frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 24 November 2022
DOI 10.3389/fenvs.2022.1082470

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 28 October 2022
ACCEPTED 07 November 2022
PUBLISHED 24 November 2022

CITATION
Li Y, Zhang Y, Zhang J, Xiang Z and Li Z (2022), Research on the influencing factors of clean heating compound transformation under the carbon neutrality goal.
Front. Environ. Sci. 10:1082470.
doi: 10.3389/fenvs.2022.1082470

Research on the influencing factors of clean heating compound transformation under the carbon neutrality goal

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The clean heating compound transformation under the Carbon Neutrality Goal is necessary for the high-quality development of the heating industry in China. Based on the literature analysis, questionnaires and semi-structured interviews, this paper identifies 15 driving factors affecting the transition at three levels: technology, organization and environment. This paper introduces Fuzzy Set Theory into Decision-Making Trial and Evaluation Laboratory method, and combined with explanatory structural models to form a combined Fuzzy-DEMATEL-ISM approach. Using the Fuzzy-DEMATEL-ISM method to analyze the degree of influence, hierarchical relationships and logical associations among the influencing factors to reveal the influence mechanism of the compound transition of clean heating. The results show that 1) the key influencing factors for the transition are energy use and delivery methods, heating system operation and maintenance management, and clean heating costs and expenses. 2) There are eight causal factors and seven consequential factors in the clean heating compound transition influence factor system. 3) The recursive structure model of influencing factors is divided into five levels from bottom to top: root level, deep level, middle level, shallow level and surface level, among which environmental and clean heating policies, clean heating technology innovation level and resource endowment status are the basic guarantees of transformation. It provides a theoretical supplement and practical guidance for the compound transition to clean heating under the carbon neutrality goal.

KEYWORDS

carbon neutral goal, clean heating, compound transformation, fuzzy-DEMATEL-ISM combination method, influencing factors

1 Introduction

To address global warming and promote high-quality economic and social development, China's 14th Five-Year Plan and the outline of its 2035 vision clearly propose to "develop a carbon emission peaking action plan by 2030" and "anchor efforts to achieve carbon neutrality by 2060". China's heating industry faces a daunting task in achieving the goal of carbon peaking and carbon neutrality. On the one hand, haze disasters occur frequently during winter heating in the North, and most of the incremental air pollutants come from winter coal-fired heating (Lin et al., 2020) On the other hand, the demand for heating in the Southern China is also exploding, leading to a further increase in carbon emissions from the heating industry (Han et al., 2021). Growing carbon emissions and energy consumption are preventing China from reaching its 2030 carbon peak and 2060 carbon neutrality goal (Li et al., 2022). In this context, balancing the relationship between heating and air pollution and achieving coal-fired replacement and clean heating is not only a practical problem that needs to be solved in the current heating industry but also an important part of China's goal to achieve carbon neutrality.

Clean heating refers to the use of natural gas, electricity, geothermal, biomass, solar energy, industrial waste heat, cleaned-up coal combustion, nuclear energy, and other cleaned-up energy sources to achieve low-emission and low-energy consumption heating through efficient energy-use systems, including the whole process of heating with the goal of reducing pollutant emissions and energy consumption. Currently, common forms of heating include clean coal-fired heating, natural gas heating, clean coal-fired heating, and another single. Single-energy model heating systems can neither meet diverse heating needs nor effectively improve heating energy efficiency levels. Wang et al. (2022) found that a multi-source composite heating model with multiple energy sources applied to the heating system can significantly improve heating energy efficiency China is vigorously promoting combined heat and power central heating under the carbon neutrality goal (Liu et al., 2021). The development trend of centralized heating at home and abroad is generally: from coal-fired steam heating to a compound heating system consisting of elements such as large-scale heat storage technology and clean energy for combined heat and power supply (Lake et al., 2017).

In this context, the heating industry is facing the resource endowment condition of "rich in coal and less in gas", prompting the heating industry to continuously explore how the clean compound model can be combined with China's heating reality, explore the clean heating compound development model to adapt to the local resource endowment condition, and make the clean heating compound transformation toward the goal of carbon neutrality. Therefore, this paper focuses on the composite transition of clean heating to conduct research in line with the current situation of heating transition and has important practical significance. However, in the process of advocating and gradually implementing the composite model of clean heating, the academic community has not yet clarified the factors affecting the composite transition of clean heating and the correlation between the factors, which will significantly hinder the process of achieving low-carbon transition of clean heating in China. In summary, based on literature analysis, questionnaire survey, and semi-structured interviews, this paper explores the influencing factors of the compound transition of clean heating, and uses the Fuzzy-DEMATEL-ISM combination method to derive the key influencing factors of the transition, the causal relationships among the influencing factors and the recursive structural model reflecting the hierarchical relationships of the influencing factors, and then proposes management inspirations to adapt to the current situation and sustainable development goals of the low-carbon transition of China's heating industry.

The remainder of this paper is structured as follows. In the Section Literature review, this paper summarizes the research status at home and abroad and finds out research gaps, providing a theoretical basis for this paper. Section Materials and methods introduces the Fuzzy DEMATEL-ISM method and data collection. Section Results and discussion summarizes the influencing factors of the clean heating compound transformation, and empirically analyzed the correlation between the influencing factors. Finally, in the Section Inclusion and enlightenment, this paper summarizes the work and puts forward suggestions accordingly.

2 Literature review

The compound transformation of clean heating is the combination, integration, and crossover of various clean energy sources with efficient CHP centralized heating and other methods, and thus the transformation and upgrading of heating modes (Lund et al., 2018).

At present, scholars at home and abroad mainly carry out research on the compound transition of clean heating in three main compound ways, such as energy sources, facilities and equipment, and heat source delivery modes. 1) Studies on the clean heating mode with the compound of multiple energy sources. Guo et al. (2021) studied a multi-energy heating system combining solar, natural gas, and air energy, which can reduce economic costs and carbon emissions compared to conventional systems. Ancona et al. (2021), Wang et al. (2021) and Jiang et al. (2022) concluded that the compound heating mode using different kinds of clean energy can improve energy efficiency and effectively reduce air pollution. 2) Research on clean heating models compounded by different equipment and facilities. Dincer and Acar (2015) are based on the energy multi output integrated system composed of a variety of equipment and facilities, which can effectively reduce the overall energy demand. Yao et al. (2020) discussed the current situation of clean heating technology in Northern China and suggested that the construction of heating system hardware facilities and software facilities is crucial to the improvement of the energy efficiency level of buildings. 3) Research on the heating compound mode of decentralized, centralized and distributed heat source transmission. Wirtz et al. (2020), Lund et al. (2018), and Ye et al. (2021) argue that suitable clean heating models should be selected based on the characteristics of different heat source delivery modes.

In summary, many scholars at home and abroad have made multi-faceted and in-depth research on the energy-saving and emission-reduction effects of the compound transition of clean heating from the main compound approaches, and their fruitful results are important inspirations for further exploring the impact paths of the compound transition under the carbon neutrality goal. However, research on the compound transition to clean heating currently suffers from the following deficiencies. 1) Existing studies mostly explore the compound model of clean heating and the benefits generated from a single dimension, and it is difficult to reflect the comprehensive influence of different dimensional factors on the compound transformation of clean heating, and the external drivers of transformation need to be further enriched and improved. 2) The importance of each driver of the compound transition of clean heating needs to be further explored, and the main driving paths of the compound transition of clean heating under the carbon neutrality goal need to be further explored. Therefore, this paper uses literature analysis, questionnaires, and semi-structured interviews to try to explore the factors influencing the compound transition to clean heating. Therefore, this paper uses literature analysis, questionnaires, and semi-structured interviews to try to explore the influencing factors of the compound transformation of clean heating, and combine the Fuzzy-DEMATEL-ISM combination method to study the logical association, degree of influence, and hierarchical relationship between each influencing factor, to provide theoretical support and practical guidance for the green transformation of China's heating industry.

3 Materials and methods

3.1 Fuzzy DEMATEL-ISM method

Decision-Making Trial and Evaluation Laboratory (DEMATEL) is a system analysis method that seeks causal relationships among factors in complex systems (Shieh et al., 2010). In this paper, Fuzzy Set Theory (FST) is combined with the DEMATEL method by adding the concepts of fuzzy set theory and triangular fuzzy number ahus avoiding the problem of excessive subjectivity in expert scoring. To deeply explore the correlations among the factors influencing the compound transformation of clean heating, this paper further introduces Interpretive Structural Modeling (ISM), which decomposes the complex system into a multi-level recursive structural form by identifying the inter-influence relationships among the system factors, thus facilitating the excavation of the internal structure of the system (Raut et al., 2017). In this paper, the improved fuzzy-DEMATEL method is combined with the ISM method, and the combined Fuzzy-DEMATEL-ISM method is formed to analyze the complex relationships among the factors influencing the clean heating compound transition. The specific implementation steps are as follows (Shakeri and Khalilzadeh, 2020).

TABLE 1 Triangular fuzzy number conversion table.

Semantic variables	Triangular fuzzy number
N (No influence)	(0.00, 0.00, 0.25)
VL (Very low influence)	(0.00, 0.25, 0.50)
L (Low influence)	(0.25, 0.50, 0.75)
H(High influence)	(0.50, 0.75, 1.00)
VH(Very high influence ())	(0.75, 1.00, 1.00)

Step 1: Based on the linguistic operator "N", "VL", "L", "H", and "VH", invite experts to assess the two-by-two relationship between influencing factors.

Step 2: Convert the original expert evaluation into triangular fuzzy numbers according to the semantic conversion table $X = (\mathrm{l, m, r})$, $l \le m \le r$, l is the left-hand side value, i.e., the conservative value; m is the middle value, i.e., the closest to the actual value; and r is the right-hand side value, i.e., the optimistic value. The paper gets $\omega_{ij}^{K} = (I_{ij}^{k}, m_{ij}^{k}, r_{ij}^{k})$, which represents the degree of influence of factor i on factor j according to the kth expert. The table of expert semantic evaluation and triangular fuzzy number conversion is shown in Table 1.

Step 3: The original data is de fuzzified by the CFCS (Converting the Fuzzy data into Crips Scores) method proposed by Opricovic and Tzeng (2003), which converts the fuzzy numbers into clear values to derive the direct influence matrix Z.

1) Normalization. $\chi l_{ij}^{k}, \chi m_{ij}^{k}, \chi r_{ij}^{k}$ are the normalized values of the left-hand side value l_{ij}^{k}, the middle value m_{ij}^{k}, and the right-hand side value r_{ij}^{k}

$$\Delta_{min}^{max} = \max r_{ij}^{k} - min\, l_{ij}^{k} \tag{1}$$

$$\chi l_{ij}^{k} = \frac{l_{ij}^{k} - min\, l_{ij}^{k}}{\Delta_{min}^{max}}$$

$$m_{ij}^{k} = \frac{m_{ij}^{k} - min\, l_{ij}^{k}}{\Delta_{min}^{max}}$$

$$\chi r_{ij}^{k} = \frac{r_{ij}^{k} - min\, l_{ij}^{k}}{\Delta_{min}^{max}} \tag{2}$$

2) Calculate the left and right standardized values. χls_{ij}^{k} and χrs_{ij}^{k} are the left normalized and right normalized values, respectively.

TABLE 2 Examples of core studies.

Influencing factors	Examples of core studies	Influencing factors	Examples of core studies
Energy delivery and utilization	Xiang et al. (2022)	Heating system operation and maintenance management	Averfalk and Werner, (2020)
Clean heating technology innovation	Cai et al. (2021)	Environmental benefits	Yan et al. (2022)
Clean heating costs and expenses	Feng et al. (2021)	Centralized or decentralized heating methods	ur Rehman et al. (2018)
Air quality and atmospheric conditions	Schmale et al. (2014)	Equipment and facilities renewal	Long et al. (2021)
International joint governance	Zhang et al. (2022)	Energy saving goal	Hepburn et al. (2020)
Environmental and clean heating policy	Ma et al. (2021)	Economic benefits	Ma et al. (2022)
Heating subsidy funds	Gong et al. (2020)	Evaluation and assessment system	Haghghi et al. (2019)
Resource endowment status	Panori et al. (2022)		

Note: When the literature is signed by several authors at the same time, only the first author is listed in this table; the content of the related literature is similar and will not be repeated.

$$\chi ls_{ij}^{k} = \frac{\chi m_{ij}^{k}}{1 + \chi m_{ij}^{k} - \chi l_{ij}^{k}}$$

$$\chi rs_{ij}^{k} = \frac{\chi r_{ij}^{k}}{1 + \chi r_{ij}^{k} - \chi m_{ij}^{k}} \quad (3)$$

3) Calculate the total standard exact value χ_{ij}^{k}.

$$\chi_{ij}^{k} = \frac{\chi ls_{ij}^{k}\left(1 - ls_{ij}^{k}\right) + \left(\chi rs_{ij}^{k}\right)^{2}}{1 - \chi ls_{ij}^{k} + \chi rs_{ij}^{k}}$$

4) Calculate the clarity value and the average clarity value to obtain the direct influence matrix Z.

$$z_{ij}^{k} = min\, l_{ij}^{k} + \chi_{ij}^{k} \times \Delta_{min}^{max} \quad (5)$$

$$z_{ij} = \frac{\left(z_{ij}^{1} + z_{ij}^{2} + \cdots + z_{ij}^{k}\right)}{k} \quad (6)$$

$$Z = \left|z_{ij}\right|_{mn}$$

Step 4: Calculate the normalized direct impact matrix M and the integrated influence matrix T.

$$M = \frac{Z}{max\left[max\left(\sum_{1\leqslant i\leqslant n^{j=1}}^{n} a_{ij}\right), max\left(\sum_{1\leqslant j\leqslant n}^{n} a_{ij}\right)\right]} \quad (7)$$

$$T = M(I - M)^{-1} \quad (8)$$

In Eq. 11, I is the unit matrix.

Step 5: Calculate the influence degree R_i, influenced degree D_i, centrality degree C_i and cause degree G_i for each indicator.Where, the influence degree R_i is the sum of each row of the integrated influence matrix T where the ith indicator is located, which indicates the integrated influence value of the factor on other factors; the influenced degree D_i is the sum of each column, which indicates the integrated influence value of the factor by other factors.

The greater the C_i, the more important the indicator is and the stronger the association with other indicators, and the importance of the influencing factors can be ranked based on C_i. G_i indicates the degree of causality between the ith indicator and other indicators, if the value is positive means the indicator is the causal factor, which means the influence of indicator i on each other indicator is greater than the influence of other indicators on indicator i, and *vice versa*, it is the resulting factor.

$$R_i = \sum_{j=1}^{n} t_{ij}, i = 1, 2, \cdots n \quad (9)$$

$$D_i = \sum_{i=1}^{n} t_{ji}, j = 1, 2, \cdots n \quad (10)$$

$$C_i = R_i + D_i$$

$$G_i = R_i - D_i \quad (11)$$

Eqs 12, 13 in t_{ij} for the combined impact matrix T of the ith element on the jth element of the impact value.

Step 6: Calculate the reachable matrix. Calculate the mean and standard deviation of the matrix T and use the sum of the mean and standard deviation as the threshold θ to obtain the adjacency matrix P based on Eq. 12, and when P satisfies Eq. 13, the reachable matrix S is obtained.

$$p_{ij} = \begin{cases} 1, t_{ij} \geq \theta \\ 0, t_{ij} < \theta \end{cases} (i, j = 1, 2, \cdots n), P = \left[p_{ij}\right]_{n\times n} \quad (12)$$

$$(P + I)^{K-1} \neq (P + I)^{K} = (P + I)^{K+1} = S = \left(s_{ij}\right)_{s\times s} \quad (13)$$

Step 7: Construct a multi-level recursive influence structure model. Determine the reachable set U_i and the antecedent set V_i of each indicator according to Eqs 14, 15, and determine whether U_i and V_i satisfy $U_i = U_i \cap V_i$, if so, then x_i is the highest level, and delimit row i and column i of the matrix S. This step is repeated until all factors are eliminated, and the multi-level recursive influence structure model of each factor

TABLE 3 Scores of indicators related to influencing factors.

Classification of influencing factors	Influencing factors	Perfect score rate	Average value	Dispersion factor
Technical level	Energy delivery and utilization	0.3500	4.1500	0.1750
	Clean heating technology innovation	0.4000	4.3000	0.1489
	Heating system operation and maintenance management	0.4500	4.3500	0.1503
	Equipment and facilities renewal	0.2000	3.7500	0.2367
	Centralized or decentralized heating methods	0.1000	3.7500	0.1660
Organizational level	Heating subsidy funds	0.3000	4.1500	0.1576
	Evaluation and assessment system	0.1500	3.8500	0.1698
	Energy saving goal	0.3000	4.0500	0.1987
	Economic benefits	0.2500	4.1000	0.1873
	Clean heating costs and expenses	0.3500	4.1333	0.1750
Environmental level	International joint governance	0.2500	4.2000	0.1652
	Air quality and atmospheric conditions	0.3000	4.0667	0.1873
	Environmental and clean heating policy	0.2500	4.1333	0.1523
	Resource endowment status	0.1500	3.7333	0.2211
	Environmental benefits	0.2000	3.8667	0.1768
	Consumption of heating resources	0.1500	3.9500	0.1492

in the system is derived according to the order of elimination.

$$U_i = \{x_i | x_i \in X, s_{ji} = 1\} \tag{14}$$

$$V_i = \{x_i | x_i \in X, s_{ij} = 1\} \tag{15}$$

The antecedent set V_j denotes the set of elements corresponding to all rows with element 1 in column i of the reachable matrix; the reachable set U_j denotes the set of elements corresponding to all columns with element 1 in row i of the reachable matrix.

3.2 Data collection

To ensure the reliability and validity of the research results, this paper uses diversified sources of qualitative data analysis, which include primary data from semi-structured interviews, questionnaires, and on-site observations as the main channels, and combines secondary data such as authoritative journals and news reports to meet the data source requirements for data triangulation verification (Walker and Myrick, 2006). Main acquisition channels.

1) First-hand data. The researchers explored the realization of clean heating, the impediments and needs of the compound transition of clean heating, and the influencing factors and their associations of the compound transition of clean heating under the carbon neutrality goal for different stakeholders of clean heating, and conducted semi-structured interviews around these issues, and later conducted telephone interviews with some of the interviewees to supplement and validate the theoretical framework until the theoretical saturation was achieved. A questionnaire survey was conducted on 20 industry experts whose research questions were related to clean heating. The 20 experts included five middle and senior managers and five grassroots technicians from Beijing Thermal Group Co. and Shenergy Group Co. Also included were five related researchers and five staff members of heating authorities.
2) Second-hand data. This paper searched the literature with the keywords "carbon neutral", "clean heating", "clean heating mode", etc. on the academic platforms such as Knowledge Network and Web of Science, and logged on the official websites of heating enterprises to find news reports about clean heating in the past 5 years. The paper also searched the official websites of heating enterprises for news reports on clean heating in the past 5 years, and used various channels to supplement the research data to further enhance the accuracy of the research data.

4 Results and discussion

4.1 Factors analysis

This paper uses the literature analysis method to initially extract the influencing factors of the compound transition of

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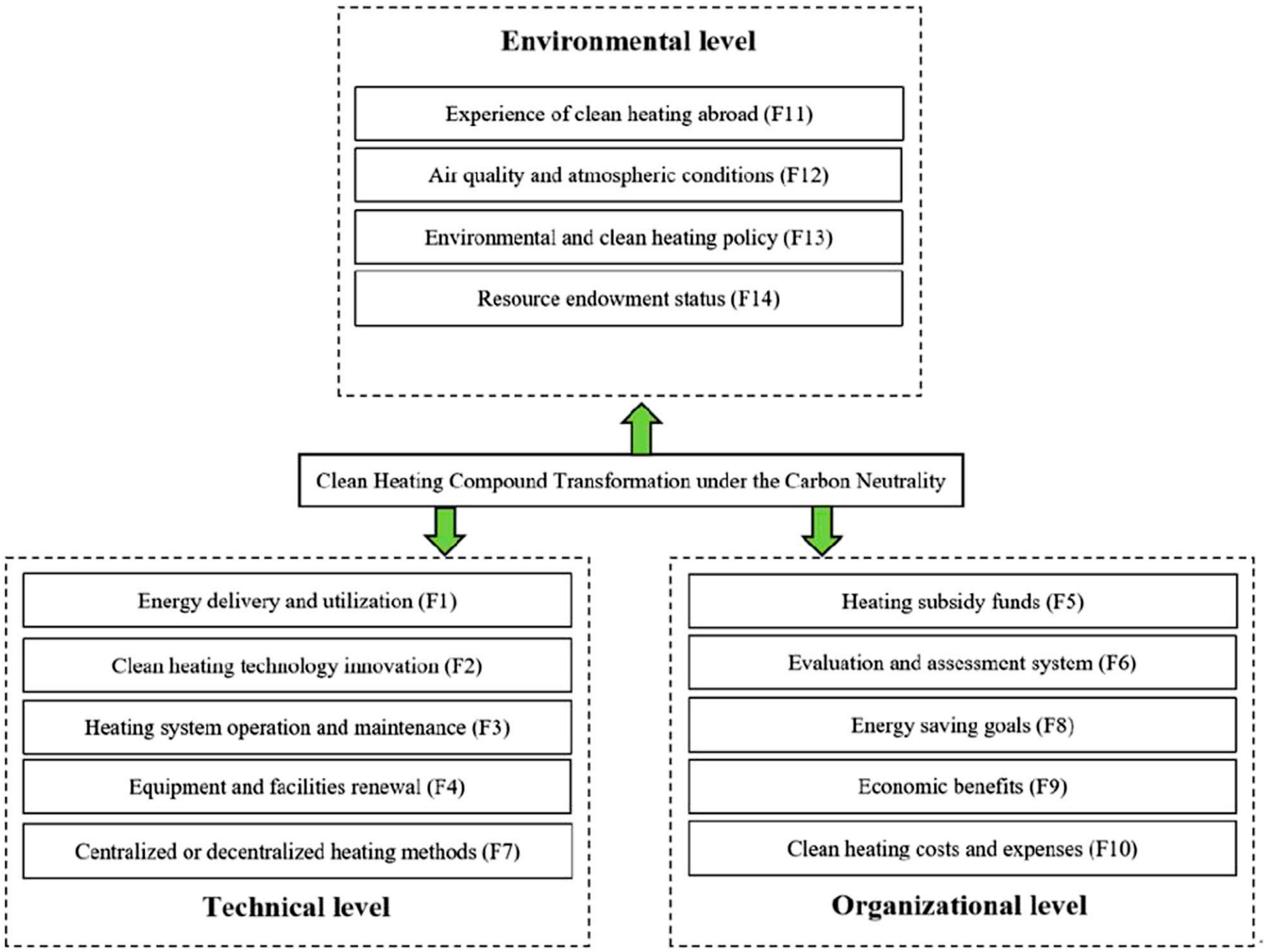

FIGURE 1
Influencing factors of clean heating compound transformation.

TABLE 4 Integrated influence matrix.

Factor	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15
F1	0.1012	0.0898	0.3384	0.0614	0.0499	0.0513	0.3008	0.2415	0.2514	0.3257	0.0595	0.2667	0.0316	0.0316	0.2390
F2	0.2770	0.0561	0.2430	0.2484	0.0411	0.0443	0.2022	0.1654	0.1629	0.1561	0.2478	0.1433	0.0294	0.0294	0.1588
F3	0.1029	0.0592	0.1145	0.0457	0.0407	0.0364	0.0826	0.2883	0.3171	0.2782	0.0393	0.0547	0.0253	0.0253	0.2522
F4	0.0933	0.0457	0.2808	0.0361	0.0319	0.0385	0.2501	0.1824	0.1728	0.1133	0.0341	0.0494	0.0231	0.0231	0.1443
F5	0.0477	0.0397	0.0875	0.0342	0.0318	0.0259	0.0579	0.0919	0.1538	0.2578	0.0279	0.0343	0.0186	0.0186	0.0989
F6	0.0657	0.0321	0.2222	0.0312	0.0293	0.0365	0.2489	0.1758	0.1643	0.0943	0.0295	0.0412	0.0215	0.0215	0.1330
F7	0.0715	0.0287	0.0700	0.0297	0.0283	0.0664	0.0617	0.2463	0.2601	0.0895	0.0281	0.0413	0.0208	0.0208	0.2091
F8	0.0297	0.0191	0.0384	0.0206	0.0198	0.0197	0.0335	0.0378	0.0500	0.0476	0.0198	0.0253	0.0150	0.0150	0.2463
F9	0.0290	0.0185	0.0374	0.0199	0.0191	0.0286	0.0340	0.0375	0.0470	0.0373	0.0194	0.0248	0.0148	0.0148	0.2262
F10	0.0961	0.0666	0.2649	0.0699	0.0710	0.0381	0.1351	0.1434	0.3411	0.1187	0.0403	0.0532	0.0249	0.0249	0.2297
F11	0.0517	0.0404	0.0474	0.0283	0.0217	0.0221	0.0424	0.0844	0.0509	0.0443	0.0332	0.2268	0.0167	0.0167	0.0918
F12	0.0675	0.0265	0.0568	0.0360	0.0253	0.0257	0.0506	0.2568	0.0748	0.0575	0.0630	0.0456	0.0193	0.0193	0.2784
F13	0.2500	0.0676	0.1645	0.0569	0.2421	0.2448	0.2104	0.1486	0.1628	0.1751	0.0453	0.0976	0.0281	0.0281	0.1426
F14	0.2543	0.0381	0.1494	0.0332	0.0299	0.0301	0.1138	0.1004	0.1090	0.1368	0.0317	0.0881	0.0207	0.0207	0.1037
F15	0.0264	0.0170	0.0352	0.0183	0.0176	0.0176	0.0300	0.0338	0.0779	0.0493	0.0174	0.0223	0.0132	0.0132	0.0460

TABLE 5 Analytical indicators of the integrated influence matrix.

Factor	Degree of influence	Rank	Degree of being influenced	Rank	Degree of causality	Rank	Degree of reason	Rank
F1	2.439 7	1	1.564 0	7	4.003 7	1	0.875 7	4
F2	2.205 1	2	0.645 0	13	2.850 1	8	1.560 1	2
F3	1.762 5	4	2.150 5	4	3.913 0	2	−0.388 0	11
F4	1.519 0	6	0.769 6	9	2.288 7	11	0.749 4	5
F5	1.026 4	11	0.699 6	12	1.726 0	13	0.326 9	7
F6	1.347 2	7	0.726 0	11	2.073 3	12	0.621 2	6
F7	1.272 5	8	1.854 1	6	3.126 5	4	−0.581 6	12
F8	0.637 7	13	2.234 4	3	2.872 1	7	−1.596 7	13
F9	0.608 0	14	2.396 0	2	3.004 0	6	−1.788 0	14
F10	1.718 0	5	1.981 5	5	3.699 5	3	−0.263 5	10
F11	0.818 6	12	0.736 4	10	1.555 0	15	0.082 3	8
F12	1.103 1	10	1.214 5	8	2.317 6	10	−0.111 4	9
F13	2.064 6	3	0.323 1	14	2.387 7	9	1.741 5	1
F14	1.260 1	9	0.323 1	14	1.583 2	14	0.937 0	3
F15	0.435 2	15	2.600 1	1	3.035 3	5	−2.164 8	15

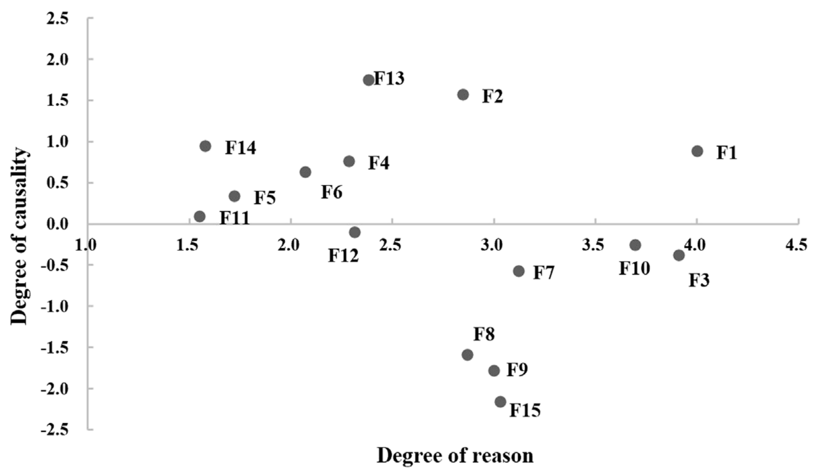

FIGURE 2
Cause-and-effect diagram.

clean heating and obtain the core research examples on the influencing factors of the compound transition of clean heating under the carbon neutrality goal. The core research examples on the influencing factors of the compound transition of clean heating are shown in Table 2.

The influencing factors in Table 2 are categorized into three types of factors: technical level, organizational level, and environmental level. The influencing factors at the technical level mainly affect the clean heating compound transition through technology utilization, including energy delivery and utilization, equipment and facilities renewal, etc., Influencing factors at the organizational level mainly have an impact on the heating transformation goals through the inter-organizational heating subjects cooperating with each other, including the evaluation and assessment system, clean heating costs and expenses, etc., Environmental-level influencing factors mainly rely on the environmental basis to influence the clean heating compound transition, including resource endowment status, air quality and atmospheric conditions, etc.,

In this paper, 20 experts were invited to finalize the influence factors by semi-structured interviews and questionnaires, and a questionnaire was set for the preliminary extracted influence

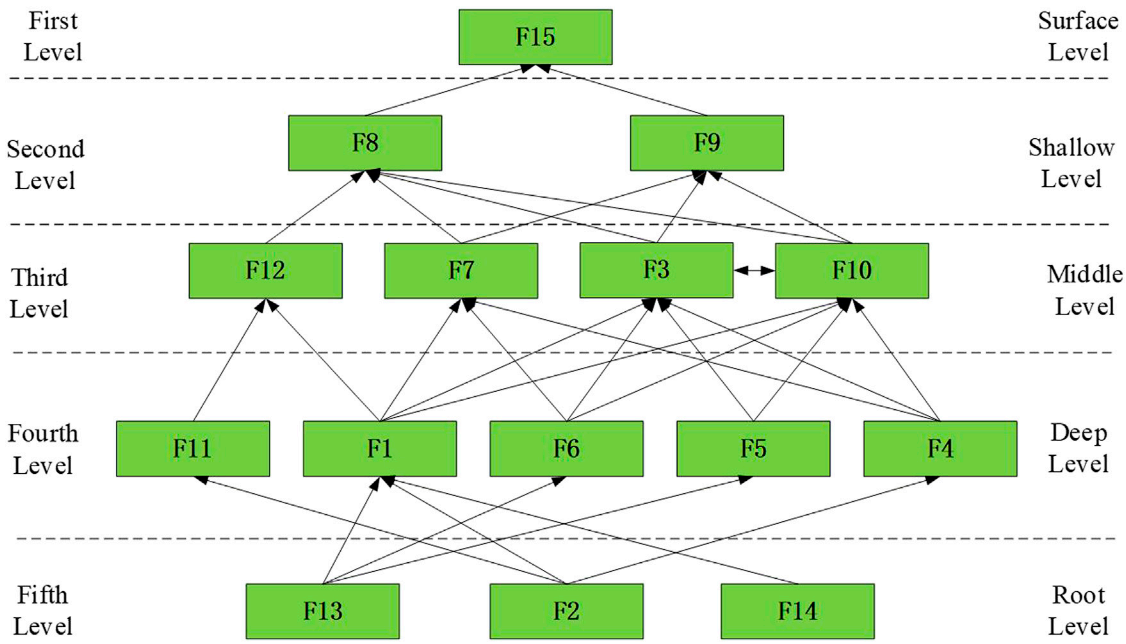

FIGURE 3
Recursive structural model of influencing factors.

factors. The options were set according to the degree of influence of clean heating transition, with 1 point for "almost no influence", 2 points for "little influence", 3 points for "medium influence", 4 points for "great influence, and "very large impact" scored 5 points. Open-ended questions were set at the end of the questionnaire to allow experts to adjust and evaluate the influencing factors.

After the survey, the full score, mean value and dispersion coefficient of each influence factor were calculated and the results were selected. Only when any one of the two scores, full rate and mean score, is higher than the threshold and the dispersion coefficient score is lower than the threshold, can the influencing factors of clean heating transition be selected. Lower dispersion coefficients indicate that the experts' scores are closer and indicate that the means are more representative. In this paper, the influence factors were selected according to the principle of "mean value not less than 3". From the results of the experts' scores, the average value of experts' scores for each factor is greater than 3.7, which indicates that the average score of experts is close to the "strong influence" set by the questionnaire; the dispersion coefficient of each influence factor is less than 0.3, which indicates that the average value is representative. The scores of relevant indexes for the influencing factors of clean heating compound transition are shown in Table 3.

The perfect score, mean and dispersion coefficients of the 15 factors initially screened met the requirements and could be included as valid factors. This paper provides further refinement of the influencing factors based on textual information from the semi-structured interviews, and open-ended questions at the end of the questionnaire, and further refinement of the influencing factors: the "international joint governance" is adjusted to "experience of clean heating abroad". The final 15 influencing factors established are uniformly represented by a capital F plus a number, as shown in Figure 1.

4.2 Causality and hierarchy analysis

According to the 15 influencing factors of the compound transition of clean heating under the carbon neutral goal, the internal relationship between the influencing factors is determined with the help of the expert interview method, and the expert scoring data are transformed into triangular fuzzy numbers. The direct influence matrix Z is obtained by defuzzification according to Step 3, and the standardized direct influence matrix M is obtained according to Eq. 7 in Step 4 (the direct influence matrix and the standardized direct influence matrix have been omitted due to space limitation). The integrated influence matrix T is also obtained based on Eq. 8, as shown in Table 4.

In order to conduct an in-depth analysis of the integrated influence matrix, the influence degree, influenced degree, centrality degree and cause degree were calculated based on Step 5, as shown in Table 5. And the causality diagram is made according to the cause degree and centrality degree, as shown in Figure 2.

1) From the degree of influence in Table 5, energy delivery and utilization (F1), clean heating technology innovation (F2), and environmental and clean heating policies (F13) have the highest degree of influence. It shows that these three influencing factors have the largest combined influence value on all other influencing factors and can link other factors together to promote the compound transition to clean heating. Therefore, the results show that in order to achieve the goal of compound transformation of clean heating, it is necessary to improve the related policies of clean heating and ensure the implementation of policies, strengthen technological innovation in energy utilization, and apply cutting-edge technologies to the energy field.
2) From the centrality of the horizontal axis of Figure 2, the centrality of the factors of energy delivery and utilization (F1), heating system operation and maintenance management (F3), and clean heating costs and expenses (F10) are larger.

It shows that the way of F1, F3 and F10 are the key influencing factors of the clean heating compound transition influence factor system, and should be given focused attention in the process of exploring the impact path of clean heating. The centrality of experience of clean heating abroad (F11), resource endowment status (F14), and heating subsidy funds (F5) is relatively low among all influencing factors, and the attention can be reduced appropriately in the process of exploring the influence path of clean heating transition. 3) In terms of the degree of cause on the vertical axis of Figure 2, there are 8 causal factors and 7 resulting factors among the overall 15 influencing factors. A positive value of the causality degree indicates that the factor is a causal factor and has a strong influence on other factors, and a negative value of the causality degree indicates that the factor is the resulting factor and is strongly influenced by other factors. This paper further constructs an explanatory structural model (ISM) of the compound transition of clean heating to explore the influence mechanism between the causal and resulting factors, and reveals the influence transmission path of key influencing factors on the compound transition of clean heating. According to Eqs 12–15 and the principle of hierarchical division, the recursive structural model of the influencing factors of the carbon neutral goal clean heating compound transition is obtained with the help of Matlab 2018a software, as shown in Figure 3.

The influencing factors of the compound transition to clean heating under the carbon neutrality goal can be divided into five tiers, and this paper divides the influencing factors in a bottom-up order. The influences from the fifth to the first level are the root level influences, the deep level influences, the middle level influences, the shallow level influences, and the surface level influences. Environmental and clean heating policies (F13), clean heating technology innovation (F2) and resource endowment status (F14) are located in the fifth level, which is the most far-reaching factor and most likely to influence other factors in the compound clean heating transition. Energy saving goals (F8), economic benefits (F8), and environmental benefits (F9) are located in the first (surface) level and second (shallow) level and are the most directly influential factors in the transition to a clean heating complex. Influencing factors in surface level and shallow level can be measured by evaluating indicators to measure the trend of change, thus enabling the study of the implementation of the compound transition to clean heating. The factors in the third and fourth levels are middle levels with 9 influencing factors. The factors in the middle level have a dependent effect on the factors in the root level and a facilitating effect on the factors in the surface and shallow levels, so the factors in the root level can regulate the factors in the middle levels and at the same time can transfer the influencing effect to the shallow and surface factors. In addition to the bottom-up hierarchical relationship, the two influencing factors of F3 and F10 are at the same level indicating a mutual influence relationship. On the one hand, the construction of heat sources for the heating system, the construction of infrastructure and the energy-saving renovation of the heating system are inseparable from the cost. On the other hand, heat companies manage the operation and maintenance of heating systems to optimize system status and equipment performance, reducing heating system operating costs in the process of improving the efficiency of clean heating systems.

5 Conclusion and enlightenment

5.1 Research conclusion

Based on the clarification of the connotation, direction, and objectives of the compound transformation, this paper uses statistical methods based on the literature analysis, semi-structured interviews and questionnaires to initially identify 15 influencing factors of the compound transformation of clean heating, and analyzes the importance, causality and hierarchical links among the influencing factors based on the Fuzzy-DEMATEL-ISM combination method.

1) In terms of the centrality of each influencing factor, energy delivery and utilization (F1) is the most important factor in the system of influencing factors for the compound transition of clean heating. The study of the innovation of various forms of energy compound realization and utilization, as well as the study of scenarios of different energy sources in multiple heating methods can strongly promote the compound transition.
2) In terms of the degree of causes of the influencing factors, half of the factors affecting heating transition are causes and half of the factors of results. The key causal factors are energy delivery and utilization (F1), clean heating technology innovation (F2), and environmental and clean heating policies (F13). The policy can provide a solid guarantee role for the achievement of the carbon neutrality goal and the compound transition of clean heating, and technological innovation provides continuous power support for the

compound transition of clean heating. A single centralized or single decentralized form of heat source delivery is not the best way to solve the heat source delivery problem at present, and the implementation of the compound of centralized, decentralized and distributed clean heating by local conditions is an important means to promote the transformation and upgrading of clean heating.

3) From the viewpoint of the hierarchical relationship of the influencing factors of clean heating compound transition, the influencing factors can be divided into five levels, the more upper-level influencing factors have a faster direct impact on the clean heating compound transition, and the adjustment of the surface-level influencing factors can have an immediate effect on the clean heating compound transition The lower the influencing factors, the slower the transition to clean heating, so governments and companies should focus on the root causes and regulate these factors to achieve long-term development of efficient heating.

5.2 Research enlightenment

The research in this paper brings the following 3 insights.

1) The government should play the function of "guarantee and promotion". On the one hand, governments at all levels should control the drivers of clean heating transformation as a whole, guide the development of the clean heating industry and regulate the system of the clean heating industry. Grasp the "fundamentals" that affect the compound transition of clean heating, focus on technological innovation of compound heating, implement guiding policies for the transition of clean heating in conjunction with local resource endowments, and ensure the rapid advancement of the compound transition of clean heating under the goal of carbon neutrality. On the other hand, local governments should explore compound models suitable for local heating conditions, develop subsidy mechanisms for enterprises and users, and establish a coordinated system for promoting regional work on clean heating according to the actual local situation.
2) Companies need to pay attention to key elements of heating systems and put into practice the construction of clean heating compound heating systems under the carbon neutrality goal. First, heating companies should strengthen the training of professional and technical staff to apply the leading international compound heating technologies to the heating field. Secondly, heating enterprises need to evaluate in the field, under the guidance of the government, clean heating energy sources that can be utilized on a large scale and their compound methods, and take into account the unity of economic, social and environmental benefits in the development and application of compound heating systems. Again, heating companies need to manage the operation and maintenance of the pipe network and equipment in the heating system to optimize the state of the heating system and the performance of the equipment. Finally, based on ensuring that northern heating users stay warm through the winter, heating companies need to gradually promote the compound transformation of clean heating towards carbon neutral goals.
3) Residents should participate in and monitor the whole process of the clean heating transition. The effective operation of the compound heating system requires regular collection and integration of the needs and feedback of heating users. The whole process work of the selection, planning, construction, post-operation, and maintenance of the clean heating compound method needs to be monitored and evaluated by users. Therefore, promoting energy saving and emission reduction by means of clean heating compound transformation is a complex and systematic project that requires the coordination and cooperation of government, enterprises and users to ensure the effective operation of the compound heating system composed of clean heating technology, clean energy and advanced heating equipment and other elements.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

Funding

This research was supported by the National Social Science Foundation of China; the grant number is 19BJY099.

Acknowledgments

The researchers would like to express their gratitude to the anonymous reviewers for their efforts to improve the quality of this paper.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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