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Carbon Neutral China by 2060: The Role of Clean Heating Systems

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Abstract: Smog pollution is a severe social and environmental concern for the space-heating regions in China due to fossil-intensive space heating. To reduce polluting emissions and improve social and environmental performance, local government agencies should choose adequate cleaner space-heating technologies based on diverse local conditions. This implies that all cleaner heating solutions should be considered, including low-emissions fossil fuel district heating and low-emissions fossil fuel decentralized heating as transitional technologies, as well as biomass and electricity-driven heat pumps as long-term solutions. However, stakeholders such as policy makers, equipment manufacturers, and house owners, often lack necessary information to assess the feasibility for installing adequate heating solutions at the local level. It is therefore necessary to establish a systematic method to evaluate each heating solution in various geolocations of China. This paper reviews the current heating situation in China and proposes a spatial system analysis method as a tool for heating-solution feasibility evaluation. By applying the spatial system analysis method, a qualitative investigation on the choice of heating solution in different regions of China is provided.

Keywords: carbon neutral; clean heating; China

1. Introduction

Anthropogenic activities have led to the rapid increase of CO2 emissions [1]. A great amount of energy input is required in the building sector of China since the country is undergoing medium to high economic growth with increased living standards. The total CO2 emissions related to the building sector mainly come from three aspects: direct emissions, indirect emissions and associated emissions. The direct emissions include direct use of carbon-rich fuels for space heating, cooking, and hot water supply. Indirect emissions come from the use of electricity and district heating. Often, such emissions are allocated to the energy sector. The associated emissions are the emissions for manufacturing the construction materials, such as steel and cement, as well as emissions during construction activities (e.g., limestone) [2].

China’s total final energy consumption was 2067 Mtoe in 2019; about 16% came from the residential sector, and just below 5% came from the commercial and public sector [3]. CO2 emissions from these sectors accounted for about 6% of China’s total CO2 emissions in 2019. Fossil fuels and fossil-based electricity are the main energy sources in the residential, commercial, and public sector [4]. Space heating plays a major role for these sectors. In the space-heating regions of China, currently coal consumption dominates the heating systems, which leads to smog pollutions during winters [5]. For urban north China, heating-only boilers and combined heat and power (CHP) are prevalent. For rural north China, 67% of space-heating area is covered by decentralized, small coal stoves, which are widely used in rural, single-family houses [6]. For urban south China, there is no central heating due to historical reasons. However, for both urban and rural south China, there is a growing demand for space-heating services, which exerts a stress on the environment if cheap fossil
fuel heating technologies are selected by end-users. It is a challenge to upgrade existing coal-based high-CO$_2$-emissions heating systems in buildings into more sustainable, lower-emission heating systems as well as choose the right clean heating technology in different regions based on local techno-economic and social feasibility. Transitioning towards cleaner district heating, implementing heat recovery for space heating, utilizing geothermal energy, as well as replacing small coal stoves with electric heat pumps for residential buildings are considered key solutions by policy makers in China. Especially as China transforms towards an advanced, high-tech, and service-based economy, the energy consumption in the building sector is foreseen to be more significant, which could be similar to that of the OECD countries.

In recent years, the research on heat pumps for space heating in China has increased. Previous research can be categorized as basic research into technical aspects of heat pumps and modelling studies exploring short- to medium-term impacts. This paper builds on earlier studies and goes beyond them by applying a system’s perspective to investigate the building heating situations in China. The analysis finds that stakeholders, such as policy makers, heat pump manufacturers, and house owners, often lack adequate information to assess the feasibility for installing one heating technology in comparison to the alternatives at the local level. In order to fulfil such a gap, it is necessary to establish a systematic method to evaluate heating solutions feasibility considering various geolocations of China.

This paper first considers the current emissions and national energy consumption situations in China and introduces the related carbon-mitigation accountability from the building sector. Then, the paper discusses the research efforts on cleaner heating solutions in China through a retrospective literature review. After that, desk-based and system research methods, and spatial analysis methods are used as a combined decision-making support tool for choosing the most feasible heating solutions in different regions of China. The theoretical background of the methods is also presented. Next, the building heating situations together with the corresponding clean heating solutions are analysed, with information on related policy support. Finally, a simplified qualitative investigation on the feasibility of each clean heating solution for both Northern and Southern China in both urban and rural areas is discussed using the aforementioned methods.

2. Materials and Methods
2.1. Overview of CO$_2$ Emissions and Energy Flows

As shown in Figure 1a, by the year 2019, the accumulated global CO$_2$ emissions have increased 4-fold to reach 2500 Gt tons compared with the value of 600 Gt in 1950 [7]. The CO$_2$ concentration is now 417ppm [8]. From Figure 1b, it can be seen that historically the UK led the global emissions at the beginning of the industrial revolution. This trend changed at around the 1850s, when other European countries (represented by France and Germany) and the United States caught up with the CO$_2$ emissions. From around 1880s, the United States surpassed European countries and kept the position of the world’s number one CO$_2$ emitter. Only from 2016 have China’s CO$_2$ emissions exceeded that of the U.S. to become the world’s largest CO$_2$-emitting country. In Figure 1c, it can be seen that the U.S. has the highest historical cumulative CO$_2$ emissions accounting from 1750. The EU-27 and China follow the U.S. in cumulative CO$_2$ emissions. In Figure 1d, it can be seen that among the top 20 GDP economic bodies, the OECD countries have the highest per capita CO$_2$ emissions, led by Australia, the U.S., and Canada.

China pledged to achieve carbon neutrality by 2060 in the 75th United Nations General Assembly [10]. The newly published China’s 14th 5-Year Plan has set up development targets on accelerating the implementation of carbon neutrality by 2060 and peaking carbon emissions by 2030 [11]. Except for CO$_2$, other greenhouse gases (GHG) emissions should also be reported to the UNFCCC under the Paris Agreement, which include methane (CH$_4$), nitrous oxide (N$_2$O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF$_6$), and nitrogen trifluoride (NF$_3$). Whether China will also mitigate other GHGs remains to be observed.
China pledged to achieve carbon neutrality by 2060 in the 75th United Nations General Assembly [10]. The newly published China’s 14th 5-Year Plan has set up development targets on accelerating the implementation of carbon neutrality by 2060 and peaking carbon emissions by 2030 [11]. Except for CO₂, other greenhouse gases (GHG) emissions should also be reported to the UNFCCC under the Paris Agreement, which include methane (CH₄), nitrous oxide (N₂O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF₆), and nitrogen trifluoride (NF₃). Whether China will also mitigate other GHGs remains to be observed.

Currently, in China, the total final energy consumption in 2019 was 2067 Mtoe, in which 346 Mtoe came from the residential sector, and 94 Mtoe came from the commercial and public sector (See Figure 2). Together, they accounted for only 21% of total final consumption and less than 30% of electricity demand, owing in part to the dominant role of the industry sector [3]. Almost 80% of energy consumption in the buildings sector is in households, and the remainder is in the services sector [12]. The associated CO₂ emissions were 542 Mt CO₂, which accounted for around 6% of China’s total CO₂ emissions in 2019. Within the residential and commercial building sector, direct use of fossil fuels and fossil-fuel-generated electricity is the main energy source [4].

Figure 1. (a) World’s annual CO₂ emissions share by countries and regions; (b) world’s annual CO₂ emissions share by countries and regions; (c) world’s accumulated CO₂ emissions by countries and regions from 1750–2019; (d) per capita CO₂ emissions for selected countries/regions in 2019 (data compiled from [9]).
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Figure 2. (a) China total energy consumption flow; (b) China total final energy consumption in residential, commercial, and public buildings (data compiled from [13]).

2.2. Previous Research

Various cleaner heating solutions have been proposed and studied to help the heating sector in China to transit towards carbon-neutral. These candidates include low-emission district heating (fourth-generation district heating), electric heating (including air-source heat pumps ASHP), geothermal heating (including ground-source heat pumps GSHP), biofuel heating, industrial waste heating, and solar heating [6]. The final goal is to replace all fossil fuel heating.

For low-emissions district heating, using cleaner coal heating and natural gas through CHP to replace heating-only boilers (HoB) is an intermediate clean energy transition solution [14], which is recommended by Chinese researchers [15]. However, the price of natural gas is 3–5 times higher than that of coal, which increases the economic burden on clean heating transition [16]. Except reducing emissions at the fuel source side, utilizing the waste heat after the co-generation cycle in combination with absorption heat pumps is being focused upon [17]. Some pilot district heating projects in north China have implemented such a heat-reuse solution [18]. Industrial waste heat is another important supplementary heat source for clean district heating transition [19]. Its concept on cascading use of heat will also enhance the implementation of circular economy [20]. However, the utilization of industrial waste heat is confined to urban areas with industries as well as the stable production operation of the factories. When there is resource availability, another potential high-quality heat sources for district heating is the direct use of the heat from dry-hot rocks at deeper underground [21]. The depth of deep geothermal resources could reach 5 km for enhanced geothermal systems, and the temperature could reach 400 °C [22].
In recent years, the research on heat pumps for space heating in China has increased, including the role of heat pumps in cold climates in north China. Previous research can be categorized as basic research into technical aspects of heat pumps and modelling studies exploring short- to medium-term impacts. Geothermal heat pumps could often be implemented as both large-scale installations for district heating or medium-small scale for one or a few buildings as well as single-family dwellings [23]. Its application potential often relies on the depth of ground-heat exchanger deployment. For horizontal GSHPs, the installation of ground coil is often 5–10-m deep. It is suitable for single-family houses, and the cost is medium [24]. For vertical borehole GSHPs, borehole drilling cost is often high, and it often requires large land areas for borehole fields when implemented in large scale [25]. This significantly hinders the application of vertical GSHPs. To reduce the life-cycle cost of GSHPs and increase its system efficiency, researchers often integrate a GSHP with solar systems or energy storages for a hybrid system [26]. The installation of GSHP should also consider local feasibility based on geographical differences, and this implies the necessity of considering spatial parameters, such as climate conditions, ground conditions, etc. [27]. Except for GSHPs, utilizing the low-grade heat in natural water bodies or sewage plants by heat pumps is another option for clean heating [28]. In this case, the spatial parameter variations of the water body should be considered.

For distributed heating solutions, especially in rural, single-family houses, ASHP is being studied the most. Previous research on the technical aspects of ASHP in colder climates in China includes studies by Ge et al. (2011) [29], Gao et al. (2015) [30], Zhang et al. (2016) [31], Zhang et al. (2017) [32], Xu et al. (2019) [33], Ma et al. (2020) [34], Yang et al. (2020) [35], Zhang et al. (2020) [36], Deng et al. (2021) [37], and Wang et al. (2021) [38]. Other studies on the role of heat pumps in China more generally include research by Dai et al. (2016) [39] and Xu et al. (2021) [40]. In terms of the most important findings of these studies, Zhang et al. (2016) [31], Zhang et al. (2017) [31], Xu et al. (2019) [33], and Zhang et al. (2019) [41] explored the technical possibilities for ASHP in cold climates in temperatures ranging to about −20 °C. Those studies proved a high heat pump efficiency even in these harsh climates and analysed the options for cleaner heating systems in north China. Dai et al. (2020) [39] argued that for cold climates in China, the most appropriate type of heat pump is a CO2 heat pump system integrated with vapor injection and dedicated mechanical subcooling (VIDMS). Ma et al. (2020) [34] modelled the role of ASHP for contributing to residential heating in rural north China by 2035 to meet the 2-degree target of the Paris Agreement. They assumed that ASHP will play a major role alongside biomass-based heating, particularly in rural areas, while coal-fired CHP is likely to remain dominant in urban areas. Yuan et al. (2020) analysed clean heating transitions using heat pumps in the Beijing-Tianjin-Hebei urban conglomerate region and found energy- and environment-related benefits while keeping costs stable for the coming decade [42]. Yu et al. (2021) [40], however, concluded that for a larger uptake, heat pumps need more government subsidies to become more competitive. Deng et al. [37] studied the economic feasibility and environmental impacts of coal boilers, biomass pellet boilers, and ASHPs in Beijing rural households. Their finding was that biomass boilers and ASHPs show the best economic feasibility and overall environmental benefits. However, for ASHPs, the analysis of the impact from governmental subsidies was neglected. It remains, however, unclear if the termination of financial subsidies for ASHP installation cost and operating cost enables ASHPs to still be economically competitive. In addition, the environmental benefits of ASHPs are very dependent on the electricity sources. Coal-fired power plants are a major electricity source for the North China power grids. Under this circumstance, an ASHP has to reach a minimum seasonal coefficient of performance (SCOP) of 2.5 to guarantee it actually saves CO2 emissions compared with coal boilers [22].

Transitioning towards cleaner district heating, implementing heat recovery for space heating, utilizing geothermal energy, as well as replacing small coal stoves with electric ASHP for rural single-family residential buildings have all been advocated by the Chinese government. However, stakeholders, such as policy makers, heat pump manufacturers,
and house owners, often lack adequate information to assess the feasibility for installing one heating solution in comparison to other heating technologies at the local level. In order to fulfil such a gap, it is necessary to establish a systematic method to evaluate heating solutions feasibility in various geo-locations of China. This paper therefore proposes a spatial systematic method to fill this knowledge gap, considering spatial parameters, such as climatic conditions, building properties, and primary energy mix, at different system boundaries.

2.3. Methods

For China to become carbon neutral by 2060, the contributions from the building sector are strongly affected by clean heating transitions since the sectorial direct emissions and indirect emissions are related to building energy activities. It has to be noticed that as a large country, it is unwise to design uniform, clean heating transition strategies for the entire country. Tailor-made clean heating solutions should be selected based on local resources, social-economic conditions, and the heating alternatives techno-economic feasibilities. The environmental impact should also be evaluated. It is important to equip the policy makers and other relative stakeholders with scientific tools to assist their decision makings towards clean heating and carbon mitigation in China. Hence, a feasibility evaluation method featured by system research and spatial considerations are recommended for this purpose. The theoretical foundation of system research and spatial considerations are summarized in the following section.

2.3.1. Desk Research

Desk research, also known as secondary research, is a method that collects and analyses existing data and information to solve a research question. Compared with primary research method, desk research method is much more cost-effective, as it makes use of already-existing data, unlike primary research, where data are collected first hand by organizations or research groups or an employed third party. In this study, numerical data and textual information from governmental archives and previous research literatures are assimilated to analyse the existing heating situation, the clean heating alternatives, and the corresponding supportive policy decisions in China.

2.3.2. System Research

System research is a set of different analyses that help model builders optimize the system of interest. Based on the philosophy of systems thinking, systems research aims to evaluate the reality of interest from multi-criteria, cross-disciplinary perspectives to achieve sustainability as well as to advise the decision-making processes. System analysis has been applied in building space-heating solutions for ground-source heat pumps [23] and seawater heat pumps’ feasibility studies [43].

In using system analysis, it is important to set the system boundary. A system boundary can be chosen based on the purpose of the analysis. To evaluate the building space-heating technology unit, the system boundary is usually chosen to be a coal/gas/biomass/electric boiler. This boundary level calculates heating technology unit efficiency, either the efficiency of a boiler or the coefficient of performance (COP) of an ASHP. Such efficiency values are the foundation for primary energy-use calculation. System boundary two often expands from system boundary one, which includes the heat sink, heat source, as well as heating unit. Heat sink is the single-family house in rural areas or a district with multi-family buildings connected in urban areas. When building, peak heating demand is obtained, and the chosen heating technology can be sized. The capacity of the heating technology determines its capital expenditure. The annual building heating demand, on the other hand, is related to heating technology operation expenditure. System boundary three considers the primary energy that is fed into the energy system, which is important for the heating technology’s environmental impacts. At this level, the energy systems become even more complex. For boilers, primary energy used can be coal, gas, biomass, or electricity. For coal boilers, coal type should be investigated to obtain emission factors. Emission factors
also need to be investigated for gas and biomass. For electric boilers and heat pumps, the electricity mix should be investigated, and fossil fuel electricity should be converted into primary energy to calculate related GHG and air pollutants emissions.

Different key performance indicators (KPIs) can be used to evaluate clean heating systems’ techno-economic, environmental, and social feasibility at all different system boundaries. These KPIs could form a matrix to quantify the advantages and disadvantages of each clean heating alternative. In this study, the feasibility evaluation is carried out on all three system boundaries. On system boundary one, market penetration potential is used as the KPI to represent the heating unit’s technical maturity. For example, combined heat and power (CHP) and heating-only boilers (HoB) are regarded as more mature and established compared with various types of heat pumps, so they have lower market-penetration potential. In system boundary two, the KPI is chosen to be economic competitiveness for the comparison between different heating alternatives. In system boundary three, which considers the primary energy input to the energy system, the KPI is chosen to be environmental benefits considering the emissions.

2.3.3. Spatial Parameter Considerations

To evaluate the potentials of the clean heating resources, spatial parameter considerations is an important aspect to help map the geolocations and the spatial cost for utilizing the heat sources. Spatial analysis is defined by the Environmental Systems Research Institute (ESRI) as the analytical techniques associated with the study of geographic phenomena locations together with the corresponding spatial dimensions and their associated attributes. Multiple papers in similar areas have used spatial analysis as a research methodology for mapping and estimating energy potential and heat recovery for heating solutions. Buhler (2017) performed an analysis of heat recovery from industrial excess heat for district heating in Denmark through spatial analysis [44]. Munkácsy (2020) performed a study on renewable-based, hybrid district-heating possibilities in Hungary utilizing a spatial analysis [45]. Su et al. studied GSHP feasibility in Qingdao, China, using spatial system analysis method [46].

In using spatial analysis to find the potentials of clean heating sources, one key prerequisite is to establish a spatial database for clean heating transition. This database needs to contain the information of the spatial parameters for technical potential evaluation of the clean energy sources, such as ground property for utilization of geothermal energy, water temperature for water source heat pumps application, or biomass yields from certain crops in a rural area for biomass boiler application. The evaluated technical potential of the clean energy sources for heating purposes should also be included. This is often determined by physical equations but should also be assigned with geographical coordinates in the database for energy economics spatial analysis. With a high-quality spatial database, energy mapping could be generated. For example, Su et al. mapped cleaner heat sources in Stockholm using high-resolution geospatial mapping [47].

In this study, spatial considerations are reflected by four different quadrants: north China, south China, rural China, and urban China. The heterogenous local spatial parameters are taken into consideration when evaluating the heating solution’s techno-economic and environmental feasibilities. For example, water-source heat pumps are thought to be more feasible in south China than in north China, as south China is much abundant in water resource and has many more rivers and lakes, which could be used as a heat pump source.

3. Results

3.1. Current Status of the Heating Systems in China

In China, building space-heating is associated with winter smog pollution due to the excessive consumptions of coal. The space heating in China should be analysed from four dimensions: north China, south China, urban areas, and rural areas. The dominating heating configurations and heating fuels are very different among those four dimensions. First, centralized heating/district heating (DH) is only provided in north Chinese provinces due to historical reasons and only in urban areas. In rural areas of north China, single
Household fossil fuel stoves and biomass stoves are the traditional heating systems widely used. In recent years, electricity-driven heat pumps have been installed in rural areas of north China under strong governmental subsidies. Historically, many Chinese households used decentralized coal or solid biomass for space heating during wintertime. Nowadays, in north China, despite DH being supplied for most urban users, there are still heat users that do not have access to DH. They currently have to resolve heating problems by using distributed heating systems, such as decentralized small coal boilers, or small gas boilers. Such systems can supply heating for one or several buildings. Some poor or old-district residents are still using household heating systems, such as electric heaters. Overall, those distributed heating solutions cover 50% of urban heat users in north China.

In Figure 3a, it can be seen that in north China, the access to DH is still not 100% for the urban inhabitants. A growing urban heat demand requires a balance between indoor comfort and clean energy supply. For supplied DH, both combined heat and power (CHP) and heating-only boilers (HoB) prevail in different provincial level administrations. In rural areas of north China, decentralized coal and biomass heating dominate, which leads to smog pollution in winter. The coal-to-clean-heating movement initiated by the government from 2014 onwards has been providing financial subsidies for installing electric heat pumps and natural gas boilers. However, due to the expensive operating cost from consuming electricity and gas, the movement brought fiscal burdens to local governments and end-users.

![Figure 3](image-url)

**Figure 3.** (a) DH supply in China; (b) delivered DH energy in north China for each province and urban population and urban access to DH in north China for each province (data compiled from [48]).
In south China, it is distributed heating systems that are dominating the market for both urban and rural areas. Electric heaters and reversible air-conditioners are the common options. In addition, there are still a large number of households in rural areas that do not have any heating equipment.

In urban areas of south China (hot summer, cold winter zone), household-distributed space-heating systems include electric heaters (such as portable heaters or electric boilers), reversible split-type air-conditioners (air-air system), and gas boilers (with radiator system). Figure 4 illustrates that the most common heating devices by households are electric heaters and reversible air-conditioners, which account for 27% and 31%, respectively. Centralized heating systems, gas boilers, and coal stoves together account for 13%. The remaining 29% of households do not have heating devices [49]. Such distributed heating systems are installed in individual apartments in multifamily houses. The floor area of each apartment is between 70 to 120 m².

![Figure 4](image-url)

**Figure 4.** Heating situations in urban and rural south China.

In rural areas of south China, decentralized small coal and biomass stoves are still widely used by single-family houses for winter space heating, which accounts for more than 40% final energy use [50]. Here, stoves refer to a traditional space-heating device without indoor radiator system. See Figure 4.

User behaviour greatly influences performance of distributed heating systems and building energy intensity in China [51]. Mainly due to economic reasons, many households only use heating devices intermittently in order to save money. In other words, people only turn on heating devices when they are inside the building and when they feel it is cold. Additionally, not all rooms are equipped with heating devices; only living rooms and bedrooms are heated. Therefore, the intermittent operation style leads to a short heating duration, which is the main reason for poor indoor thermal comfort in south China [52]. With this user behaviour, results from [53] showed that heating energy intensity for reversible split air-conditioner in south China can be 18.4 kWh/m², and heating energy intensity for gas boiler can be 83.3 kWh/m². With increasing of income level, people’s need for better heating services will grow, which leads to potential for renewable distributed heating solutions.

3.2. **Clean Heating Technical Alternatives**

For China’s carbon neutrality by 2060, the contribution from the heating sector should be focused on clean heating transitions for both urban and rural heat users. The choices and strategies should also be made based on the different local conditions in north and south China. A universal solution is not possible since the country is vast, and regional natural endowments are heterogenous.

3.2.1. **Cleaner District Heating in Urban North China**

Coal-fired CHP and coal-fired HoB dominate the building heating sector in urban north China at the moment. For the heating systems to gradually become carbon-neutral
but still able to satisfy the level of heat demand, the first step is to increase the efficiency of the fossil fuel heating technologies [6]. Therefore, for CHPs, it is possible to increase the heat recovery from the exhaust steam through back pressure [54]. It is also possible to recover heat through absorption heat pumps [55] or electricity-driven heat pumps [56]. For HoB, decentralized boilers are continuously being phased out since 2017 [57]. Coal-based, large central HoB will serve as intermediate solutions, and gas-fired boilers will also increase their share in the heating market. Carbon capture and storage (CCS) has been discussed, and only a few pilot projects were carried out to test its feasibility. However, due to the high economic expense, this technical option is not prioritized [58].

To transition from fossil fuel to cleaner sources, waste to heat should be considered. The urban areas in Chinese cities generate much municipal solid waste (MSW) every year [39]. With the implementation of waste sorting and recycling, it is possible to reuse many of the combustible wastes for energy purposes. MSW-based CHP or HoB could partly contribute to the carbon-neutral target. Another option is to use biomass. Kang et al. estimated the biomass generation for China each year and discussed the possibility of reuse for energy purposes [60].

Industrial waste heat is still under exploited. In China, industrial activities generate a huge amount of waste heat, such as the steel and iron industry, cement industry, chemical industry, and ferrous industry. It is both wise in terms of both energy and economy to recovery such heat for DH purposes to nearby neighbourhoods. Large-scale heat pumps are also possible alternatives for clean heating transition, such as large-scale GSHP or water-source heat pumps utilizing the low-grade heat from natural water bodies, such as rivers and lakes. Sewage waste heat should also be considered in combination of heat pumps. With more diverse heat sources being integrated, the urban DH system will gradually transit towards the fourth-generation heating system, which could operate with lower supply temperature and return water temperature to reduce heat loss and consequently reduce carbon emissions.

### 3.2.2. Cleaner Decentralized Heating in Rural North China

To phase out decentralized coal consumption in rural north China for the purpose of improving the atmospheric quality, several solutions are recommended: shaped coal boiler (Figure 4a), gas boiler (Figure 4b), biomass boiler (Figure 4c), and electricity-driven air-source heat pumps (ASHPs, Figure 4d). At the indoor terminal side, usually water-borne radiators are used for all solutions, with exceptions for some ASHPs that use fan-coil units. See Figure 5 for decentralized heating solutions.

![Figure 5. Cleaner decentralized heating solutions for rural north China, from left to right: shaped coal boiler; gas boiler; biomass boiler; ASHP (data source: the author [61]).](image)

Except for the cleaner heat sources, the demand side improvements are also important. In north China, rural buildings are often poorly insulated, which leads to excessive energy consumption. Rural building retrofitting is an important direction to improve the energy performance of the overall heating system. It can significantly reduce energy consumption and mitigate associated air pollutions.

In recent years, the research on heat pumps for space heating in China has increased, including on the role of heat pumps in cold climates in north China. Previous research
usually calculates ASHP coefficients of performance under one pair of source and load temperature. Air-source heat pump (ASHP) space heating is regarded to be a feasible candidate to replace decentralized coal consumption in rural, single-family houses and thereby to reduce greenhouse gas emissions (GHG) and local air pollution. Meanwhile, currently in China, the sustainable space-heating technology implementations are policy-driven, which are based on experts’ endorsements and governmental financial incentives.

North China is a vast area with heterogeneous local conditions; yet, the ASHP incentive policies are often universally applied to the whole country, which lacks a holistic consideration from a systems point of view. The Chinese Prime Minister also pointed out that the coal-to-clean-heating movement in north China should be implemented based on local conditions. Especially for ASHP, policy makers are still limited by insufficient understanding of the conditions under which to choose ASHP as a proper space-heating technology to compete with alternatives. A systematic evaluation for feasibility decision-making of space-heating technologies at different geo-locations of China is urgently needed. On the other hand, previous studies only calculate ASHP coefficients of performance under one pair of source and load temperature. Seasonal coefficients of performance (SCOP) should be used to calculate heat pump efficiency through the entire heating season.

3.2.3. Clean Heating Solutions in South China

In urban areas of south China, reversible air conditioners and portable electric heaters are the most common residential building heating systems being installed. If the electricity comes from renewable sources, such as hydro, wind, and solar, such heating systems are very environmentally friendly. However, the indoor comfort is very poor when using the reversible air conditioners. The warm air remains at the top of the room, and cold air stays at the bottom. The natural heat convection cannot be triggered, and the air blown from the indoor unit is dry. Another challenge for the reversible AC and portable electric heater is that the electricity cost for heating purpose is expensive if the heating device is turned on for the entire heating season. Therefore, most residents choose to use the heating device only when they are inside the room. This user behaviour saves operating cost but reduces indoor comfort.

Driven by rising incomes and improved qualities of life, an increasing number of multi-family-house construction companies gradually choose to install heat pumps for the entire building or the mini-district. Such heat pumps often use geothermal energy as heat source or the water body nearby (rivers, lakes). Some use seawater as the heat source for heat pumps (seawater heat pumps, SWHP). Some successful applications have been reported in Wuhan, China, by using river-water heat pumps (RWHP) [28]. This is a new trend for clean heating transitions in urban south China. The indoor comfort is guaranteed because of the use of radiators or floor heating as indoor terminals.

For the rural areas of south China, decentralized clean heating solutions are the best technical option to choose. Income levels are the main determinant for a household to determine the choice of heating technologies [62]. A majority of the households do not have any heating devices installed, and the income level is not sufficient enough for many of the house owners to install a clean heating device.

3.3. Clean Heating Policies

Many of the clean heating policies are released targeting north China provinces since the air-quality issue is more urgent and severe than that of south China. For example, the Clean Winter Heating Plan in North China (2017–2020) was enacted in December 2017. By now, many of the previous enacted policies are reaching the end of their timeframe. The evaluation of the outcomes of those policies are still ongoing. New policies are also being developed. Under the new slogan of carbon neutrality by 2060 in China, the two most recently and important policies associated with clean heating is the China’s 14th 5-Year Plan, published in 2021, and the 14th 5-Year Circular Economy Development Plan [63].
The 14th 5-Year Plan is the core plan covering all national social-economic targets, i.e., economy, technology, manufacturing, energy, health, education, etc. Within the plan, clean energy transition targets and carbon-mitigation targets are introduced from the production sites down to the consumption sides, under the background of climate change. The Plan states that China will reach carbon peak by 2030, and major decarbonization sectors include industry, building, and transportation. By the end of the 5-Year Plan, the CO\textsubscript{2} emissions per GDP should be reduced by 18% compared with current numbers. Clean heating in north China is still a focus for the next period, and the transition work should be based on local conditions. Associated with heating energy consumption, the air quality in south China should also continuously be improved.

The 14th 5-Year Circular Economy Development Plan, on the other hand, focuses on reusing waste heat for clean heating transitions. Waste heat recovery from large industries, such as iron and steel and the chemical industry, should improve their energy performance by reusing the low-grade heat to supply district heating for neighbourhood residential buildings. For urban areas, municipal solid waste should be sorted and recycled for generating energy, including heat. Centralized heating systems should be promoted instead of decentralized heating in cities and industrial parks.

### 3.4. Feasibility of the Clean Heating Solutions

Through the proposed methods and the heating solution analysis results from Sections 3.1, 3.2 and 3.3, the feasibility of each heating solution is scored at three KPIs: market-penetration potential, economic competitiveness, and environmental benefits. The evaluated heating solutions are coal combined heat and power (CHP coal), coal heating-only boiler (HoB coal), gas CHP, gas HoB, ground-source heat pump (GSHP), seawater heat pump (SWHP), river-water heat pump (RWHP), large-scale air-source heat pump (ASHP), waste heat recovery mainly from industries, shaped coal boiler, single-family gas boiler, biomass boiler, and single-family ASHP. The scoring of each heating solution is listed in Table 1. On the other hand, the implementation geolocations of each heating solution are also accounted and skewed towards the more feasible areas, which are represented by four quadrants: north and south China and urban and rural China (see Figure 6).

| Heating Solution         | Market-Penetration Potential | Economic Competitivity | Environmental Benefits | Total Score |
|--------------------------|------------------------------|------------------------|------------------------|-------------|
| CHP coal                 | 1                            | 2                      | 1                      | 4           |
| HoB coal                 | 1                            | 1                      | 1                      | 3           |
| CHP gas                  | 2                            | 2                      | 2                      | 6           |
| HoB gas                  | 1                            | 1                      | 2                      | 5           |
| GSHP                     | 2                            | 1                      | 3                      | 6           |
| SWHP                     | 1                            | 1                      | 2                      | 4           |
| RWHP                     | 3                            | 1                      | 3                      | 7           |
| ASHP large-scale         | 1                            | 1                      | 1                      | 3           |
| Waste heat recovery      | 2                            | 2                      | 3                      | 7           |
| Shaped coal boiler       | 1                            | 1                      | 1                      | 3           |
| Gas boiler single-family | 2                            | 1                      | 2                      | 5           |
| Biomass boiler           | 3                            | 3                      | 2                      | 8           |
| ASHP single-family       | 3                            | 2                      | 3                      | 8           |

1 Scoring of feasibility: 3, strong; 2, moderate; 1, weak.
It can be seen from Figure 6 that single-family ASHP and biomass boiler have the highest potential in both north and south China and only in rural areas due to their low system cost, installation quantity, and high CO$_2$-saving potential for the large, rural, single-family houses in China. For south China’s urban areas, due to relatively abundant rich resources of rivers and lakes, river-water heat pumps and ground-source heat pumps have high feasibility. In north China, waste heat recovery from various industries has the highest feasibility in urban areas. On the other hand, gas CHP has better feasibility to replace coal HoB at the moment. All coal systems are regarded as low potential since they are restricted in the market and emit much more CO$_2$ compared with other systems.

4. Discussion

The methods of system research and spatial considerations can better evaluate the feasibility of different heating solutions in China. In order to implement such methods, it is important to define the system boundaries with clear key performance indicators and obtain necessary spatial parameters. The desk analysis on the current building heating situations in China, the features of different heating solutions, and the related policy decisions provide a basis for the successful qualitative implementation of the system research method and the spatial considerations. In the future, a deeper quantitative analysis can be conducted for a comprehensive understanding of the clean heating transitions in China. Extensive system data and spatial data need to be collected and complied to support the decision making on choosing the proper heating solution in different locations of China.

5. Conclusions

For China to become carbon neutral by 2060, clean heating can play an important role. Based on local conditions, different heating solutions should be applied in north China, south China, urban areas, and rural areas accordingly. This type of decision making requires systematic and careful investigation of the local conditions. System research method and spatial parameter considerations are therefore introduced to solve the problem of lacking tools. This paper hereby proposes such methods to fill this knowledge gap. This paper carried out a simplified qualitative heating solution feasibility evaluation using the proposed methods. The analysed heating solutions are coal combined heat and power, coal-heating-only boiler, gas combined heat and power, gas-heating-only boiler, ground-source heat pump, seawater heat pump, river-water heat pump, large-scale air-source heat pump, waste heat recovery mainly from industries, shaped coal boiler, single-family gas boiler, biomass boiler, and single-family air-source heat pump. By considering the spatial

Figure 6. Relative feasibility and market-penetrating potential for building heating solutions.
parameters in north and south China as well as rural and urban China at different system boundaries, it is found that industrial waste heat recovery for space heating has the highest feasibility in north urban China. River-water heat pumps have the highest potential in south urban China. Biomass boilers and single-family air-source heat pumps have the highest potential in both north and south rural China. A further quantitative analysis can be carried out once the necessary system data and spatial data are acquired.

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