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Recent advances in decarbonising heating in rural China: A review

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ABSTRACT

Space heating in rural China is dominated by solid fuels, with high levels of associated carbon emissions. Despite government efforts to shift from traditional biomass to modern energy systems, progress remains modest. To assess the current advancements in this field and identify remaining obstacles, this study systematically and comprehensively reviews 178 sources published during a recent five-year period on rural household space heating in China. Guided by an assessment framework triangulating governance, technology, and equity, this review highlights a wide array of technical solutions in the field of low-carbon energy, which, nevertheless, remain disconnected from the social and equity realities. Extant approaches are dominated by technological modelling and top-down 'one-size-fits-all' solutionism, while the real-world application of technology, users' experiences, socioeconomic considerations, and local contexts are largely neglected, impeding the transition to low-carbon heating and raising the inequality of energy poverty. These findings speak for the importance of integrating social and spatial aspects in future research and reemphasizing households and communities in energy transitions towards the United Nations Sustainable Development Goals, especially Affordable and Clean Energy (SDG7).

Abbreviations

kWh	kilowatt hour
CO_2	Carbon Dioxide
ASHP	Air Source Heat Pump
GSHP	Ground Source Heat Pump
CNY	Chinese Yuan Renminbi

1. Introduction

As one of the world's largest energy consumers and carbon emitters, China has committed itself to reducing carbon emissions by 60–65 % per unit of Gross Domestic Product in 2030, compared to 2005 [1]. One element of this colossal task is reducing carbon emissions in the residential sector, which ranks second in emissions in China [2] and significantly impacts the quality of life [3].

In the residential sector, the rural dimension plays a vital role. Although rural areas have smaller total energy consumption and carbon emission footprint than urban areas, they nevertheless have comparable per capita energy consumption and even higher per capita carbon emissions [3–6]. Moreover, the rural residential sector shows a higher annual rate of growth of carbon emissions (4.8 %) [5,7] due to its energy use patterns. In China, energy sources are classified as commercial and non-commercial. Commercial energy sources include coal, gasoline, diesel, liquefied petroleum gas and electricity, while non-commercial sources mainly consist of straw, firewood, animal dung, biogas and solar energy. Rural energy is dominated by non-commercial energy sources - traditional biomass (especially firewood) and coal, despite a significant increase in commercial energy consumption during the past thirty years [8–11]. Of total commercial energy consumption, electricity uptake continues to growth in rural households (31.5 % in 2016) [12], with average annual electricity consumption increasing from around 1200 kWh per household in 2016 to approximately 1500 kWh per household in 2020 [13]. However, most rural households consume less than 1000 kWh annually [14], which barely meets their basic electricity demand, estimated at about 1600 kWh per household [15].

Space heating, the second most energy-intensive demand, accounts for about 40 % of the total energy consumption in China and 44 % of primary energy usage in the rural sector, being heavily dominated by solid fuel combustion [16]. There are yet noticeable differences between the Northern and Southern parts of the country. For instance, the

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average energy consumption in Northern China is 1311 kg of standard coal [17], per household, which is 37 % more than that in Southern China (958 kg of standard coal per household), and its annual energy consumption per square meter is twice as much as in Southern China [10,16]. To achieve the nation's goal of carbon neutrality, it is imperative to shift rural household heating from traditional energy sources towards cleaner fuels and improve its efficiency, which could affect 22.7 billion m^2 of building space in rural areas [18] and bring intangible health benefits to over 510 million people, such as reducing dementia risks [19,20] and respiratory infections [21,22] by minimizing air pollution and prolonged exposure to cold temperatures.

The Chinese government has issued a series of policies and launched demonstration projects nationwide (e.g., 'Coal-to-Gas' and 'Warm-house Project'), targeting updating heating fuels and improving rural houses [23–26]. Much research has been conducted to buttress these political activities, such as developing heating techniques, evaluating rural households' willingness to engage with clean heating, and providing technical guidance on how to achieve improved thermal performance in housing construction and renovation [27–31]. However, the progress on the ground remains much slower than expected [3,6,32–35], which questions on impediments to this transition to low-carbon heating.

Despite the critical need of clarity on this issue, there are no studies that would examine the cutting-edge solutions for decarbonizing rural residential heating across political, architectural, and engineering domains, particularly related to the realities of implementing these solutions on the ground. Current reviews (e.g. Refs. [36,37], and [38]) are not comprehensive enough to address this need or focus on other sectors, such as low-carbon cities, industries and nationwide energy structure [39], decarbonizing residential cooking [40], and upgrading district heating systems with renewable energy and waste fuels [41]. Therefore, this study comprehensively assesses, analyses, and synthesizes the state-of-the-art literature providing solutions for decarbonizing household heating in rural China. Through bibliometric, thematic, and content analyses, it aims to answer this question: What are key solutions for decarbonizing household heating in rural China and why do they still have limited impact in practice? Addressing this question, this study identifies research trends and gaps and highlights horizons for future research. Meanwhile, it contributes towards the UN Sustainable Development Goals, especially Affordable and Clean Energy (SDG7), by not only advancing this low-carbon transition in rural China but also offering a distinctive reference for other developing countries that undergo energy transition and face challenges in enhancing the climate change resilience of rural regions.

This study is informed by the framework introduced by Golubchikov and Deda [42], which proposes an integrated approach to low-carbon energy transitions, centred on the triad of governance, technology, and equity. In this framework, governance denotes institutional, policy, and fiscal measures for improving the energy and carbon performance of housing; technology denotes the development and deployment of technological innovation and existing technical solutions; equity contains the important attention to the multiple social aspects of transition such as affordability, social vulnerabilities, cultural awareness, and participation. It is argued that only by a well-balanced and integrated approach, coordinating these three pillars, more sustainable and just pathways for transition emerge [43,44]. Through this review, this study assesses these three dimensions and explores whether recent studies demonstrate sufficient development and balance across these dimensions.

This study is structured as follows. Section 2 explains the methodology employed for identifying different types of solutions for heating improvements and shows results from bibliometric and thematic analyses. This is followed by the sections outlining the results of a critical content analysis of recent studies on implementing and assessing heating techniques (Section 3.1), passive heating strategies (Section 3.2), and the Clean Heating program and its related projects (Section 3.3). Section 4 discusses opportunities and challenges for future research on this topic and concludes by summarizing key findings and addressing limitations.

One key conclusion from this study is that the literature is dominated by technological modelling and top-down technocratic solutionism, while the real-world application of technology, users' experiences, social considerations (such as acceptability, affordability, vulnerability, justice) and local contexts remain largely neglected. This conflicts with the realities where households in rural China are among the poorest and most vulnerable strata of the population, lacking the capacities, resources, and skills required to adopt clean technological solutions. Despite a great variety of technical ideas that are available to decarbonise heating, those solutions are still disconnected from their feasibility and implications on the ground. These findings stress the importance of intensified research into equity and affordable aspects of energy transitions and the imperative of empowering households and communities in these transitions.

2. Methodology

This study adopts a systematic review approach that contributes to the identification and critical appraisals of relevant research with minimized bias [45]. Articles retrieved were collected from Scopus and Web of Science and were mainly published within the five years between January 2018 and April 2023, aiming to reflect the latest technical advancements, research trends, and policy discourse regarding solutions for improving rural household space heating. Fig. 1 highlights keywords used in this search, including: 'rural', 'China', 'energy', and 'heating', since they are descriptive and relevant for a collective understanding of the topic. The collected publications include journal articles, proceeding papers, and reviews, but exclude books due to resource constraints.

This initial keyword search yielded almost 700 papers (Fig. 1), out of which 460 articles were retained after removing duplicates. An initial review of titles, abstracts, and keywords of these articles was then conducted to filter the most relevant articles. The criteria used for exclusion during the initial review are listed below.

- Other disciplines (n = 173), such as Health, Agriculture, Environmental chemicals, Heat islands, Resource Assets, and Industrial Centralization.
- Other research contexts (n = 27), such as other countries or urban China.
- Other building types (n = 4), such as office buildings, schools, and greenhouses.
- Other residential activities (n = 11), such as cooking, cooling, and lighting.
- Emission topics in general (n = 18), such as carbon neutrality, black carbon emission, carbon footprint, spatial-temporal variation of carbon emissions, and historic development.
- Energy consumption topics in general (n = 29), such as historic development, characteristics and influencing factors, spatial variation of energy consumption, regional disparities, and energy mix.
- Review articles that do not align with the research goal of identifying and analysing primary research studies to generate new empirical data (n = 7).
- Studies on rural residents' thermal comfort only (n = 4).
- Articles with no access (n = 9).

The remaining publications concerning solutions for improving rural household space heating in China were 178 in total. They were retained for the bibliometric, thematic, and content analyses.

After selecting all relevant articles (n = 178), a bibliometric analysis was undertaken to reveal trends. Firstly, all articles were grouped and counted by the year of publication. As shown in Fig. 2, there is a growing interest in investigating solutions for improving household space heating in rural China, with an average of 32 articles published per year from 2018 to 2022 in this area.

Secondly, all articles were grouped and counted by the source title

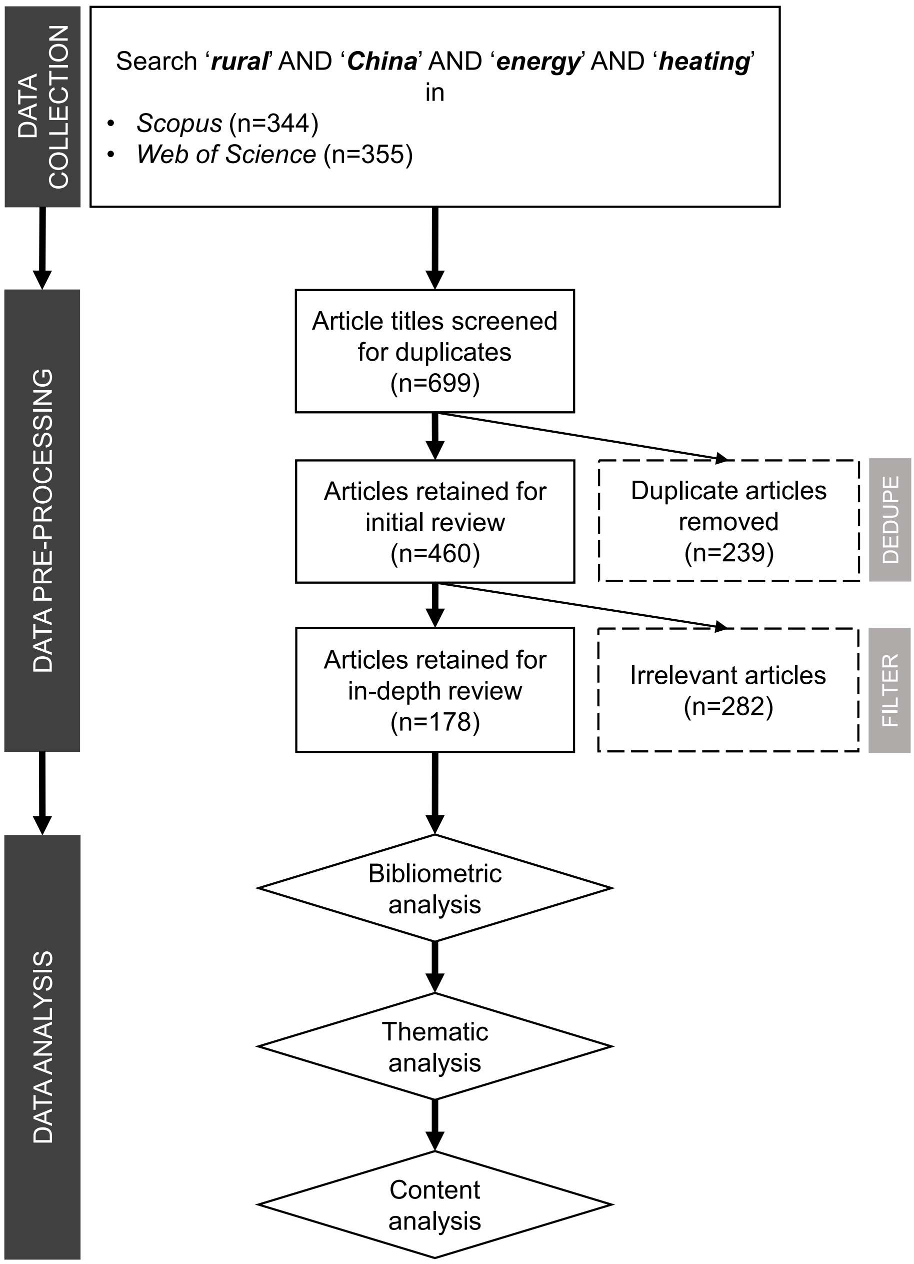

Fig. 1. Methodology framework.

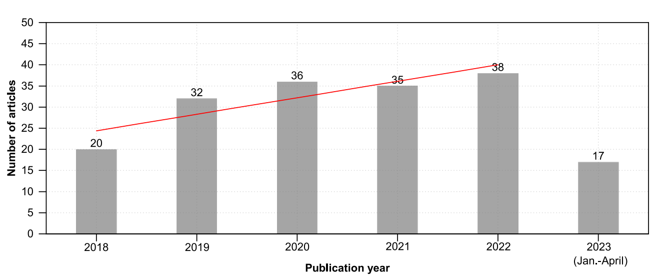

Fig. 2. Number of publications over time.

and arranged in rank order based on the total number of articles (Fig. 3) in an attempt to identify the main themes for analysis. Noteworthy, Fig. 3 shows that publications come mostly from journals focusing on engineering, energy, and interdisciplinary fields, including those that cover social sciences (e.g., Energy Policy and Energy Economics), but not many publications are published in other social science journals.

Following the bibliometric analysis, a thematic analysis was undertaken based on the articles' full texts (n = 178) to extract the main topics discussed in each article. Three main themes regarding solutions for improving rural household space heating were identified (Table 1 and Fig. 4).

Fig. 4 illustrates a persistent and strong research interest in heating techniques with an average of 16 articles per year, around half of the total number of articles published annually. Articles related to the Clean Heating program and passive heating strategies started drawing more attention from 2019, with an average of 8 articles published per year in these areas.

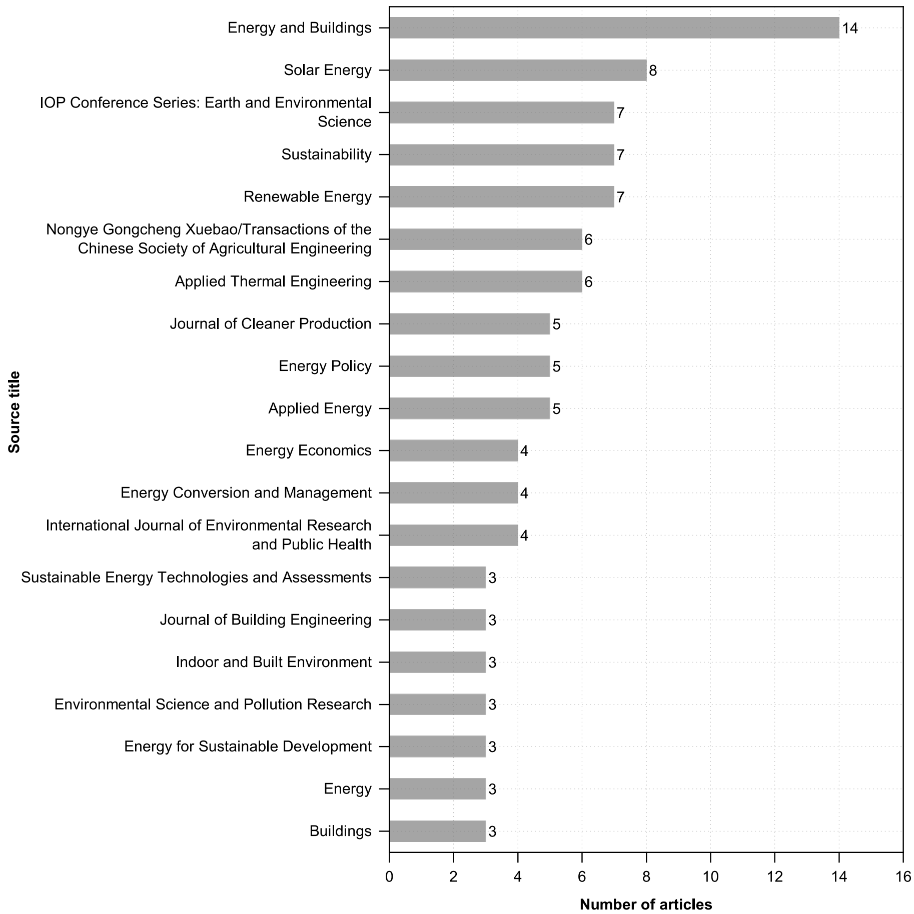

Fig. 3. Number of articles by source titles with three or more counts.

Table 1
Three themes and corresponding sub-themes for decarbonising household heating in rural China.

	Themes	Sub-themes
1	Heating techniques	Technical feasibility of renewable heating systems and their combination with other systems; improving household stoves and processed fuels; increasing efficiency of traditional heating methods; and performance evaluation of different heating systems.
2	Passive heating strategies	Technical feasibility of passive heating strategies, mainly building envelope and solar strategies; and economic analysis of passive heating strategies.
3	Policy interventions: the Clean Heating program and related projects	Environmental benefits versus affordability; rural household acceptance of the program; adjustment to subsidies; and locally tailored implementation strategies.

3. Results and discussions

3.1. Heating techniques

Literature regarding heating techniques mainly focuses on utilizing renewable energy systems for heating, improving household stoves with processed fuels, optimizing Kangs, and evaluating different heating techniques with advanced assessment tools. Various heating systems were mainly developed and optimized through laboratory experiments or simulations.

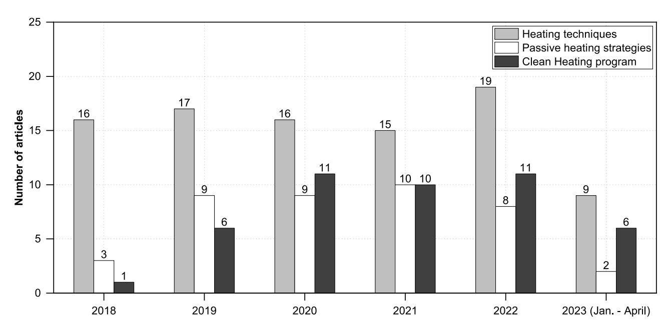

Fig. 4. Number of articles on each theme over time.

3.1.1. *Renewable systems*

The main research interest (84 out of 92 articles) lies in developing renewable heating systems or integrating renewable energy with conventional heating devices. By counting the number of articles investigating different renewable energy resources, it is found that solar energy is the most frequently renewable system discussed, often in combination with air heat (10 mentions), biomass (8 mentions) or used alone (8 mentions), while wind power is the least investigated renewable system with only one mention [46], (Fig. 5).

3.1.1.1. Solar heating systems. Utilizing solar energy for heating has large environmental benefits and is cost-effective, but solar heating systems usually have limitations in providing a stable heating performance due to fluctuating solar radiation availability, varying from

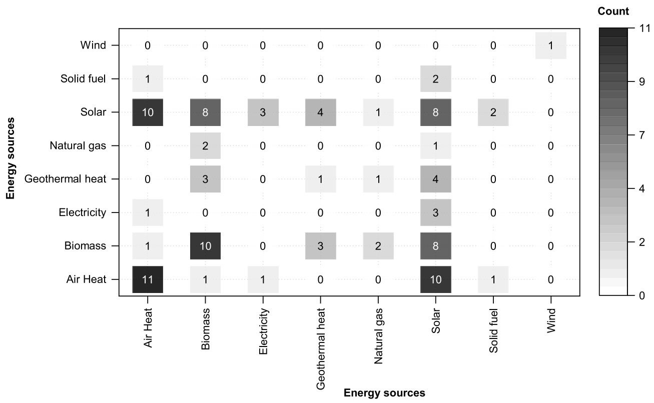

Fig. 5. Pairwise comparison of different renewable energy resources investigated in the relevant literature.

region to region and with different times and seasons [47,48].

For a stable heating performance, it is proposed to combine solar heating systems with heat storage, such as phase change energy storage [48–52] and seasonal thermal energy storage [53,54]. From experiments and in-situ measurements, this combination increases the heating capacity of solar heating systems, delivers continuous heating throughout the day, improves occupants' thermal comfort, and reduces operating costs. For example, compared to electric boilers, solar heating systems could reduce annual operating costs by nearly 50 % when integrated with phase change energy storage [49] and by around 73 % when combined with seasonal thermal energy storage [54]. Apart from the utilization of heat storage, adjusting the time interval of the water supply is found to be effective in increasing the solar fraction, decreasing heat loss rates, and reducing energy consumption of underfloor heating systems [55], meaning it is worth investing in the fine tuning of these combined systems.

Research was also conducted to integrate solar energy with other heating systems, including electric heating systems [51,56], coal stoves [57], combined heat and power systems [58,59], CO_2 heat pumps [52], biogas heating systems [60], and especially Air Source Heat Pumps (ASHPs) [61–66]. The integration of solar energy with electric heating systems, for example, can significantly reduce carbon emissions by approximately 13–27 tons [51]. It brings notable economic benefits by reducing life cycle costs to 38 %, for instance, when integrated with biogas [60]. It also lowers operating costs to nearly 8000 CNY during the heating season when, for instance, integrated with ASHPs [64].

Utilizing solar energy for heating has many advantages, but these benefits cannot be guaranteed without rural households' acceptance and adoption. Although there is a case study [61] claiming that most rural households are satisfied with the on-site performance of photovoltaic coupled with ASHPs and wish for more application of this system, it is unknown whether this is still valid when rural residents have to pay for this system themselves without any government subsidies. Moreover, there is no research into how much rural households can afford or are willing to pay for solar heating systems which are normally sophisticated and expensive. Although studies [49,50,56,57,62,67] show systems in operation, little knowledge is provided regarding the installation and maintenance of these systems in rural contexts either at the household level or at the neighbourhood level. For example, installing a solar water heating system to be shared between two neighbours seems to be a solution for reducing heating installation costs and increasing market penetration [68] but is sharing acceptable in rural communities? Are the proposed methods easy to deploy in rural communities so they can be installed or repaired by rural residents themselves? Do rural households encounter any difficulty in operating the system? These questions are not addressed by extant literature on the subject.

3.1.1.2. Biomass heating systems. Utilizing biomass energy for heating is also highly discussed. Biomass energy is an abundant and affordable energy resource in vast rural areas and is widely and traditionally used for space heating and cooking, but, as a renewable source, it has been undervalued. For example, straw, being regarded as agricultural waste, is often ignited in the farmland, which results in severe air pollution [69,70]. To effectively use this cheap energy for heating, the following techniques are suggested, including energy conversion systems that turn straw, solid waste and other rural biomass resources into power, heat and gas via, for instance, pyrolysis or waste gasification [71], biomass direct combustion systems [72], straw combustion boilers [73,74], and biomass pyrolytic poly-generation technology [75].

Biomass energy in combination with solar energy could improve household heating thermal performance, reduce carbon emissions, and bring economic benefits. Examples include a plant-scale solar-biogas system that utilizes manure waste [76] and solar-biomass systems offering diverse cost benefits, such as lowered life cycle costs [77], reduced operating costs (by 65 % compared to the traditional coal-fired boilers) [78], reductions in capital and operational costs of approximately 12 % [79], and a short static payback period of 3.1 years [80]. Biomass energy is also integrated with heat pumps, including ASHPs [81,82] and Ground Source Heat Pumps (GSHPs) [83], and multi-energy complementary systems [84,85] to improve heating efficiency, increase energy savings, and boost renewable energy usage.

To facilitate the deployment of biomass energy in rural heating, some studies compared the investment and annual heating costs of using different straw heating techniques either decentralised (in each household) or centralised at the village level. Small villages with less than 200 households, or villages with scattered households having pipeline network distances over 27m per household, are suitable for decentralised systems, such as individual household heating with straw-densified solid fuel or pyrolytic carbon with an average cost of 2368 CNY per household [86]. This expenditure sounds attractive, as it fits within 12 % of the disposable income per capita of rural residents [87], but no statistics are available to show if rural households would be willing to commit 12 % of their income to this type of heating technique. It is also unclear whether rural families would have the intention and/or incentive to invest in these proposed heating techniques rather than directly burning straw.

Although processed biomass fuel has less carbon emissions and higher thermal efficiency, its price in the trading market is relatively high for rural families to afford. Therefore, a distributed heating/centralized trading mode was proposed by Ref. [88], through a bidirectional Customer-to-Supplier relationship between the energy service station and rural households to significantly lower the commercial price of processed biomass briquette fuel. Additionally, a barter mode for straw pellets was developed by Ref. [89], to make straw fuel more affordable for low-income families and has been successfully applied in a pilot project. This is a research area to be pursued, from assessing and increasing the affordability of processed fuels to coupling them with different types of trading systems.

3.1.1.3. Heat pumps. Heat pumps refer to systems that extract heat from sustainable sources, including air, water, the ground and wasted heat, for space heating purposes [38]. Of different heat pump technologies, ASHPs are the most discussed, followed by GSHPs, and other air heat pumps using traditional refrigerants or CO_2 as the refrigerant.

ASHPs have been promoted in rural China by the Chinese government in recent years to displace solid fuel heating in rural families. This is related to its advantages in flexibility, simple installation, compact design, and affordable upfront cost, compared to other types of heat pumps [90]. Simulations show that ASHPs save more energy, reduce carbon emissions, and cost less during the heating operation than traditional coal heating methods and electric heating methods [91,92]. However, they have several technical issues, including limited heating capacity, risk of frosting, and low coefficient of performance [93]. To tackle these issues, research has been conducted on developing new refrigerants for ASHPs [93], exploring the most appropriate water volume ratio [94], and identifying optimal control strategies for ASHPs considering not only technical parameters (e.g., relative humidity, indoor temperatures, and water temperatures) but also occupants' thermal comfort satisfaction [95].

GSHPs, which absorb heat from the ground, are considered to be more competitive than ASHPs in terms of seasonal coefficients of performance and operating costs throughout the heating period (November to March), varying from 532.4 CNY to 1388.9 CNY as per in-situ measurements [96]. These operating costs are claimed to be acceptable by most surveyed households in this study, but the sample size is very small with only 20 households in total. In addition, it is unknown whether the initial investment of GSHP is acceptable to rural households.

Both ASHPs and GSHPs are often integrated with solar energy generation, leading to the development of various hybrid systems, such as the PV/T-air dual-source heat pump system based on a three-fluid heat exchanger [29], large flat plate solar collectors coupled ASHP systems [63,64], solar-assisted vapour injection heat pumps [66], an ASHP assisted solar evacuated tube water heater [65], a split-type GSHP with solar photovoltaic-thermal modules [97], a photovoltaic/thermally assisted GSHP [98], solar-assisted GSHPs [99,100]. Moreover, ASHPs and GSHPs could effectively assist other energy systems [101–103]. For example, combining GSHP with anaerobic digesters could not only reduce soil thermal imbalance but also contribute to efficient biogas production during winter and transition seasons [103].

In addition, there are few studies analysing other types of air heat pumps, including air-to-water heat pumps [104] and air-to-air heat pumps [105,106], and optimizing CO_2 heat pumps by integrating them with solar heat pumps [52] and thermal energy storage systems [90, 107]. Besides, agricultural needs are also part of the agenda when promoting these types of technologies, such as cooling spaces for storing grain, fruits, and vegetables through an integrated system based on heat pumps [108]. Further studies on this topic can be found in research related to agriculture but are beyond the scope of this study.

Research into heat pumps shows technical advances but with experimental results rather than with field measurements in rural households' operations. Whole-house heating and continuous heating are not necessarily part of rural households' lifestyles [96,109]. Households tend to intermittently heat their houses [96], which turns out to be an optimal control strategy for ASHPs, meeting rural residents' thermal demand with minimal energy consumption [95]. More information on real-world operation is needed as residents may not operate heat pumps as instructed, leading to unexpected performance gaps.

3.1.1.4. Summary of renewable heating systems. Overall, studies on renewable heating systems are mainly system-centred, rather than focus on users' experiences. Few studies show rural residents' perception and operation of these systems, despite a group of studies, especially those on biomass heating systems, investigating coupling with renewables, cost and deployment to improve accessibility and affordability to rural communities. Most rural residents show a preference for using ASHPs [110], but it is unknown whether ASHPs are still favoured when compared to other types of heat pumps, such as GSHPs.

Insufficient knowledge of how rural households operate these systems also raises questions about their operation. Do these systems satisfy rural residents' flexible heating needs during winter? Since rural households do show adaptive behaviours, such as adjusting clothes and actively engaging in heating control, these behaviours influence the design of heating control systems and affect the choice of heating systems. For example, are high-tech heating systems needed/appropriate for rural residents and rural homes? It is important to acknowledge adaptive behaviours during the heating operation and to understand the reasons behind these behaviours. Are adaptive behaviours motived by the intention to save operating costs [67] or influenced by outdoor temperature fluctuations [106]?

Furthermore, research into renewable heating techniques often focuses on the system itself with less consideration for different types of living spaces and the activities happening in them, which might be different in rural homes. However, incorporating an architectural perspective into developing different heating systems to meet rural residents' flexible heating needs is highly relevant. The importance is not only reflected by rural residents' varied thermal demands in different living spaces [109] but also shown by their spontaneous measures to reduce heating demand during winter, such as integrating some room functions into one space to avoid any 'unnecessary' heating energy consumption or reducing heating hours during winter [111].

3.1.2. Improved household stoves and processed fuels

Optimizing traditional household stoves is considered both an affordable and environmentally friendly way to improve rural household heating conditions. Laboratory tests demonstrated that improved stoves with processed fuels, such as bituminous coal pellet stoves [112, 113], semi-coke burning stoves [114], and methanol burning stoves [115], are effective in reducing $PM_{2.5}$, CO, CO_2, SO_2 emissions, compared with traditional stoves using raw coal. However, the performance of these stoves in real-world operation is questionable compared to laboratory results. For example, the operation of semi-coke burning stoves on-site could increase CO, CO_2, and NOx emissions [116], and using biomass pellet stoves could increase $PM_{2.5}$ and NO_X emissions [117] much more than what was indicated by laboratory results [118].

Aside from studies that focus on stoves, research was also conducted exploring affordable fuels for household stoves, such as waste oils. The combustion of waste oils, especially waste cooking oil, in laboratory tests shows higher thermal efficiency and lower pollutant emissions and can be much cheaper than using natural gas, electricity, or biodiesel [119,120]. Waste oils seem to be a promising solution to reduce solid fuel consumption and emissions, but it is unknown whether they are accessible to rural residents or not, and little knowledge is there about their real-world applications.

3.1.3. New Kangs

Traditional Kangs (an easy and cheap-to-build bed heating system with a history of over 2500 years) are widely used by rural households in Northern China for heating during winter. Traditional Kangs heat the space by gradually releasing the high-temperature smoke heat kept in the Kang body from solid fuel combustion [121,122]. However, they have low efficiency, a short period of effective heating and several problems that include uneven surface temperature, high heat losses in combustion, and high discharge of flue gas.

Therefore, different novel Kangs are proposed. For example, the Burning Cave-Pipe Coil-Kang [123], energy-saving elevated Kang [124], Kang with phase change materials [125], and combinations of Kangs with other heating systems, including the flue composite walls [126], floor heating systems [127–129], and radiator heating systems [130]. Besides, Kangs are under exploration to integrate with renewable energy resources, such as bed-heating systems driven by ASHPs [122,131,132] and solar energy technologies [133,134]. Besides, there are studies exploring heating devices that heat space similarly to Kangs, for example, fire wall heating systems that store waste heat from the household cooking activity inside a wall and release this heat gradually to the indoor space [135,136], and floor heating systems integrated with a double-pipe phase change materials [137].

Although new Kangs have a higher technical performance, there is little evidence about how acceptable these Kangs are to rural households, especially considering Kangs are part of the traditional rural lifestyle. Do rural residents still prefer to use Kangs at present? Even if Kangs were preferred, there is no information about users' willingness to pay for new Kangs or issues related to refurbishing old ones. More research is needed to investigate the feasibility of Kangs in modern rural homes.

3.1.4. Performance evaluation of different heating techniques

Apart from developing and optimizing renewable and conventional heating systems, research has also been undertaken regarding the performance evaluation of different heating techniques. Not only were these techniques compared in terms of their technical, environmental, and economic benefits, such as weighted environmental impacts and life cycle costs [138], but also different assessment methods for multi-objective evaluation were proposed to select optimal heating systems for rural households. Examples include a PMV-PPD indexed system for evaluating ASHPs, solar heating, gas furnace and electric heating systems [139], an evaluation system combining Analytic Hierarchy Process with Fuzzy Comprehensive Evaluation methods for various heating systems [140], and a comprehensive evaluation index system combining a novel integral weight method with extended multi-objective optimization for selecting renewable heating systems [141].

Although articles regarding performance evaluation play a vital role in systematically assisting decision-making processes through quantifiable benefits, they appear far less in the literature compared to articles related to the development and optimization of heating techniques. Furthermore, with the exception of [141], performance evaluation tends to happen out of context, normally in ideal environments (e.g., laboratories or controlled conditions) rather than in-situ, making it difficult to assess quantifiable benefits in actual rural environments.

3.2. Passive heating strategies

Studies on passive heating strategies are mainly developed for rural houses located in the following three climate zones: Severe Cold zone, Cold zone, and Hot Summer and Cold Winter zone, as per the name in the Design standard for energy efficiency of rural residential buildings (GB50824-2013) [142]. Although rural housing typologies may differ from region to region, most houses are poor in insulation, cold during winter in Northern China, and hot during summer in Southern China [143]. Articles regarding passive heating strategies mainly focus on changes to the building envelope and the use of passive solar heating techniques, particularly sunspaces and Trombe walls. These approaches improve rural household heating conditions by reducing heat losses, increasing winter indoor temperatures by taking advantage of solar energy, and decreasing heating energy consumption and carbon emissions together with their associated costs.

3.2.1. Building envelope

Optimizing the building envelope, including roof, walls, doors and windows, is demonstrated to be the most important strategy to improve household heating efficiency, reducing heating energy consumption and carbon emissions [144–150].

Of all building envelope components, the performance of walls is widely investigated and shows the best results in improving indoor thermal environments at relatively low costs. Research on walls mainly includes developing different wall materials (e.g., KPI porous brick [151], bio-based material [152], phase change material integrated walls [153], seven types of conventionally-used wall blocks [154]), identifying optimal insulation thicknesses [155–157], and assessing their effects on heating demand reduction, economic and environmental benefits. Additionally, optimizing the north and south window-to-wall ratio can moderately reduce heating energy consumption. For example, increasing the south Window-to-Wall Ratio of rural houses located in the previously mentioned climatic zones could reduce energy consumption during winter, albeit to different extents, whereas increasing north Window-to-Wall Ratio could reduce energy consumption of rural houses located in Hot Summer and Cold Winter zone but increase energy consumption of houses located in Cold and Severe Cold zones [158–160].

However, unlike modern urban residential buildings, rural housing has a typical role in representing local cultural identity [161]. This means external wall insulation needs to be carefully assessed before installation as it can significantly affect the façade aesthetic depleting rural houses' cultural characteristics. Studies such as [162] showing Structural Insulated Panel wood walls as an envelope structure for traditional or vernacular wood houses are rare.

Although insulating the building envelope has many benefits, there are drawbacks regarding the implementation in retrofitting. For example, adding internal insulation to existing walls could reduce the building's indoor area [147], cause inconvenience to occupants during the renovation [147], and increase moisture leading to condensation, mould growth, and freeze-thaw damage [163]. Besides, studies do not report whether these proposed building envelope measures are accessible to rural residents and if rural builders are equipped with the relevant knowledge or received any training to implement them. Both are likely to discourage rural households' adoption of wall insulation, potentially compromising the feasibility of this approach.

3.2.2. Sunspaces and Trombe walls

From building simulations and field measurements, passive solar heating strategies, particularly sunspaces and Trombe walls that absorb solar radiation and heat the indoor air through convective heat transfer, contribute significantly to improving the winter indoor thermal environment, reducing heating energy consumption, and lowering heating costs. Therefore, sunspaces are regarded as a promising solution to alleviate energy poverty in underdeveloped rural areas (e.g., Qinghai-Tibet Plateau) [164,165].

Technically speaking, adding sunspaces performs better in heating rooms and saving energy than using double-glazed windows [166]. Sunspaces can be attached and aligned with building facades, placed on top of building roofs, or overlaying courtyards, but adding sunspaces on building façades and rooftops shows a better performance in reducing heating energy consumption and improving the indoor thermal environment [160,167,168].

To maximise the performance of sunspaces, as well as Trombe walls, optimization studies have focused on identifying optimal parameters for a solar house [169], adding vents to facilitate convective heat transfer between sunspaces and adjacent indoor spaces [170], selecting proper glazing units for sunspace construction [171], integrating phase change material in louvres with sunspaces [172], integrating Trombe walls with Venetian blinds and a basement to lessen indoor temperature fluctuations [173], and identifying key factors influencing the performance of Trombe walls, such as south Trombe wall-to-wall ratio vs. glazing slope angles [174].

The beneficial effects of passive solar heating strategies could be further boosted by combining them with other measures, such as applying proper window materials [175], combing with exterior envelope insulation [157], equipping them with heating systems [165,176], and integrating them with heat storage materials [177]. Although sunspaces are good for improving household heating, they may cause overheating during summer if without proper ventilation, raising health and safety issues, such as soot poisoning and allergic rhinitis, especially in rural homes with coal stove heating [171,178].

Besides, there are studies investigating the application of passive solar heating strategies based on rural occupants' perspectives, such as rural residents' differentiated indoor thermal comfort demands [179] and influencing factors behind the adoption of solar houses. The latter unfolded that rural residents' perceived value is a key factor influencing owners' attitude and willingness to adopt solar houses [180]. Studies of this type are important to assess the adoption and promotion of passive solar heating strategies, but few of them appear in the literature in comparison with studies focusing on technical optimization.

3.2.3. Economic analysis of passive heating strategies

Studies regarding the economic analysis of passive heating strategies mainly focus on initial and lifecycle costs with payback periods, such as construction costs of a new energy-efficient house for single families [181], construction costs of adding sunspaces and their respective paybacks [167], and material and labour costs of adding different exterior wall insulations with their respective paybacks [155]. Additionally, there is a synergistic effect between reducing energy consumption and investment costs on passive heating strategies, that is, the higher the initial investment, the lower the total energy consumption [182].

However, there is a lack of consideration of rural residents' affordability, which plays a dominant role in influencing the adoption of passive heating strategies. Although small in amount, there are studies demonstrating that rural residents are unwilling to undertake changes due to high costs [183,184]. Considering rural residents' financial difficulties, several studies have provided qualitative guidance on the adoption of passive heating strategies, such as prioritizing the optimization of the component with the best thermal performance, when a complete building renovation is not affordable [144,147,182,185]. Even so, there is little data on rural households' ability and willingness to pay for passive heating strategies.

External financial support is demonstrated to be important for encouraging rural households' adoption of passive heating strategies, especially those measures with higher costs but larger environmental benefits [147]. Being considered a strong potential financial source, government subsidies can effectively reduce rural residents' burden in adopting passive heating strategies [164]. However, subsidy mechanisms for implementing these strategies have not been explored in the relevant literature. Should subsidy mechanisms be developed to promote a specific type of passive heating strategy? Or should they be in place to support low-income families or assist families with poor housing conditions to implement whatever passive heating strategy is best for their house? In which case, who will be the judge for this and what scheme would be in place for households to claim this subsidy?

3.3. Policy interventions: the clean heating program and related projects

The Clean Heating program was launched by the Chinese government in 2017 as a major heating reform, aiming to replace traditional biomass and inefficient heating facilities with cleaner energy (natural gas, electricity, geothermal energy, biomass, solar energy, industrial waste heat, clean coal, nuclear, etc.) and more energy-efficient heating systems [186]. This program has involved a series of measures focusing on renovating heating supply and demand [37], with heat energy source improvements and energy-efficient retrofits being the most important [187].

As a political intervention, this program and related projects (e.g., 'Coal-to-Gas', 'Coal-to-Electricity', 'Clean Coal Replacement') were implemented and subsidized by both the Chinese central government and governments at lower administrative levels [188]. Through government subsidies, clean heating equipment and discounts on energy prices, mainly electricity or natural gas, were made available to rural households during the heating period. For example, from 2017 to 2018, the government financed almost 60 % of the cost of this clean heating reform, with residents who joined this program paying for the rest [189].

Having benefited from subsidies of over 100 billion CNY [190], the Clean Heating program made rapid progress. Clean Heating projects were carried out in 88 cities (containing both urban areas and rural areas) in Northern China by 2022, affecting over 100 million rural residents [191,192]. However, despite good penetration of the program, the uptake is still lower than originally expected [33]. A few recent studies have attempted to understand why this might be the case. These studies focus on environmental and well-being benefits versus affordability, rural residents' acceptance of the Clean Heating program, adjustments to government subsidies, and locally tailored implementation strategies, as stated beneath.

3.3.1. Environmental and health benefits versus affordability

The Clean Heating program and related projects contribute significantly to both indoor and outdoor air quality improvement by reducing pollutants, such as $PM_{2.5}$ emissions [193–196]. By phasing out the use of solid fuel for heating, the program is claimed to be beneficial in reducing carbon emissions [37]. However, this effect is argued to be limited [197]. An increase in electricity demand means an increase in electricity generation, which still mostly comes from low-efficiency coal-fired power plants, and electricity is transmitted and distributed to households with energy losses [198]. This begs the question to what extent the program is merely transferring emissions from the demand side to generation and effectively reducing emissions as a whole.

In any case, reducing air pollution locally does provide benefits to public health, such as lowering the risk of chronic lung diseases and asthma [199]. However, elderly people and women are found to have had less health benefits than men during the implementation of this program [199], although these groups of people tend to suffer more from indoor air pollution. More research is needed to reveal the reasons behind this phenomenon. Apart from gaining less health benefits, elderly people are more likely to suffer from energy poverty due to lower income, while women are only passively involved in the decision-making regarding household energy consumption [200], despite being in greater need of clean energy heating.

Moreover, some Clean Heating projects are found to affect energy affordability and make people limit their energy use to detrimental effects on their well-being. For example, the 'Coal-to-Electricity' project and the 'Coal-to-Gas' project could worsen energy poverty, compared to the 'Clean Coal Replacement' project [35], due to an overall increase in heating expenditure. Since Clean Heating projects are usually carried out by local governments, under the pressure of achieving program goals, they often perform aggressive measures to promote the transition to natural gas and electricity through a complete ban on solid fuel burning [201]. In this way, rural households are forced to give up accessible solid fuels, such as firewood, and use clean energy for heating, thereby experiencing greater heating costs. If they cannot afford this, they are likely to turn the heating off, thus suffering from cold more than before. Examples can be found for the 'Coal-to-Gas' projects in developed areas [202] and underdeveloped areas [203].

Despite receiving government allowance in support of transitioning to clean heating, rural residents living in less developed regions are more likely to experience difficulty in paying for heating costs than those living in more developed regions. This is related to income inequality and disparities in subsidy standards across different cities, which are tailored to the local conditions alongside local government funding sources [186]. For instance, Beijing and Tianjin have a higher subsidy level than Henan [189]. Poor families that cannot afford clean energy for heating are trapped in maintaining a legal or illegal practice of using more accessible and dirtier solid fuels [204].

As a cumulative result, low-income rural households, especially those with less education, smaller household sizes, and large building areas, were found to be more likely to suffer from energy injustice, energy vulnerability, and energy poverty [35,205,206].

3.3.2. Rural residents' acceptance of clean heating

Rural residents' acceptance of the Clean Heating program and its deployed heating systems is usually assessed based on Satisfaction [110,207,208], Willingness-to-Pay for clean heating facilities, either in general [200,207,209] or more specifically (e.g., low temperature ASHP [210], clean coal and stoves [211]), and Willingness-to-Adopt [210,212]. Assessment is done through questionnaires and interviews.

Evidence from different studies shows that rural residents think positively about the Clean Heating program. For instance, rural residents show a supportive attitude towards this program in Henan province [207] and overall satisfaction with this program in Shandong province [208]. However, they are discouraged from adopting it due to costs and insufficient subsidies provided for them to buy and use heating equipment and fuel [208].

The actual subsidy amount, both for capital and operating costs, can determine the impact on rural residents' acceptance of using clean energy for heating [213], affecting overall household willingness for Clean Heating [207,209,211]. Despite varying from region to region and from household to household, it is the subsidy amount that establishes a larger or narrower gap between low Willingness-to-Pay [200,209] and the costs of using clean heating methods [214,215].

Regarding the impact of clean heating in indoor air conditions, results from Ref. [208] indicate that rural residents are unsatisfied with indoor temperatures when using natural gas or electric heating. However, this publication does not discuss what these indoor temperatures are or what indoor temperatures households are satisfied with when clean heating systems are in operation. More research is needed regarding rural residents' indoor thermal comfort, occupancy satisfaction and accepted temperature thresholds with different clean heating methods in operation.

Compared to studies on rural residents' acceptance of the Clean Heating program, research regarding the acceptance of clean heating systems deployed by the program is limited. It is found that most rural residents show a preference for ASHP [110], but this may vary with geographical locations. For example, rural residents who live in mountainous areas, experiencing a colder climate and fewer energy choices, have a higher Willingness-to-Adopt and Willingness-to-Pay for ASHP than those living in hilly and plains areas [210]. This also suggests a geographically sensitive approach to promoting clean heating alternatives, acknowledging differences in climate conditions and local infrastructures.

Analysing rural residents' acceptance of different clean heating systems is also vital from the grid stability and grid cost perspective. For example, promoting solar-assisted electric heating systems could effectively reduce the grid company's investment in the construction of power grids and relieve the government from electricity subsidies [56], as well as reduce electricity fluctuations and demand increases caused by electric heating uptake. If rural residents were found to have a high acceptance of these systems, these proved benefits would be achieved and could be deployed at scale, effectively contributing to reducing electricity demand and, as a result, carbon emissions.

Sociocultural factors can have a unique and profound role in facilitating the heating transition in rural China, which is characterized by an acquaintance society [216], referring to a local society in which everyone is familiar with everyone else [217]. For instance, relatives and close friends can influence rural households' adoption of biogas [218], and neighbours can influence households' fuel choices, despite hardly stimulating low-income families [219]. Studies on these perspectives are important and relevant, but they are few. More research is needed not only to unearth the function and limitation of different sociocultural factors in rural households' decision-making processes about choosing heating fuels, heating systems, and other heating improvement measures but also to integrate this knowledge with the application of heating techniques or passive heating strategies at a neighbour level.

3.3.3. Adjustments to government subsidies

Considering rural residents' overall problems with affordability and willingness to pay, continuous subsidies are essential [211]. Not only a long-term subsidy for clean heating is necessary, but also a subsidy mechanism leaning towards low-income groups and those living in extremely cold areas to ensure social welfare [220–223]. Nevertheless, some studies disagree with a long-term subsidy scheme as this considerable investment has already exacerbated the government's financial expenditure [188,190,222], or even shows poor economic performance [202,224], and promotes an increase in energy consumption [220]. So, these studies propose to phase out clean heating subsidies and provide an optimal scheme concerning different clean heating methods, aiming at keeping subsidies at a minimum level and avoiding negative impacts on rural residents' adoption of clean heating [190].

Other ways of optimizing subsidies are also suggested in the literature. For instance, it is highlighted as important to consider the actual heating area of rural homes in the calculation of subsidies and demonstrate the advantage of paying rural residents a fixed clean heating allowances every month rather than paying them in full, both of which could increase the effectiveness of government subsidies [203]. Other studies argue that the Clean Heating program and its related projects have put much more emphasis on updating heating fuels than improving building thermal performance, but the latter is urgently needed due to: (i) poor thermal conditions of existing rural houses [111] and (ii) the known contribution of improving building thermal performance in reducing heating costs and emissions [225,226]. Therefore, it is argued that more subsidies should be invested in building retrofits rather than heating fuel replacement [225]. To this end, a trade-off framework is developed, which evaluates building retrofits considering carbon emissions, indoor thermal comfort, and cost under scenarios of low-carbon or zero-carbon [226]. More research is needed to aid decision-making on investments towards improving building thermal performance.

Besides, subsidies are under exploration to reduce electricity fluctuations and demand increase, as a result of promoting electric heating [227], such as a dynamic subsidy price generation framework for regenerative electric heating users [228], taking advantage of wind power from the surrounding areas to support electric heating at night together with a feasible nighttime electric heating price [229], and offering rural residents compensation prices to motivate them to participate in peak-load regulation [230].

Overall, adjusting government subsidies is a prevailing discussion in recent studies to further propel the clean heating reform. Discussions provide insights on economic benefits, social welfare, sustainability of the Clean Heating program and carbon emission reduction. Since there is always a dilemma between financial efficiency and social equity [231], which do not necessarily work well with each other, as reducing subsidies could worsen equity [232]. Besides, adjusting government subsidies alone is not enough to achieve the goals of this heating reform. It is vital to motivate rural residents' uptake and buy-in to transition to clean energy and clean heating systems.

3.3.4. Locally tailored implementation strategy

Apart from adjusting government subsidies to promote the Clean Heating program, research has also criticised this government's top-down approach. The program is considered as 'one-size-fits-all' showing deficits in sustainability and replication [233] due to poor consideration of geographic differences in ecology, energy resources, economic level and such like. To address these problems and to achieve success in this reform, locally tailored strategies for implementing the Clean Heating program and related projects are advocated.

Explorations have been made in different ways towards this aim. For instance, the implementation of the Clean Heating project in rural Gansu comprehended deploying a gas-electricity-heat-fertiliser cogeneration system to make full use of energy resources in different zones within it, combining organic agricultural production with biomass production and consumption, and improving building envelope in all zones within rural Gansu [111]. Other examples illustrate methodological perspectives on evaluating and selecting suitable energy resources and heating technologies, for different rural contexts. For instance Ref. [233], proposed an index system and a fuzzy comprehensive evaluation method to prioritize suitable energy sources for clean heating in different areas across Northern China. Others, such as [234], assessed four clean heating techniques by using indoor air temperature, economy, energy conservation, and environmental benefits as indicators and demonstrated that the biomass pellet heating boiler and low ambient temperature air-to-air heat pump are the best clean heating solutions for Northern rural China. These studies provide insights into how to better match clean heating fuel and heating techniques to local conditions, but they are few and lack perspectives from either the government or rural residents who are key stakeholders.

4. Conclusions

This study examined recent advances in decarbonizing household heating in rural China from the literature, with a wide range of engineering, architectural, and political solutions identified. Research in this field is dominated by technological modelling and technocratic solutionism, and integrating renewable energy into heating systems and passive heating strategies prevails in extant literature. In comparison, there is insufficient investigation of real-world applications of these technical advancements and little effort on incorporating the knowledge of end-users into developing heating techniques, passive heating strategies, and implementation strategies for the Clean Heating program and its related projects. In addition, this study raised concerns about the impact of clean heating strategies on energy poverty by linking the low affordability of Chinese rural households to their inability to afford the capital and operating costs of clean heating, which highlights current subsidies are insufficient to help this population transition from space heating to cleaner fuels.

The main findings are summarized in Table 2, showing benefits, missed opportunities and drawbacks behind research into heating techniques, passive heating strategies, and the Clean Heating Program and its related projects. In one respect, there are multiple initiatives to deploy advanced renewable and sophisticated heating technologies to rural areas, technologies which are not necessarily new but a mirror of what is being deployed in other places. Here they are being exploited based on high technical performance, CO2 emission reduction and cost effectiveness, potentially becoming cheap with widespread adoption. In another respect, context-based technologies are developed, particularly biomass heating systems and Kangs, suitable and promising due to the proximity to large crop residues and the benefits of reviving indigenous heating methods rooted in rural China. However, there is a clear bias towards focusing on technical solutions with inadequate consideration of end-users in the deployment and operation of these solutions. Technical studies show little knowledge of rural households' affordability and acceptability of the technologies proposed, lack of consideration for spontaneous and flexible heating behaviours, and households' lifestyles in relation to space heating activities. Similar considerations can be drawn for research focusing on passive heating strategies.

Insufficient knowledge about rural households' practices, aspirations and needs is also reflected in the wide disparity between the number of articles showing laboratory tests and/or building/systems performance simulation versus the number of articles looking into real-world applications of these technical measures. Despite uncertainty about claimed technical and environmental performances in real-world settings, questions are raised about the feasibility of various heating techniques and passive heating strategies. A grounded investigation into the installation, operation, and maintenance of these technical measures is necessary for ascertaining their feasibility and barriers once deployed in rural contexts, considering local builders' knowledge and training, households' affordability, and the capacity of communities to improvise and adapt the use of these strategies throughout their lifespans.

Understanding rural households and their varied heating dynamics is urgently needed, not only because it contributes to eliminating the performance gap between experimental/simulation results and real-world operation, directing technological advancements, and fostering the widespread adoption of heating techniques and passive heating strategies, but also because it advances successful end-user buy-in. This has been acknowledged by several studies, such as [235–237], though most of them are carried out in developed countries. Since rural residents are key stakeholders, incorporating their perceptions, knowledge, and preferences contributes to enhancing and promoting the Clean Heating program and related projects in different aspects, such as subsidizing heating devices fit-for-purpose to their preferences and specific housing conditions and creating subsidy schemes fit-for-purpose in terms of affordability, heating habits, and investment preferences.

Besides, it is possible to conclude that rural households' low affordability is a real challenge for achieving the low-carbon transition through the proposed engineering, architectural, and political solutions. To address this challenge, it is vital to identify what this low affordability means statistically, especially in terms of operating different heating techniques and implementing passive heating strategies. Previous studies do provide knowledge about capital and operating costs, as well as life cycle costs with payback periods, for using different heating systems and adopting passive design strategies, but little evidence is available concerning the impact of these costs on rural residents' budgets. Are these so-called cost-effective heating techniques and passive heating strategies economically feasible for rural households?

Exploring affordability in more detail also enables one to query whether, for instance, rural residents prefer to use and pay for advanced solar heating systems than those optimized household stoves with processed fuels. What if they prefer to use advanced solar heating systems but can only afford improved household stoves with processed fuels? Would they use and pay for improved household stoves with processed fuels?

Similar questions can be raised for the adoption and implementation of passive heating strategies. Are rural households willing to pay for the installation of sunspaces? Do they prefer internal or external wall insulation measures, and are they willing to pay for these? Would they prefer to undertake a whole house renovation but can only afford the replacement of windows and doors? These questions should be answered to support decision-makers of all sorts, not only those designing or optimizing technical solutions but also those selecting and promoting solutions with effective economic incentives.

Questions on rural households' affordability of clean heating systems and fuels and passive heating strategies need to have qualitative and quantitative answers to effectively aid decision-makers in advancing energy transition to phase out emissions whilst addressing the inequity in this low-carbon transition. The affordability of systems, fuels and housing retrofits need to be considered together. Looking at any of these aspects in isolation could result in failure in the adoption of clean heating alternatives, e.g., Ref. [238].

This study overall highlights the urgent need for knowledge of household heating practices, lifestyles, thermal comfort preferences, and sociocultural practices in the context of rural energy transition to low-carbon heating, as well as research on integrating this knowledge into technical advancements and political developments, exactly user-centred studies on heating techniques and passive heating measures and locally tailored political interventions. Both are critical to the success of this low-carbon transition, particularly in assuring rural households of affordable clean heating.

CRediT authorship contribution statement

Shuye Wang: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Clarice Bleil de Souza:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Oleg Golubchikov:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, authors used ChatGPT and Grammarly to improve the language of the manuscript after peer review, particularly in enhancing language conciseness while reducing the word count to meet the editorial requirement. While using ChatGPT, authors edited some sentences or parts of sentences in the abstract, introduction, and conclusion sections. Edits were made with track changes to show where this happened in relation to the first submission. Grammarly was used to assist authors in proofreading the entire manuscript after the completion of the peer-review process. Edits were made with track

Table 2
Summary of main findings of solutions for decarbonizing household heating in rural China.

Initiative		Main findings & Benefits	Missed opportunities & Drawbacks
Heating techniques	Renewable systems •Solar heating system •Biomass heating system •Heat pumps	•Heating systems powered by renewable or mixed energy resources provide large environmental benefits (emission reduction and energy conservation), showing higher technical performance at lower cost. •Contextualised biomass heating techniques and trading strategies seem promising in rural China. •ASHPs and GSHPs are the most investigated heat pumps, while ASHPs are actively promoted in rural China.	•Little knowledge regarding rural households' acceptance and uptake of different renewable heating systems. •Little research shows the operation of renewable heating systems and heat pumps in rural homes. •Little evidence regarding the installation and maintenance of renewable heating systems and heat pumps in rural areas. •Little investigation of incorporating rural households' lifestyles in relation to space heating activity (e.g., combining room functions) with developing or optimizing renewable heating systems or heat pumps.
	Improved household stoves and processed fuels	•Improved household stoves seem to be affordable and feasible to be implemented in rural homes. •Waste oils seem an alternative fuel with lower emissions and cheap prices.	•Inconsistent results of laboratory tests with on-site measurements in relation to emission reduction of improved household stoves. •Little information about real-world applications of waste oils, especially accessibility to rural households.
	New Kangs	•Optimized Kangs and their integration with other heating systems seem promising in terms of energy efficiency and emission reduction. •New Kangs can be powered by renewable energy resources.	•Little knowledge shows rural households' acceptance and adoption of new Kangs. •Emphasis on technological advancements without consideration of the feasibility of installing and operating new Kangs in rural homes.
	Performance evaluation of different heating techniques	•Multi-objective evaluation regarding technical, environmental, and economic performances with different assessment methods.	•Evaluations are mainly technical and disconnected from real-life contexts to quantify benefits to rural environments.
Passive heating strategies	Building envelope	•Insulating envelope is the most effective strategy to improve rural housing heating efficiency, especially insulating walls.	•Renovating internal wall insulation reduces indoor areas, brings inconvenience to occupants, and increases moisture. •Little studies on changing cultural identity when implementing passive heating strategies. •Little information about rural residents' intention to adopt envelope insulation measures and local builders' ability to implement passive heating strategies.
	Passive solar heating strategies	•Attaching sunspaces or Trombe walls seems promising for improving indoor thermal environments, reducing heating energy consumption, and alleviating energy poverty by lowering heating costs. •Passive solar heating strategies can be boosted in combination with other passive building measures or heating techniques.	•Passive solar heating strategies can cause overheating during summer and raise health and safety issues in rural homes using traditional household stoves. •Few studies have investigated rural residents' thermal comfort and their perceptions of adopting passive solar strategies.
	Economic analysis of passive heating strategies	•Capital and lifecycle costs with payback periods are provided for passive heating strategies. •Considering rural residents' financial difficulty, investing in passive heating strategies with the best performance is recommended. •Government subsidies are important in supporting/ stimulating the uptake of passive heating strategies.	•Little studies show rural households' affordability of passive heating strategies. •Little information on subsidy mechanisms for promoting these strategies.
The Clean Heating program and related projects	Environmental and well-being benefits versus affordability	•Intervention reduces air pollution, bringing better indoor and outdoor air quality and intangible public health benefits.	•Improper implementation by local governments increases heating costs, resulting in energy consumption inequality and energy poverty. •Program potentially transfers emissions from the household level to the energy generation level, therefore not reducing emissions as a whole. •Women and elderly people have less health benefits than men during the implementation of this program.
	Rural residents' acceptance of Clean Heating	•Rural residents show a supportive attitude to the Clean Heating political intervention. •The subsidy amount is key to rural residents' willingness to pay for clean heating. •Promoting the solar-assisted heating method would upgrade the program and reduce government subsidies in the medium term contributing to emission reductions at the power plant generation level. •Sociocultural factors impact on clean heating transition.	•Rural residents' overall low willingness to pay for clean heating is related to low affordability, high heating costs, and insufficient subsidies. •Rural residents' dissatisfaction with indoor temperatures provided by natural gas or electric heating systems. •No quantitative data showing indoor thermal comfort, occupancy satisfaction and temperature thresholds of different heating methods.
	Adjustments to government subsidies	•Subsidies are a prominent topic in current research agendas. •Continuous government subsidies are essential for promoting the adoption of clean heating, especially among low-income groups and in extreme cold areas. •Strategies for optimizing current subsidies by considering the actual heating area in rural homes, emphasizing more building renovation, and motivating residents to participate in peak-load regulation initiatives.	•Long-term subsidy increases government financial expenditure, show poor economic performance, and increase energy consumption. •The current subsidy mechanism undervalues the contribution of building retrofits to improving the indoor thermal environment, reducing energy consumption, and lowering heating costs. •More research is needed to motivate rural residents' buy-in for transitioning to clean heating alternatives.
	Locally tailored implementation strategy	•Locally tailored strategies consider local energy resources, agricultural production, residents' lifestyle, etc. •Quantitative evaluation methods are provided for selecting the best matches between context-based energy resources and heating technologies.	•Studies on locally tailored implementation strategies are few in amount. • More research is needed to involve the main stakeholders, the local government and rural residents, in developing locally tailored implementation strategies.

* Benefits identified may only apply to rural Northern China being not necessarily generalizable to other settings (e.g., urban China). Opportunities & Drawbacks are context and time depended as they are related to external factors such as regulatory changes, new research and technologies that emerged after this study, to cite a few.

changes to show where this happened in relation to the third submission. Authors take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Shuye Wang reports financial support was provided by China Scholarship Council. Shuye Wang reports financial support was provided by Great Britain China Centre. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

This is a literature review. Full data is in the paper.

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