

Article

Comprehensive Evaluation of Different Heating Modes in Northeast China

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Abstract: Given the freezing temperatures and extended winters, heating is essential for residents living in Northeast China. When selecting the optimum heating mode for the region, various factors are taken into consideration, such as the impact on the environment, financial cost and energy consumption. However, it is uncertain which heating mode can fulfill all conditions and requirements. In this study, seven heating modes were selected from the national and northeastern heating strategies. A comprehensive index system based on the life cycle theory was developed from the perspectives of energy, the environment, the economy, technology and society. Additionally, a comprehensive evaluation of the seven heating modes was performed using the analytical hierarchy process (AHP) and gray relation analysis. The results of this research showed that, from a complete standpoint, the ground-source heat pump heating mode (HM_g) had the best comprehensive benefit, with a correlation of 0.8173, followed by the coal-fired cogeneration heating mode (HM_{cc}), which had the highest correlation degree among the centralized heating modes at 0.6111. Based on the findings of our thorough examination, a recommended scheme made up of HM_g, HM_{cc}, the electro-thermal membrane heating mode (HM_{ef}), the natural gas boiler room regional central heating mode (HM_{grc}) and the natural gas boiler room decentralized heating mode (HM_{grd}) was established. The recommended scheme can provide a theoretical basis for the implementation of clean heating policies in Northeast China.



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Keywords: Northeast China; heating mode; the life cycle theory; comprehensive benefits

1. Introduction

The demand for energy in China has significantly increased with the rapid development of the economy. In 2020, China's total energy consumption was 49.8×10^8 tce, an increase of 29% compared to 2011 [1]. Specifically, the energy consumption in building operation accounts for up 21.3% of total consumption, with 10.6×10^8 tce [2]. According to the Energy Consumption Standard for Civil Buildings (GB/T51161-2016), building operation energy consumption refers to the energy input from outside during the use of a building, including the energy used to maintain the building environment (such as heating, cooling, ventilation, air conditioning and lighting) and the energy used for various building activities (such as offices, home appliances, lifts, domestic hot water, etc.), with heating having the highest energy consumption, especially for Northeast China [3]. Northeast China straddles the mid-temperate and cold temperate zones from south to north and has a temperate monsoon climate. Therefore, it has a lower winter temperature and longer heating cycle for the extended winter season. In Northeast China, heating is important, and heating energy is mainly derived from coal [4], which makes the air quality worse during the heating season and affects people's physical and mental health. In addition, the urbanization rate in Northeast China has been increasing at an annual rate of 1.2% since

2010 [5–7], which makes the heating energy consumption and pollution problems of new residences more serious. Thus, it is necessary to find a more environmentally friendly and energy-efficient heating mode that is suitable for the residents of the Northeast.

With the improvement in economic standards, people are seeking a high quality of life. As a result, the demand for heating modes is not only limited to the economy, energy and the environment, but also requires heating equipment that is aesthetically beautiful and safe. Recently, comparative studies of heating modes have been conducted from the perspective of energy [8], the economy [9], technology [10] and the environment [11]. However, some scholars have analyzed different heating modes from a single perspective. For example, Xie et al. [12] concluded that the economic cost of electric heating is higher than that of coal-fired boiler heating. Additionally, there are also scholars who have analyzed heating modes from multiple perspectives. Kroetz et al. [8] analyzed the heating modes in Northern England from economic and energy perspectives, and concluded that the region was suitable for heating modes using wood energy as the heat source. Xu et al. [13] constructed a comprehensive evaluation index system for clean heating energy solutions in rural northern China from energy, economic and social perspectives. Cui et al. [14] concluded that gas heating had fewer pollutant emissions than coal heating, but challenges existed, including less gas storage and weak peaking capacity [15]. However, most research aims to compare one or two aspects, including the economy, energy consumption and environmental benefit, and do not consider the whole life cycle process of the heating system.

Once the evaluation perspectives and evaluation indexes have been determined based on the whole life cycle process, a comprehensive analysis of the heating modes is required. This means that the results of the evaluation from the different perspectives mentioned above are used to obtain a combined value by applying some kind of calculation method. A variety of methods have been selected to evaluate heating modes, including the analytical hierarchy process, grey relational analysis and fuzzy comprehensive evaluation analysis. The analytic hierarchy process method is a systematic analysis method proposed by the American operations researcher Saaty [16]. According to the nature of the problem and the overall goal to be achieved, this method decomposes the problem into different constituent factors, and aggregates and combines the factors at different levels according to the interrelated influence and affiliation relationships between the factors to form a multi-level analytical structure model. The advantages are the possibility of combining qualitative analysis and quantitative calculations [17,18], as well as the flexibility to integrate various assessment factors [19]. At present, this method is mainly used to construct hierarchical models and determine weights, and in combination with other evaluation methods [20]. Based on the similarity of the set shapes of the reference data column and several comparison data columns, the gray relational analysis method determines the closeness of the connection, so as to determine the correlation degree. When combined with the analytical hierarchy process method, the strength and magnitude of the relationships between factors can be described using the grey correlation degree [21]. This method does not have excessive requirements for the size of the sample, and the calculation amount is relatively small. In contrast, when the number of indicators is large, the use of the fuzzy comprehensive evaluation method [22] will lead to small weight coefficients and ultra-ambiguity, resulting in evaluation failure. Therefore, the analytic hierarchy method and grey correlation analysis were selected in this paper to determine the index evaluation model and comprehensively evaluate different heating modes.

Under the incentive of national policies, China's heating industry has formed a market pattern dominated by coal-fired heating, gas-fired heating and electric heating. Among them, scientifically and reasonably choosing a heating mode that is more suitable for China's energy structure, ecological environment, economic level, technical level and social status has become a major problem. It is more difficult to build a suitable heating system according to different geographical areas in China. So, in order to analyze the heating system of Northeast China, evaluation indexes based on the whole life cycle theory were created from energy, environmental, economic, technical, and social perspectives. Then,

a comprehensive evaluation model that applied the hierarchical structure of the AHP method was constructed to derive the weights of different indexes. Additionally, the gray relational analysis method was used to calculate the correlation coefficients under different perspectives to evaluate heating modes. After performing the comparison, heating modes with the highest comprehensive efficiency were selected as the recommended solution in our study. Accordingly, the recommended scheme was simulated with other heating scenarios in terms of pollutant emissions, aiming to provide viable solutions for implementing clean heating in Northeast China. Further, this will contribute to improving the energy structure of the heating industry and to the achievement of carbon neutrality.

2. Materials and Methods

2.1. Research Subject

The study area of this paper includes three provinces in Northeast China, Heilongjiang, Jilin and Liaoning, as shown in Figure 1. The common heating modes in Northeast China are shown in Table 1.

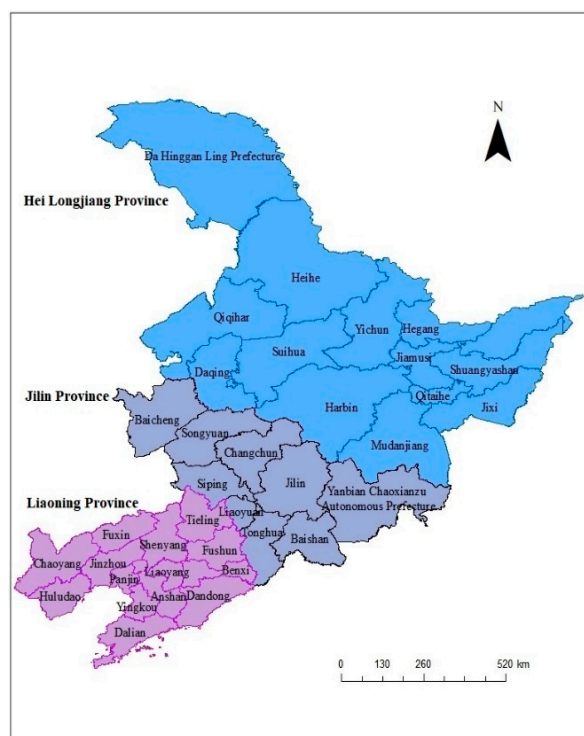


Figure 1. Research scope of Northeast China (Map source: BIGEMAP).

According to the policy requirements, the small coal-fired boiler room heating, coal-fired decentralized heating, bulk coal heating and gas cogeneration heating modes were excluded. In the electric heating modes, compared with the direct electric heating mode, an electric boiler with heat reservoir heating has the benefit of low-cost electricity at night for heat storage, thus extending the heating time and helping to mitigate power supply constraints. Compared to the heating cable heating mode, the electro-thermal membrane heating mode is easy to install, simple to maintain, and simple and safe to use without dangerous hazards [23]. Heat pumps for heating are divided into air-source heat pumps and ground-source heat pumps. Since the air temperature is too low in the northeast of China, relying only on the heat provided by air-source heat pumps cannot guarantee the heating of residential buildings, and the power consumption of ground-source heat pump systems is less than that of air-source heat pumps, so air-source heat pump heating was not considered [24].

Table 1. Policies of different heating modes.

Heating Mode	National Policy	Specific Content
Coal-fired cogeneration heating	Management Measures for Cogeneration 2016	In severe cold and cold areas, it is a priority to plan and build combined heating and power systems.
Large coal-fired boiler room heating	Notice on the Comprehensive Work Plan for Energy Conservation and Emission Reduction during the 13th Five-Year Plan	The development of cogeneration and central heating is accelerated.
Small coal-fired boiler room centralized heating	Action Plan of Air Pollution Prevention and Control	Small coal-fired boilers are comprehensively improved. New coal-fired boilers with a power of less than 20 t of steam per hour are prohibited.
Coal-fired boiler room decentralized heating	Action Plan of Air Pollution Prevention and Control	Decentralized coal-fired boilers will be phased out through centralized construction of cogeneration units.
Bulk coal heating	Work Plan for the Treatment of Bulk Coal in Shenyang in 2018	Total bulk coal consumption will be reduced.
Gas-fired combined heat and power plant	Strategic Action Plan for Energy Development (2014–2020)	Natural gas is not used for cogeneration or is used to a lesser extent.
Gas-fired boiler room decentralized heating	Three-Year Action Plan to Fight Air Pollution	The proportion of natural gas in total energy consumption is expected to reach 10% by 2020.
Gas-fired boiler room centralized heating		
Electric boiler heating	Three-Year Action Plan to Fight Air Pollution	Electric heating is recommended, such as regenerative heating.
Heating cable, electro-thermal membrane heating	Guidelines from the Energy Administration on Promoting Clean Urban Heating in Northern Heating Areas	Gas heating and electric heating are promoted.
Heat pump heating	Liaoning Province Promotes Clean Heating Three-year Rolling Plan (2018–2020)	In areas with better geological conditions, a shallow ground-source heat pump is provided.

To sum up, the final selected heating modes and their representation symbols are shown in Table 2. Among them, the centralized heating modes include HM_{cc} , HM_{cr} , HM_{grc} and HM_{re} , and the others are decentralized heating modes.

Table 2. Commonly used heating modes in Northeast China.

Number	Heating Mode	Abbreviations
Program One	Coal-fired cogeneration heating mode	HM_{cc}
Program Two	Large coal-fired boiler room heating mode	HM_{cr}
Program Three	Natural gas boiler room regional central heating mode	HM_{grc}
Program Four	Natural gas boiler room decentralized heating mode	HM_{grd}
Program Five	Electric boiler with heat reservoir heating mode	HM_{re}
Program Six	Electro-thermal membrane heating mode	HM_{ef}
Program Seven	Ground-source heat pump heating mode	HM_g

2.2. Evaluation Index System

According to the whole life cycle theory [25], residential building heating systems can be divided into three main stages (planning and design, operation and maintenance and scrap recycling), as shown in Figure 2. In the planning and design phase, the scope of heating needs to be determined, the heating area and heat load calculated, and based on this the infrastructure costs, piping costs and purchased energy costs calculated. In the operation maintenance phase, the issues involved include the maintenance costs of the equipment, the heating costs for the residents, the suitability of the room temperature, the

availability of a stable supply of energy, the emission of pollutants from coal- and gas-fired heating and the safety of the heating system. The heating medium absorbs heat at the heat source and is transported through the pipe network to the heat consumer's end, where issues such as whether there are heat losses and whether they can be reduced need to be considered. In the scrap recycling phase, the focus needs to be on the operating costs of the system, the costs of dismantling the site at end-of-life, etc.

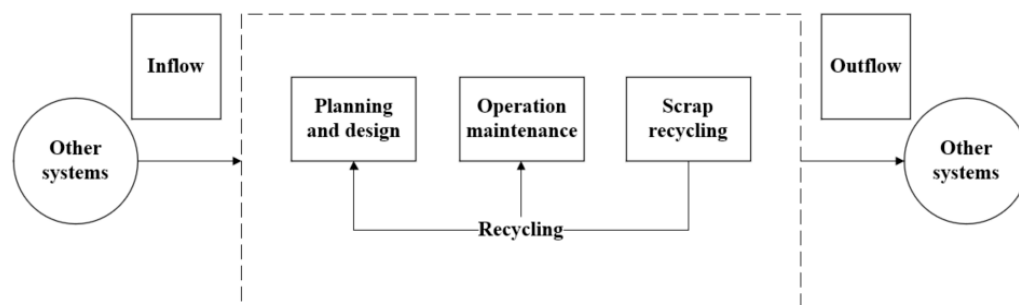


Figure 2. The life cycle model of the heating system.

The above three phases include energy, environmental, economic, technological and social aspects, from which 15 evaluation indexes were selected. The index layers were clustered and combined in layers according to the mutual influence and affiliation between evaluation angles and evaluation indexes to form a stepped and ordered hierarchical structure model, as shown in Figure 3. Among them, the target layer A includes a comprehensive evaluation of different heating modes in residential buildings. The rule layer B includes the above five perspectives. There are 15 indexes in index C. More detailed explanations of the evaluation indexes are shown in Table 3.

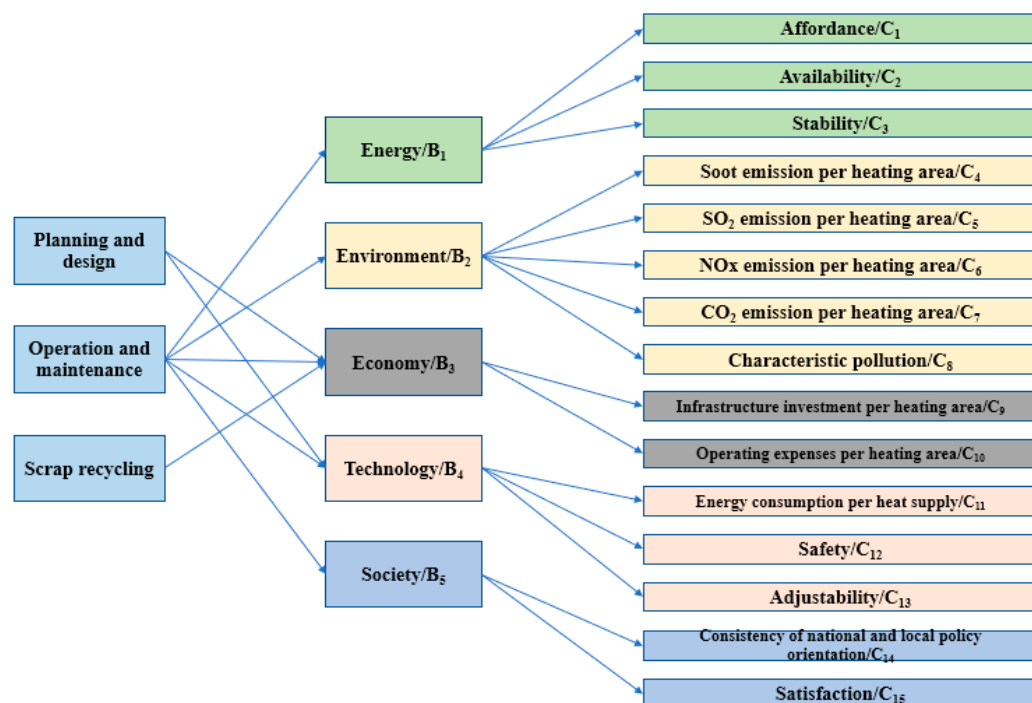


Figure 3. Evaluation indexes of heating modes in Northeast China.

Table 3. Interpretation of evaluation indexes.

Indexes	Interpretation
C ₁	Considering the direction of energy restructuring, whether the energy consumed by the heating mode has sufficient reserves needs to be judged.
C ₂	It is necessary to determine how easy access to energy resources is in the northeast based on the national energy distribution.
C ₃	The stability of the energy supply needs to be compared. Will there be a failure to match supply with demand in a timely manner?
C ₄	The pollutant selected mainly refers to the urban waste gas in the China Statistical Yearbook, and the CO ₂ emissions of different heating modes are added in consideration of the carbon emission control requirements of China's Double Carbon Policy.
C ₅	
C ₆	
C ₇	
C ₈	Unique pollution is something that some heating modes have and others do not, such as PM _{2.5} emissions from coal-fired heating and groundwater contamination from ground-source heat pump heating.
C ₉	This index reflects the investment costs of different heating modes.
C ₁₀	Operating costs are related to the level of consumption of the population, and the level of this cost determines whether a certain heating mode can be successfully promoted or not.
C ₁₁	The energy consumption per unit of heat supply is related to the thermal value of different heat sources and the efficiency of heat networks, including the efficiency of primary pipe networks, secondary pipe networks and heat exchange stations. Some centralized heating pipe networks are used for a long time, which makes the loss of hot water or steam increase in the process of transmission. In order to ensure that the indoor temperature of all households meets the standard, the boiler operation parameters have to be increased, resulting in overheating in the rooms of users close to the heat source. In the absence of indoor temperature control devices, the only way to dissipate heat is by opening doors and windows, which results in a huge waste of heat.
C ₁₂	The safety and proper operation of the heating system affects the promotion of the heating mode. Therefore, different heating modes must ensure a certain safety factor and stability.
C ₁₃	Maintenance difficulty and simplicity refers to the speed of repair and the amount of money consumed in the routine maintenance process or after an operational failure occurs.
C ₁₄	C ₁₄ refers to the degree of compliance with national and local policies. Heating modes that comply with policies will not only receive financial subsidies, but may also be promoted as demonstration projects.
C ₁₅	This index is judged according to the cost of heating for residents, the ease of regulation based on user feedback and whether the heating mode affects the aesthetics of the city and the physical and mental health of residents.

2.3. Calculation Method of Evaluation Indexes

2.3.1. Qualitative Index

C₁, C₂, C₃, C₈, C₁₂, C₁₃, C₁₄ and C₁₅ are all qualitative indexes. The procedure of determining the value of the qualitative index is as follows: The first is advantage rating. According to the content of each index, the advantages of energy and heating modes are ranked, and then, the value interval is divided. According to the rating series in step one, 0~100 is divided into the corresponding value range of the series. Finally, the value is determined from the divided value interval.

2.3.2. Quantitative Index

(1) Pollutant emissions per heating area (C₄~C₇) [26]

$$E_{i,n} = m_n \times EF_{i,n} \quad (1)$$

In the above equation, $E_{i,n}$ is the emission of pollutant i from the n energy source per heating area, g/m²; m_n is the n energy consumption per heating area, as shown in Equation (6); $EF_{i,n}$ is the emission factor of pollutant i from the n energy source, where the units of emission factors for coal, natural gas and electricity are g/kg, g/m³ and g/kW·h, respectively; and pollutant type i includes soot, SO₂, NO_x and CO₂.

(2) Infrastructure investment per unit area (C_9)

The infrastructure investment includes the investment costs of heating equipment, heating pipe network and heating equipment. Due to the different service lives of heating equipment, this paper used the annual cost (AC) method to calculate infrastructure investment, as shown in Equation (2) [27]:

$$AC_j = \frac{i \times (1+i)^{n_j}}{(1+i)^{n_j} - 1} \times k_j \quad (2)$$

where k_j is the capital construction investment of the heating system j , CNY; i is the base discount rate, taking 8% within the department [28]; and n is the usage life. Based on a survey of online equipment data from heating companies, the service life of a boiler is 15 years, that of a ground-source heat pump is 25 years, that of primary and secondary pipe networks is 15 years, that of household equipment is 50 years, and that of electric heating is 30 years.

(3) Operating expenses per unit area (C_{10})

The cost mainly comprises fuel cost, maintenance cost and depreciation cost, and the rest of the cost is difficult to calculate accurately, so it is not considered. Fuel cost, maintenance cost and depreciation cost are shown in Equations (3)~(5) [29], respectively:

$$\text{Fuel cost : } C = m_n c \quad (3)$$

$$\text{Maintenance cost : } W = \eta_{wx} \times n \times T \quad (4)$$

$$\text{Depreciation cost : } Z = G_y \times a_z \quad (5)$$

where C is the fuel cost per unit area, CNY/m²; m_n is the energy consumption per unit area, and its units are kg/(m²·a) (coal), m³/(m²·a) (natural gas) and kW·h/(m²·a) (electricity); and c is the unit price of fuel, and its units are CNY/kg (coal), CNY/m³ (natural gas) and CNY/kW·h (electricity), respectively.

In Equation (4), η_{wx} is the maintenance rate of the heating system. With a boiler room heating system taking a value of 2~3%, this paper takes an average 2.5% [27]; the other heating systems take a value of 0.5~0.8%, and this paper takes a value of 0.75% [30]; n is the coefficient, taking a value of 95% [30]; T is the infrastructure investment of each heating system, CNY/m²; a_z is the basic depreciation rate, taking a value of 6.3% for heat and pipe networks and 1.9% for household equipment [30,31]; and G_y is the original value of fixed assets, CNY/m².

(4) Energy consumption per unit heating area (C_{11}) [32]

$$m = \frac{tq}{I_{PER} Q_{dw}} \quad (6)$$

$$m_s = \frac{1}{I_{PER} Q_{dw}} \quad (7)$$

In the above equation, m is the energy consumption per unit heating area (kg/(m²·a) (coal), m³/(m²·a) (natural gas), kW·h/(m²·a) (electricity)); t is the annual heating time in Northeast China, 160 days; q is the comprehensive heating index, W/m²; I_{PER} is the primary energy ratio; Q_{dw} is the low heat of standard coal; m_s is the energy consumption per unit heating quantity, kg/GJ.

2.3.3. Data Sources

By searching the Statistical Yearbooks of Heilongjiang, Jilin and Liaoning Provinces and the related literature, the following data were identified:

- ① Heating days in Northeast China: Heating in Northeast China lasts 160 days, from November to April.
- ② The comprehensive index in Northeast China is set at 57 W/m^2 , according to the design specification of urban thermal pipe network (2002) [33].
- ③ The energy price in 2022 and a low calorific value are shown in Table 4. The coal price came from survey data.
- ④ Some heating modes pose a great threat to the environment, mainly from the combustion of fuel in the heating process. The emission of pollutants is divided into two forms: the first is that pollutants from fuel combustion are directly emitted into the air; the second is that the electricity required for electric heating mainly comes from fossil fuel combustion, which leads to indirect emissions of pollutants in the process of electricity generation. Four pollutants, soot, SO_2 , NO_x and CO_2 , were selected for this paper. Their emission factors are shown in Table 5.
- ⑤ Based on the equipment costs [27] collected for the seven heating modes, the infrastructure investment cost is calculated using Equation (2), as shown in Table 6. HM_g has the highest infrastructure investment cost of 215 CNY/m^2 , which is 2.1 times that of HM_{grd} with the lowest investment cost.
- ⑥ The primary energy utilization rate is shown in Table 7.

Table 4. Energy price and low calorific value.

Energy	Coal	Natural Gas	Electricity
Price	635 (CNY/t)	3.55 (CNY/m ³) [34–36]	0.56 (CNY/kW·h) [37–39]
Low calorific value	29,308 kJ/kg	36,000 kJ/m ³	3600 kJ/kW·h

Table 5. Pollutant emission factors of different heating modes [32,40].

Heating Mode	Unit	Soot	SO_2	NO_x	CO_2
HM_{cc}	g/kg	0.11	0.39	0.557	1980.397
HM_{cr}		0.11	0.39	0.557	1980.397
HM_{grc}	g/m ³	0.26	0.65	2.60	1940
HM_{grd}		0.26	0.65	2.60	1940
HM_{re}	g/kW·h	Pollutant emission factors for coal-fired boilers are used for the thermal power generation component.			
HM_{ef}					
HM_g					

Table 6. Infrastructure investment per unit area of different heating modes (CNY/m²).

Heating Supply Equipment	Pipe Network			Heating Equipment	Infrastructure Investment
	Primary Pipe Network	Heat Exchange Station	Secondary Network		
HM_{cc}	27	22	12	70	158
HM_{cr}	39	22	12	70	170
HM_{grc}	26	22	12	70	178
HM_{grd}	22	0	0	70	103
HM_{re}	25	22	11	70	156
HM_{ef}	0	0	0	134	171
HM_g	80	0	0	98	215

Table 7. The primary energy utilization rate of each heating mode [41].

Heating Mode	HM_{cc}	HM_{cr}	HM_{grc}	HM_{grd}	HM_{re}	HM_{ef}	HM_g
The primary energy utilization rate	0.9017	0.9017	0.7935	0.8800	0.2779	0.3082	1.4569

2.4. Weights of Different Evaluation Indicators

In this paper, the AHP method was chosen to calculate the weights of different evaluation indicators, i.e., the degree of influence of each level of factors on the previous level [16,42]. The specific calculation process is as follows:

Firstly, the degree to which elements contained in the same level affect the indicators of the previous level is compared, and a comparison matrix according to the degree of impact is constructed, as shown in Equation (8):

$$A = (a_{ij})_{n \times n} \quad (8)$$

where $a_{ij} > 0$, $a_{ji} = 1/a_{ij}$ ($i \neq j$), $a_{ii} = 1$, $i, j = 1, 2, 3, 4 \dots n$. a_{ij} is derived from the judgment matrix scale (Table S1); the specific data are shown in Tables S2–S8.

Secondly, arithmetic averaging is used to calculate the weights.

$$p_i = \frac{1}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_{x=1}^n a_{xj}} \quad (9)$$

$$CR = \frac{\lambda_{\max} - n}{(n - 1)RI} \quad (10)$$

where $\lambda_{\max}$ is the largest feature root, $\lambda_{\max} = \sum_{i=1}^n \frac{(AP)_i}{np_i}$; RI is the random consistency index, as shown in Table S9; and CR is the test coefficient. When $CR < 0.10$, the weight value of the indicator is reasonable; otherwise, it needs to be recalculated until $CR < 0.10$.

$$CR_A = \sum_{i=1}^{n_{A-B}} \frac{p_i \times CI_i}{p_i \times RI_i} \quad (11)$$

When $CR_A \leq 0.10$, the synthetic weights of each indicator for the total target are calculated.

2.5. Correlation Degree of Different Heating Modes

Based on the weights of different indicators, the proximity of different solutions to the ideal solution is calculated using grey correlation analysis, i.e., the grey correlation degree [43]. These data are used as a basis for evaluating different heating modes, and the calculation process [29] is as follows:

$$\gamma_{ij} = \frac{\min_j \min_i |X'_{0j} - X'_{ij}| + \rho \max_j \max_i |X'_{0j} - X'_{ij}|}{|X'_{0j} - X'_{ij}| + \rho \max_j \max_i |X'_{0j} - X'_{ij}|} \quad (12)$$

where $|X'_{0j} - X'_{ij}|$ is the absolute difference between the value X'_{ij} and the value X'_{0j} ; $\min_j \min_i |X'_{0j} - X'_{ij}|$ is the minimum value of the difference, and $\max_j \max_i |X'_{0j} - X'_{ij}|$ is the maximum value of the difference; and ρ is the resolution coefficient, whereby the smaller its value, the greater the resolution ability, and this paper takes a value of 0.5.

Combining the weights p_i of each indicator with the correlation coefficient matrix R , the correlation degree can be calculated as follows:

$$\lambda_{0i} = p_i \times R^T \quad (13)$$

3. Results and Discussion

3.1. Analysis of Evaluation Index Weights

The test coefficients and weights are shown in Figure 4.

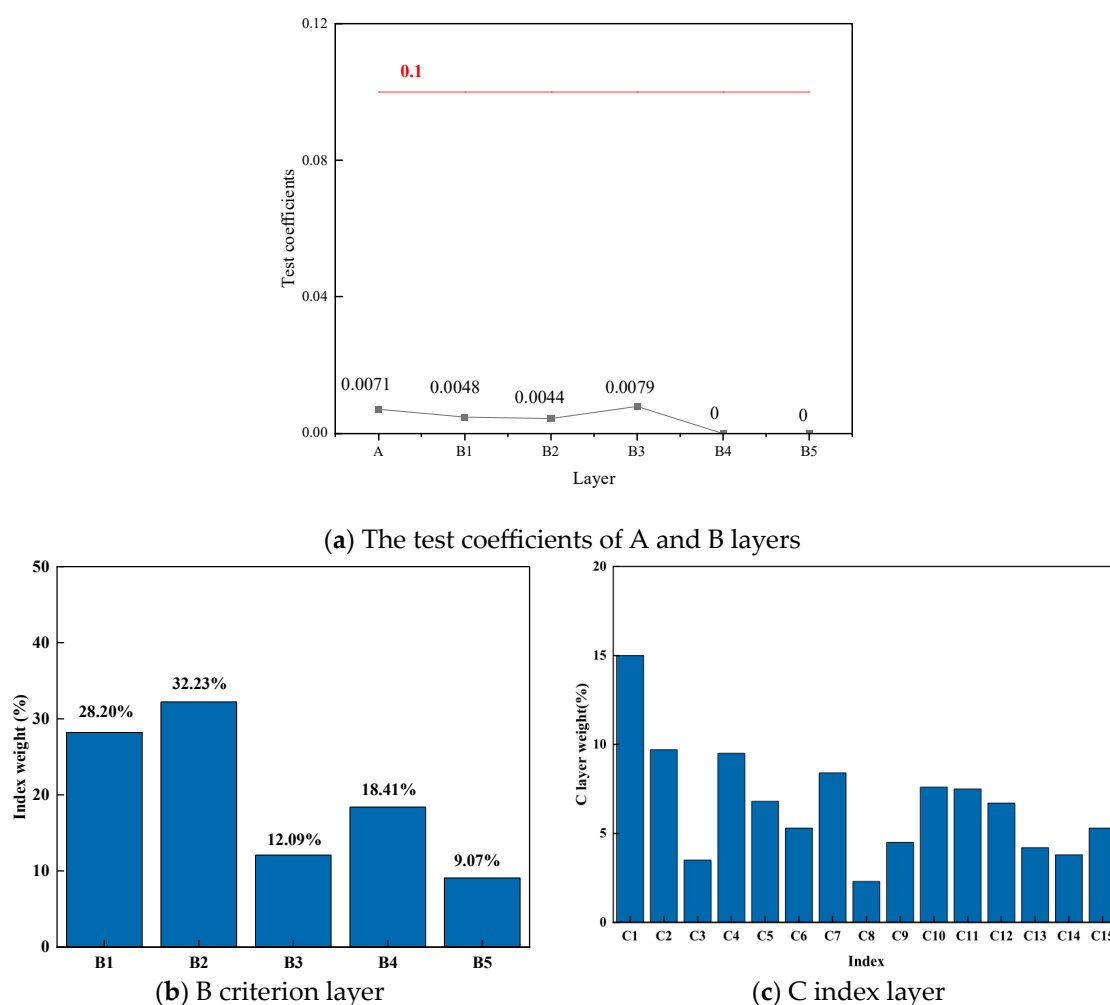


Figure 4. The test coefficients and index weights.

In Figure 4a, the test coefficients of both the A and B layers are less than 0.1, indicating that the hierarchical structure constructed in this paper meets the requirements.

In Figure 4b, the relative importance of each subsystem in the criterion layer B is ranked as $B_2 > B_1 > B_4 > B_3 > B_5$. This indicates that environmental and energy issues in the Northeast are important influencing factors.

In Figure 4c, the top rank indexes are C_1 and C_2 with weighting of 15.0% and 9.7%, respectively. This highlights that energy reserves and energy accessibility are crucial considerations to prioritize when dealing with heating solutions in Northeast China. And the heat sources should be selected according to local conditions. In addition, soot emissions are weighted at 9.5% and ranked third in the total indexes. Coal combustion leads to more severe haze in the northeast, and the government of Liaoning Province has set a target of reducing the province's $PM_{2.5}$ concentration to $42 \mu g/m^3$ by 2020 [44].

3.2. Analysis of Evaluation Indexes

3.2.1. Energy Indexes

The heat sources include coal, natural gas and electricity in several heating modes. The indexes of heating modes with the same heat source take the same value, as shown in Figure 5. For index C_1 , the policy of the Three-Year Rolling Plan for Clean Heating requires acceleration of the development of natural gas heating modes, making HM_{grc} and HM_{grd} take the largest value. On the contrary, for indexes C_2 and C_3 , HM_{grc} and HM_{grd} take the lowest values. This is because natural gas needs to be imported to meet the demand in Northeast China, and the access method is harder than coal-fired heating and electric

heating. In addition, the natural gas heating modes often have poor emergency reserve capacity due to low gas storage.

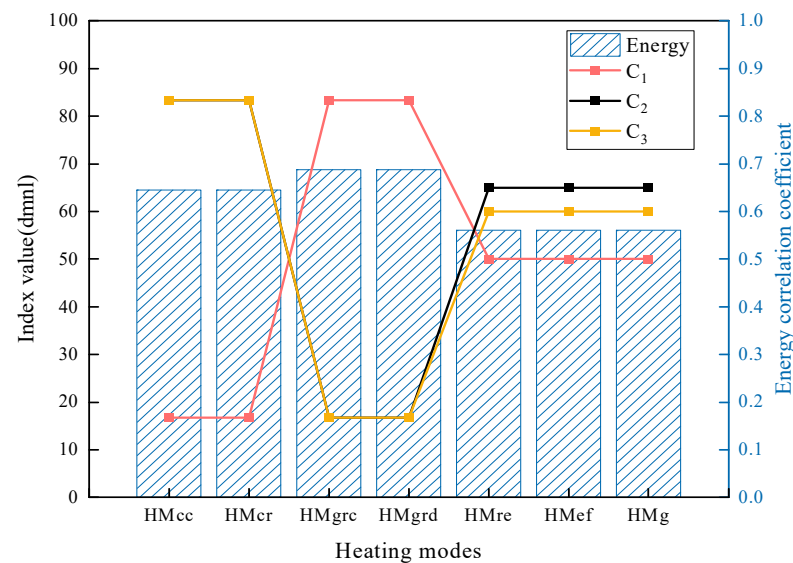


Figure 5. Energy index values and correlation coefficient of different heating modes.

Based on the index values and weights, the correlation coefficient from the energy perspective is calculated. The correlation coefficients of the different heating modes are ranked as $HM_{grc} = HM_{grd} > HM_{cc} > HM_{cr} > HM_{re} = HM_{ef} = HM_g$. Natural gas heating modes have the highest correlation of 0.6880, which is strongly promoted by the state. This is followed by coal-fired heating with a correlation of 0.6453, and finally, electric heating with a correlation of 0.5573, which is 81% of the value of natural gas heating. The energy correlation coefficient of electric heating modes can be increased by increasing the proportion of electricity generated from renewable sources.

3.2.2. Environment Indexes

The values and environmental correlation coefficients of the different evaluation indicators are shown in Figure 6.

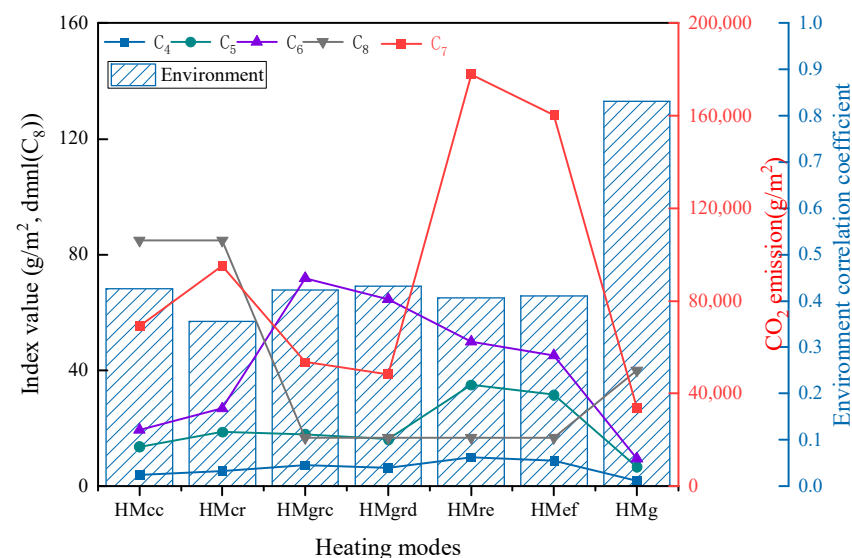


Figure 6. Environmental index values and correlation coefficient of different heating modes.

For index C_4 , it ranks first among the environmental indicators, with weights 1.40, 1.79 and 1.13 times those of C_5 , C_6 and C_7 , respectively. Among the different heating modes, the highest emission of soot is from HM_{re} with 9.87 g/m^2 , while HM_g has the lowest emission with 1.88 g/m^2 . In terms of different heat sources, electric heating modes emit more soot than gas heating modes, which is mainly due to the fact that the northeast region is dominated by thermal power generation, which accounts for 79.16%. The coal-fired heating modes emit less soot than the gas-fired heating modes, which is mainly related to the implementation of the ultra-low emission policy for coal-fired and gas-fired boilers in the Northeast. Coal-fired boilers are required to emit a soot concentration of 10 mg/m^3 , which is 50% that of gas-fired boilers. For indexes C_5 and C_7 , emissions from electric heating modes are the highest, with a similar trend to C_4 . For indicator C_6 , natural gas heating modes have the highest NO_x emissions, with HM_{grc} and HM_{grd} being 71.72 g/m^2 and 64.67 g/m^2 , respectively. To reduce the NO_x emission level, the government needs to step up its efforts in controlling the emissions from newly built gas boilers.

For index C_8 , only the heating modes with coal as the heat source and a ground-source heat pump heating mode produce unique pollution. During the heating season, heating systems with coal-fired heat sources emit large amounts of $\text{PM}_{2.5}$, which seriously affects people's physical and mental health. The unique pollution of the ground-source heat pump heating mode mainly arises from the impact of buried pipes on groundwater. Therefore, among the seven heating modes, the severity of the unique pollution situation is as follows: coal-fired $\gg$ ground-source heat pump $>$ electricity = natural gas.

For the environmental correlation coefficient, the ranking of the different heating modes is $HM_g \gg HM_{grd} > HM_{cc} > HM_{grc} > HM_{ef} > HM_{re} > HM_{cr}$. HM_g is the most environmentally friendly with a correlation of 0.8310, while the correlations of the other heating modes are similar. For centralized heating, HM_{cc} has the highest correlation of 0.4260, while HM_g is the most environmentally friendly among the decentralized heating modes.

3.2.3. Economy Indexes

The values and economy correlation coefficient of the different evaluation indicators are shown in Figure 7.

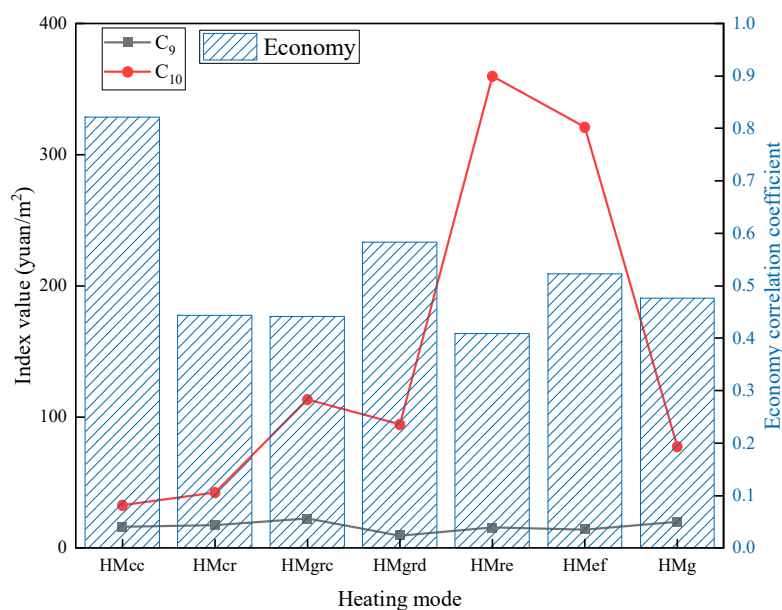


Figure 7. Economic index values and correlation coefficient of different heating modes.

In Figure 7, the infrastructure cost of HM_{grc} reaches the highest value, at 22.31 CNY/m^2 , which is 2.3 times higher than that of HM_{grd} , mainly because the former requires a higher cost for the pipe network. In terms of operating costs, the annual operating cost per unit

heating area of HM_{cc} is the lowest, at 32.81 CNY/m^2 , which is related to the lower price of coal and higher utilization of primary energy. HM_{re} has the highest operating cost per unit area due to high fuel cost, at 11 times higher than that of HM_{cc} . With flexible opening and closing methods, the annual operating cost per unit heating area of the natural gas decentralized heating mode is less than that of HM_{grc} , which is the same as the status quo of the high price and high burden of residents for gas and electric heating. Especially for electric heating, the feasibility of this method is really too low without reducing the economic burden of residents.

For the economy correlation coefficient, the correlation degree is ranked as $HM_{cc} > HM_{grd} > HM_{ef} > HM_g > HM_{cr} > HM_{grc} > HM_{re}$. Due to the absence of heat loss from the pipe network, decentralized heating has advantages over centralized heating, among which the advantage of HM_{grd} is the most obvious, with a correlation of 0.5833, second only to HM_{cc} .

3.2.4. Technology Index

The values and technology correlation coefficient of the different evaluation indexes are shown in Figure 8.

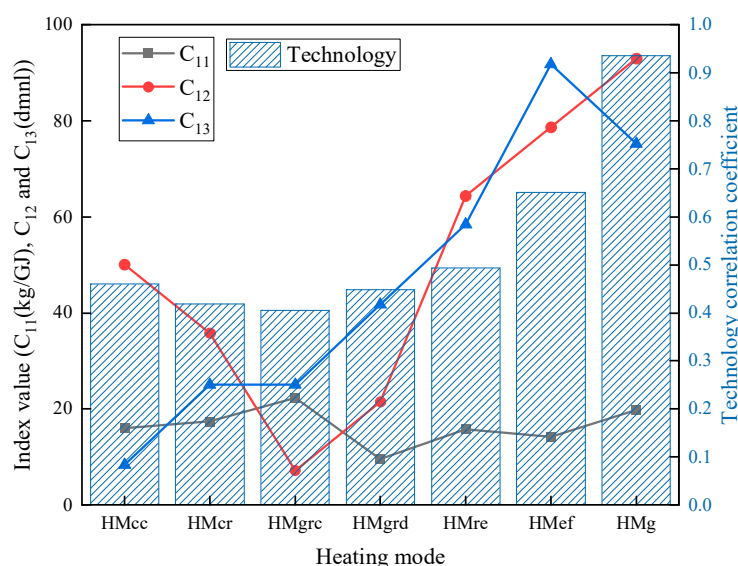


Figure 8. Technical index values and correlation coefficient of different heating modes.

In Figure 8, for index C_{11} , HM_{grd} is the lowest, at $9.58 \text{ m}^3/\text{GJ}$. For index C_{12} , the safety of electric heating is better than that of natural gas and coal-fired heating, which is because coal-fired heating modes have the risk of gas poisoning, while natural gas decentralized heating modes have the problems of natural gas leakage. Collectively, the heating methods under this index are ranked as $HM_g > HM_{ef} > HM_{re} > HM_{cc} > HM_{cr} > HM_{grd} > HM_{grc}$. For index C_{13} , the larger the heating area, the more difficult it is to regulate the convenience, so the indexes of centralized heating modes take lower values than decentralized heating modes, where HM_{cc} is the lowest at 8.35.

For the technology correlation coefficient, it was found that the ground-source heat pump heating mode is the most compliant, with a correlation of 0.9359, followed by HM_{re} , which is 2.2 and 1.6 times higher than HM_{cr} , respectively. This proves that decentralized heating meets the requirements better than centralized heating under the technical index requirements.

3.2.5. Society Index

The values and society correlation coefficient of the different evaluation indexes are shown in Figure 9.

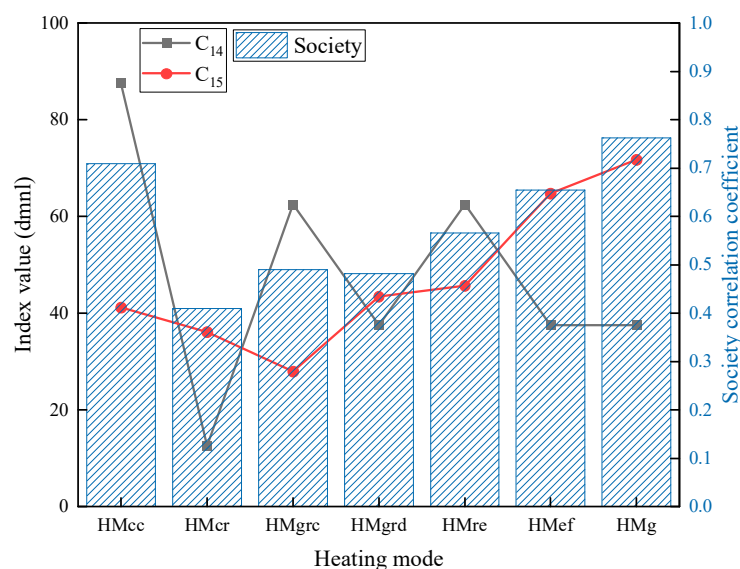


Figure 9. Social index values and correlation coefficient of different heating modes.

In Figure 9, for social index C_{14} , the ranking of heating modes is $HM_{cc} > HM_{re} = HM_{grc} > HM_{ef} = HM_g > HM_{grd} > HM_{cr}$, due to the strong support for “coal to gas” and “coal to electricity” in China, which gives priority to centralized heating modes and supports the construction of cogeneration in Northeast China. For index C_{15} , the satisfaction degree of residents is determined by three conditions: the level of fees, the degree of controllability and whether it affects the aesthetics of the city. Among them, the tariff and the degree of adjustable convenience have been analyzed in the economic and technical indexes, and thus, the degree of aesthetic impact is analyzed here. The ranking of different heating modes in terms of aesthetics is: $HM_g > HM_{ef} > HM_{re} > HM_{grd} > HM_{cc} > HM_{cr} > HM_{grc}$.

For the society correlation coefficient, after considering the national policy direction and residents’ satisfaction, the three heating modes that best meet the demand are ground-source heat pump heating (0.7623), the coal-fired cogeneration heating mode (0.7087) and the electro-thermal membrane heating mode (0.6545). Therefore, coal-fired cogeneration is best for the centralized heating modes, and the decentralized heating modes suits the electro-thermal membrane heating mode or the ground-source heat pump heating mode well according to their own conditions.

3.3. Comprehensive Evaluation

Based on the above index data and index weights, the comprehensive benefits of heating modes are calculated according to the gray correlation method, as shown in Figure 10.

In Figure 10, the overall benefits of the centralized heating modes are ranked as $HM_{cc} > HM_{grc} > HM_{cr} > HM_{re}$. And the overall benefits of the decentralized heating modes are ranked as $HM_g > HM_{grd} > HM_{ef}$. It can be seen that the correlation coefficient of the ground-source heat pump heating mode is the highest at 0.8173, which is 1.3 times that of HM_{cc} . This is mainly because the fuel price and infrastructure cost of HM_{cc} are lower than that of HM_g . On the contrary, from the residents’ point of view, with government subsidies, residents only need to pay for electricity for heating. In this case, the relevance of HM_g is much higher than that of HM_{cc} . By the same token, this is another reason for the lower overall benefits of the electric heating modes in this paper. According to the assessment of Hubei DiDa heat energy technology Co., Ltd. (Wuhan, China) [45], ground-source heat pumps are the best solution for winter heating in the northeast. This is because the outdoor temperature in winter can be as low as $-20\text{ }^{\circ}\text{C}$, but the temperature of groundwater at a depth of 80 to 160 m is maintained at a stable temperature of around $12\text{ }^{\circ}\text{C}$ to $14\text{ }^{\circ}\text{C}$ all year round. In winter, the ground-source heat pump unit absorbs heat

from the groundwater through a compressor and heat exchanger, and the temperature of the water can reach up to 90 °C when heating. In addition, the largest demonstration base of ground-source heat pumps for clean energy supply in Northeast China will be constructed in 2023 [46].

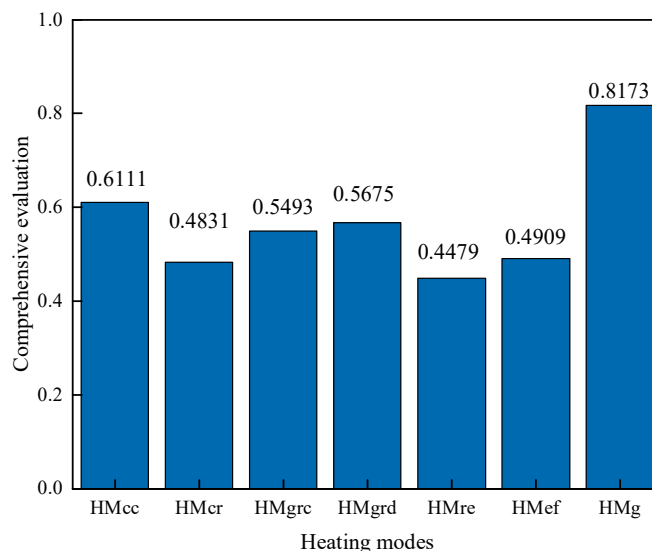


Figure 10. Comprehensive evaluation of different heating modes.

In addition, natural gas heating modes are more suitable for Northeast China than electric heating modes. The comprehensive benefits of HM_{grc} and HM_{grd} are 0.5493 and 0.5675, respectively, which are 1.2 and 1.3 times higher than those of HM_{re} . According to *the China Bulk Coal Comprehensive Management Research Report 2021*, it is required to take into account the economic effect of reducing pollution and carbon, and to give priority to industrial waste heat, cogeneration and geothermal heat in urban centralized heating areas. In urban villages with the necessary foundation and conditions, direct heaters and storage heaters are promoted cautiously, and “coal to gas” is consolidated and steadily promoted. This is the same as the result of our comprehensive evaluation.

Compared with the evaluation of heating modes in other regions, the comprehensive evaluation results are different due to the different heating modes, evaluation perspectives, research methods and other factors. For example, according to the heating situation in Xi'an, Meng [27] compared the comprehensive benefits of cogeneration heating, large coal-fired boiler room central heating, oil-fired boiler central heating, gas boiler central heating, small gas furnace heating, electric heating film heating and heat pump heating (including energy, environmental, economic, technological and social perspectives), and believed that HM_{cc} had the highest comprehensive benefit, while the heat pump heating mode ranked third. In addition, Hou [47] compared the heating modes in North China, comprehensively considered technical, energy consumption, economic and environmental factors, and determined that the comprehensive benefit of the ground-source heat pump heating mode was the best. Taking Urumqi as their research area, Li [29] recommended the use of gas wall-hung furnace heating and did not recommend HM_{cc} under the comprehensive consideration of resource, environmental, economic, technological and social perspectives.

3.4. Scenario Analysis

3.4.1. Scenario Building

From the comprehensive evaluation ranking, the top five heating modes were selected as the recommended solution because they have fewer restrictions and are more widely used. In addition to the recommended heating options, the top 5 heating modes were selected from the energy, environmental, economic, technical and social perspectives to form the scenarios, respectively. According to the Plan for Clean Winter Heating in

Northern Areas (2017–2021), the proportion of various heat sources in the heating industry in northern areas of China in 2020 was plotted. Among them, the proportion of clean coal is 58%, natural gas 14%, electric heating 8%, ground-source heat pumps 4%, biomass 15% and other heat sources 1%. Based on the proportion of heat sources and the gray correlation obtained from the above analysis, the proportion of each heating mode in the six scenarios was derived, as shown in Figure 11.

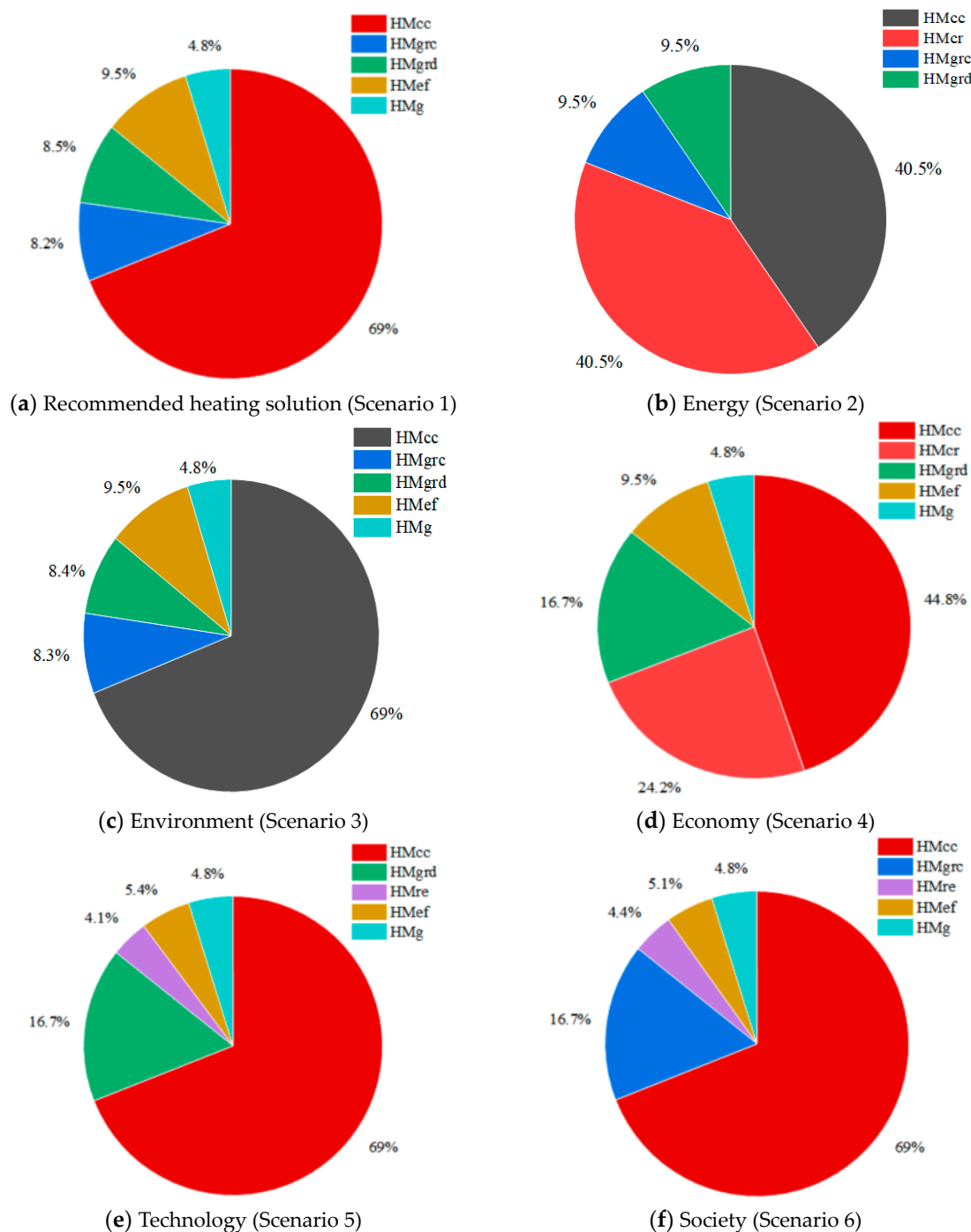


Figure 11. Percentages of different heating modes.

3.4.2. Pollutant Emissions of Different Scenarios

As shown in Figure 12, Scenario 4 and Scenario 5 have the highest soot emissions at 248,048 t and 247,466 t, respectively. As a comparison, Scenario 1 (the recommended

scenario) has a soot emission of 131,067 t. It can be seen that the haze phenomenon in the Northeast will become more and more serious if only economic and technological factors are taken into consideration while environmental factors are ignored. For CO₂ emissions, the recommended scenario has the lowest emissions of 161,997,786 t, which is 12,967,360 t less than the emissions from Scenario 4 (the economic scenario). For other pollutant emissions, the recommended scenario also demonstrates significant emission reduction advantages and is suitable for promotion and use in the northeastern region.

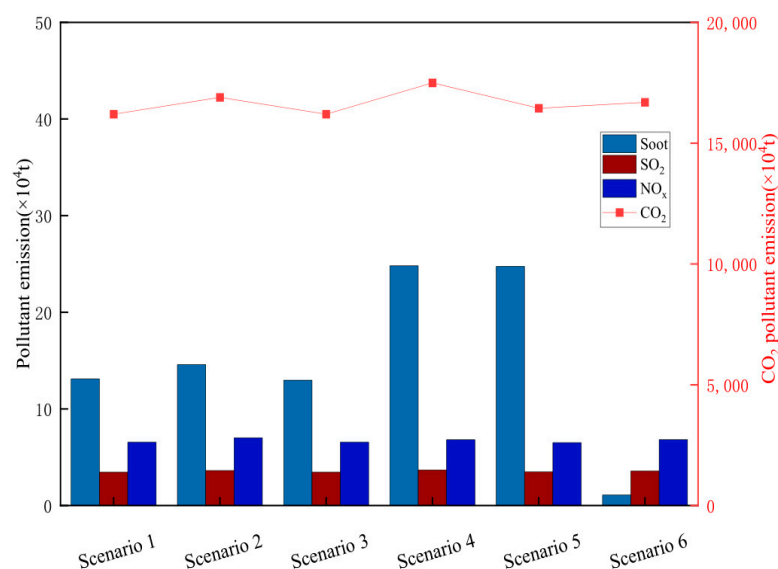


Figure 12. Pollutant and CO₂ emissions of different scenarios.

4. Conclusions

This paper analyzed seven heating modes in Northeast China and constructed an evaluation index system covering energy, the environment, the economy, technology and society. The conclusions are as follows:

- (1) From an energy perspective, the natural gas heating mode has the highest correlation of 0.6880, followed by the coal-fired heating modes and the electric heating modes.
- (2) From an environmental perspective, on the premise that thermal power is the energy supply, the correlation degree is ranked as $HM_g > HM_{grd} > HM_{cc} > HM_{grc} > HM_{ef} > HM_{re} > HM_{cr}$. HM_g is the most environmentally friendly with a correlation of 0.8310, and the other heating modes have similar relevance.
- (3) From an economic perspective, the correlation degree is ranked as $HM_{cc} > HM_{grd} > HM_{ef} > HM_g > HM_{cr} > HM_{grc} > HM_{re}$. It is more advantageous to use coal as a heat source in addition to the natural gas decentralized heating mode.
- (4) From a technical perspective, the correlation degree is ranked as $HM_g > HM_{ef} > HM_{re} > HM_{cc} > HM_{grd} > HM_{cr} > HM_{grc}$. The advantages of electric heating modes are more obvious, in which the ground-source heat pump heating mode has the highest correlation of 0.9359.
- (5) From a social perspective, the correlation degree is ranked as $HM_g > HM_{cc} > HM_{ef} > HM_{re} > HM_{grc} > HM_{grd} > HM_{cr}$. HM_g has the highest correlation of 0.7623, followed by the coal-fired cogeneration heating mode.

In our comprehensive view, the correlation ranking is $HM_g (0.8173) > HM_{cc} (0.6111) > HM_{grd} (0.5675) > HM_{grc} (0.5493) > HM_{ef} (0.4909) > HM_{cr} (0.4831) > HM_{re} (0.4479)$. The top five heating modes are selected as the recommended scenario in Northeast China, which is consistent with the national policy. The emissions of soot pollutant, SO₂, NO_x and CO₂ from the recommended scenario in Northeast China are 131,067 t, 34,501 t, 65,485 t and 161,997,786 t, respectively. The recommended scenario has significant emission reduction advantages compared to the other scenario options.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su151813494/s1>, Table S1: The judgment matrix scale; Table S2: Weight of indexes in A layer; Table S3: Weight of indexes in B₁ layer; Table S4: Weight of indexes in B₂ layer; Table S5: Weight of indexes in B₃ layer; Table S6: Weight of indexes in B₄ layer; Table S7: Weight of indexes in B₅ layer; Table S8: Total weight of indexes for A layer; Table S9: Mean randomized consistency indicator (RI) standard value.

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