BD scenario. However, the economic affordability was still high. Apart from Shanxi, the heating operation and maintenance costs in other regions demonstrated high economic affordability in the HD scenario. Importantly, there are no energy poverty issues that have arisen in all rural areas of the north.

As shown in Table 4, the PCDI in rural areas of the Henan, Hebei, and Shandong regions was similar (around 17000-20000 CNY). Nevertheless, as heating demand rises, Shanxi rural residents' economic affordability for heating operating and maintenance costs decreases significantly. Notably, Shanxi has the lowest PCDI (about 15000 CNY) within these regions.

5 Discussion

There are significant regional differences in rural areas, especially regarding resource endowment and economic development levels^[44]. However, few studies have evaluated the regional energy and economic affordability after large-scale clean-heating applications. Most previous studies^[9-14, 19-20, 54-59] analyzed the suitability of clean-heating implementation in northern regions from technical and economic micro perspectives. However, these evaluations fail to consider regional energy and economic affordability after clean heating applications. With the continuous promotion of clean heating by ASHP, the dispersed heating electric load aggregation puts energy consumption pressure on regional energy, affecting the regional energy structure and the structure of rural household living energy consumption. Thus, this study established a regional-scale evaluation indicator for the energy and economic affordability of ASHP heating in rural areas. As such, this study proposed an ASHP heating suitability evaluation framework based on energy and economic affordability from a regional perspective. To assess the performance of the evaluation framework, three heating demand scenarios based on the field investigation of ASHP heating characteristics in rural areas were proposed. Additionally, the energy and economic suitability of ASHP heating after large-scale applications in rural areas in northern China were evaluated. Compared with existing studies^[54-59], this study focuses on analyzing the energy transition of ASHP heating in rural areas on a regional scale. From a macro-regional perspective, this study simultaneously explores the challenges faced by ASHP heating in terms of the security of energy supply and the economic burden on rural residents. The research findings will provide a scientific basis and guidance for energy planning and the formulation of clean heating policies in northern rural areas.

Household heating energy consumption varies significantly depending on the heating demand scenario. Higher heating demand corresponds to higher energy consumption. Rural households are distinguished by their large building areas and complex population structure^[20]. When comparing the MD

and HD scenarios to the BD scenario, the heating energy consumption intensity increases 5-6 times for households with a complex household structure (three or more occupants). During the winter, to meet heating demands, the heating energy consumption intensity of rural households will increase. Moreover, as the clean heating technology of ASHP is widely promoted, the overall energy consumption of the region will also rise. Therefore, ensuring energy supply and energy security is crucial for the promotion and development of ASHP clean heating technology in rural areas.

The finding of this study suggests that energy and economic affordability play essential roles in promoting ASHP heating technology in rural areas of China's northern regions. When implementing ASHP heating on a large scale in rural areas of the north region, the matching of energy demand and regional energy supply in each region should be considered to avoid energy shortages. Under the BD scenario, the promotion of ASHP heating technology in rural areas of six provinces and cities in northern China has demonstrated high energy affordability in each region. However, in the BD scenario, only one ASHP heating unit is installed per household, which may not be sufficient to meet the heating demands of the entire household. Therefore, the residents are likely to adapt personal heating devices, such as electric blankets and oil-filled electric heaters, to keep warm in the room^[20]. If these thermal adaptation approaches cannot eliminate dwellers' cold sensation, there is a risk that residents will return to the "old" heating way (burning raw coal)^[14]. Although some regions under the BD scenario showed sufficient energy affordability, it may not satisfy the actual demand of residents with complex population structures and diverse heating demands in rural households^[60]. Thus, compared with the BD scenario, the MD and HD scenarios thoroughly considered the difference in heating demand caused by household size. However, each region has shown weak energy affordability under this scenario, especially for the Shanxi and Henan regions. Therefore, it is essential to evaluate the power system to ensure that the energy supply side can meet the increased load requirements.

Compared with clean heating, traditional heat-

ing methods and fuels (coal and wood) are widely used in rural areas due to their lower initial investment and operating costs. A higher initial investment will reduce residents' willingness to adopt clean heating, and a higher operating cost will affect clean heating's long-term use^[61]. The analyses of each region's economic affordability under different demand scenarios reveal that rural residents in provinces and municipalities with high economic development levels commonly had high economic affordability for both initial investment and operation costs. This study found that the heating operation costs under three different heating scenarios were all within 10% of disposable income, and no fuel poverty was occurring. However, particularly under the MD and HD scenarios, when the initial investment was taken into consideration, fuel poverty was becoming an issue. A previous study supports this finding; the high cost of purchasing heating devices usually requires one-time fiscal subsidies, which may be a significant barrier to clean heating adoption^[57]. Due to the subsidy scheme, households only bear a portion of the cost of replacing the heating equipment. Once there is no financial subsidy, the equipment replacement cost makes the energy poverty issue more serious^[62].

This study has some limitations. When setting up the heating scenarios, this study has classified three different scenarios of heating demand, using household structure as the main factor influencing heating demand. However, considering the complexity of rural household structures and large populations, the current assumed scenarios may not yet be able to cover all situations fully. The boundary conditions for energy affordability consider only thermal power units as energy sources. However, technological advancements in renewable energy utilization contribute to sustainable development, and the high penetration of renewable energy is crucial for decarbonizing the power system^[63]. In 2023, 34% of China's energy came from renewable sources, marking an increase of 8.5% compared to the previous year^[44]. In the future, with the development of carbon neutrality, the proportion of renewable energy electricity is increasing, particularly distributed solar photovoltaics in rural areas^[64]. Furthermore, the data analyzed in this study are mainly derived from statistical year-

books, which are dynamic in their characteristics. Therefore, the conclusions of the study may be adjusted accordingly as the data are updated in real-time. Further work will focus on the rural distributed energy system and assess the impact of heat electrification, which includes feedback on the power system and the change in rural residents' heating demand characteristics.

6 Conclusions

This study examines the energy and economic challenges associated with the comprehensive electrification of space heating in rural areas of northern China. It establishes a framework for evaluating the suitability of a large-scale framework for assessing the suitability of ASHP heating based on energy and economic affordability. From a macro-regional perspective, this paper analyzes the impact of three different demand scenarios of ASHP heating in rural areas of Beijing, Tianjin, Hebei, Shandong, Shanxi and Henan provinces, focusing on both energy consumption and economic affordability.

(1) Our analysis shows that the energy affordability was adequate under the BD scenario in each region. However, as the heating demand of rural residents increased, energy affordability declined. Notably, Henan and Shanxi will be the first to face energy affordability pressure under the high-demand scenario. The energy system, household size and traditional energy-consuming lifestyle (burning fuelwood or coal) were identified as the primary factors influencing energy affordability.

(2) Regarding the economic affordability of ASHP clean heating, the results show that ASHP-heating operation and maintenance costs accounted for less than 10% of residents' incomes for all regions in the scenario analyses, and no fuel poverty risk was discovered in each area. However, under the medium and HD scenarios, these regions held weak economic affordability in the initial investment of ASHP equipment. Therefore, it is recommended that the government provide a one-time financial subsidy to support the development of rural areas.

(3) This study establishes a suitable evaluation framework for ASHP clean heating based on China's context. The evaluation method may help provide a

reference for clean heating in other regions and countries, helping to better understand the potential impacts of promoting the large-scale application of ASHP heating. This research is vital for regional energy planning in northern rural areas, the scientific regulation of clean heating policies, and the development of effective clean heating schemes.

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