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A systematic review

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Published in:
Energy

DOI (link to publication from Publisher):
10.1016/j.energy.2024.130788

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Energy 294 (2024) 130788

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Review

Renewable energy and waste heat recovery in district heating systems in China: A systematic review

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ARTICLE INFO

Handling editor: Soteris Kalogirou

Keywords:
District heating
Renewable energy
Waste heat recovery
Excess heat
China
4th generation district heating
Smart energy systems

ABSTRACT

Decarbonising the heating sector is one of the key elements to realizing the ambitious dual carbon goals of China, which is the largest carbon emitter and energy consumer globally. Currently, district heating (DH) systems have penetrated approximately 88% of the urban heating areas in Northern China. Nevertheless, around 90% of the heating demand in China still relies on fossil fuels. A larger scale integration of renewable energy and waste heat sources into the DH systems is critical for decarbonising the entire heating sector in China. However, a deeper level of comprehension is required to harness its full potential. This paper provides a thorough investigation of the status, potential, and national policy schemes of renewable energy and waste heat recovery in the DH systems of China. Combined with a critical review of recent literature on relevant areas published in both international and Chinese domestic sources, the trends, challenges, and future perspectives are discussed from scientific research and practical implementation aspects. This paper highlights the synergy of the integration of renewable energy and waste heat sources in DH, the energy efficiency improvements as well as the use of thermal storage technologies through the implementation of 4th generation district heating and smart energy systems that could offer a more economically viable pathway forward.

1. Introduction

1.1. Background

Heating represents almost 50% of the global final energy consumption in the building sector [1]. Among many other heating techniques, the district heating (DH) system is outstanding as an attractive option for a stable supply of space heating and domestic hot water (DHW) for buildings. This is due to its potential to provide an energy-efficient and cost-effective heating supply, especially in dense urban areas with concentrated heat demands that are within economy-of-scope [2]. Nevertheless, the decarbonising potential for DH systems remains largely unexplored, given the dominant role of fossil fuels which account for about 90% of the total heat supply in the global DH networks and contribute significantly to greenhouse gas emissions and air pollution [3]. This is especially the case of China – the largest market for DH worldwide – which has an extensive network of DH pipelines with over 507 thousand kilometres by 2020 [4]. To achieve the global climate target to limit global warming to 1.5 °C, significant mitigation is needed in CO_2 emissions from the Chinese energy system.

The use of DH for space heating in China can be traced back to the 1950s when a few pilot cities explored the substitution of traditional coal-based individual heating with DH to improve residential welfare. After the 1980s, the DH system in Northern China underwent a rapid and substantial expansion. A more detailed timeline of the development of the DH systems in China can be found in Fig. 1 (details of the figure will be introduced in Section 3). DH accounted for 88.2% of the heating demand in the urban areas of Northern China in 2020; however, around 72% of the total heating area remained supplied by coal-fired combined heat and power (CHP) plants and coal boilers [5]. For comparison, coal made up 56.8% of the national primary energy consumption in China for all sectors in the same year, whereas 15.9% was from non-fossil fuels [6]. In 2020, China committed to reaching its peak CO_2 emissions by

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https://doi.org/10.1016/j.energy.2024.130788
Received 13 November 2023; Received in revised form 18 January 2024; Accepted 22 February 2024
Available online 29 February 2024

Abbreviations

BERC	Building Energy Research Center (BERC) at Tsinghua University
BMF	Biomass molded fuel
CHP	Combined heat and power
CNKI	China National Knowledge Infrastructure
CO_2	Carbon dioxide
COP	Coefficient of performance
DH	District heating
DHW	Domestic hot water
FYP	Five-Year Plan of China
HP	Heat pump
MEE	Ministry of Ecology and Environment, People's Republic of China
MOC	Ministry of Construction, People's Republic of China
MOF	Ministry of Finance, People's Republic of China
MOHURD	Ministry of Housing and Urban-Rural Development, People's Republic of China
NDRC	National Development and Reform Commission, People's Republic of China
NEA	National Energy Administration, People's Republic of China
PtX	Power-to-X
RE	Renewable energy
REWH	Renewable energy and waste heat sources
SES	Smart energy systems
TS	Thermal storage
WH	Waste heat
4GDH	4th generation district heating

2030 and achieving carbon neutrality before 2060 (aka dual carbon goals or "3060" goals). In light of this, the decarbonisation of China's DH system has become increasingly critical.

Phasing out coal stands as the foremost priority in China. During the past few decades, many national policies and regulations have been put forward to promote the development of DH systems and building efficiency. Nevertheless, compared to other sectors, especially the electricity sector, the decarbonisation of the heating sector and the corresponding green transition received relatively late and less attention. After the announcement of the national dual carbon goals, clearer guidelines for promoting renewable heating were suggested. It should be emphasized that DH is a long-term investment [7]; therefore, long-term goals and policies are needed to ensure a development that does not hinder but supports the dual carbon goals.

1.2. Renewable energy and waste heat as promising sources for DH

The experiences and practices gained from other leading countries of DH in similar climatic conditions, such as Denmark and Sweden, have already shown promising benefits of integrating renewable energy (RE) sources and recovering waste heat (WH), aka excess heat in literature, into the DH systems. A similar integration could potentially provide substantial benefits also in the Chinese context. The reduction of temperatures in the DH grids has been shown to reduce the costs of the energy system and allow for more efficient integration of RE and WH into the overall energy system. Lower grid temperatures reduce the loss from the grid and, more importantly, increase the coefficient of performance (COP) of heat pumps (HPs) and allow for more WH to be utilised directly in the DH grid [8–10].

Especially, the concepts of 4th Generation District Heating (4GDH)[1] [11] and Smart Energy Systems (SES) [12] have emerged as efficient approaches to integrating RE and WH in the DH systems, which have been widely investigated in the European context. The main idea of 4GDH is to better utilise future non-fossil fuel heat sources to decarbonise the DH systems. An illustration of the progress of the concept of 4GDH from the previous three generations is shown in Fig. 2 [13]. Unlike the first three generations of DH systems – from steam systems to

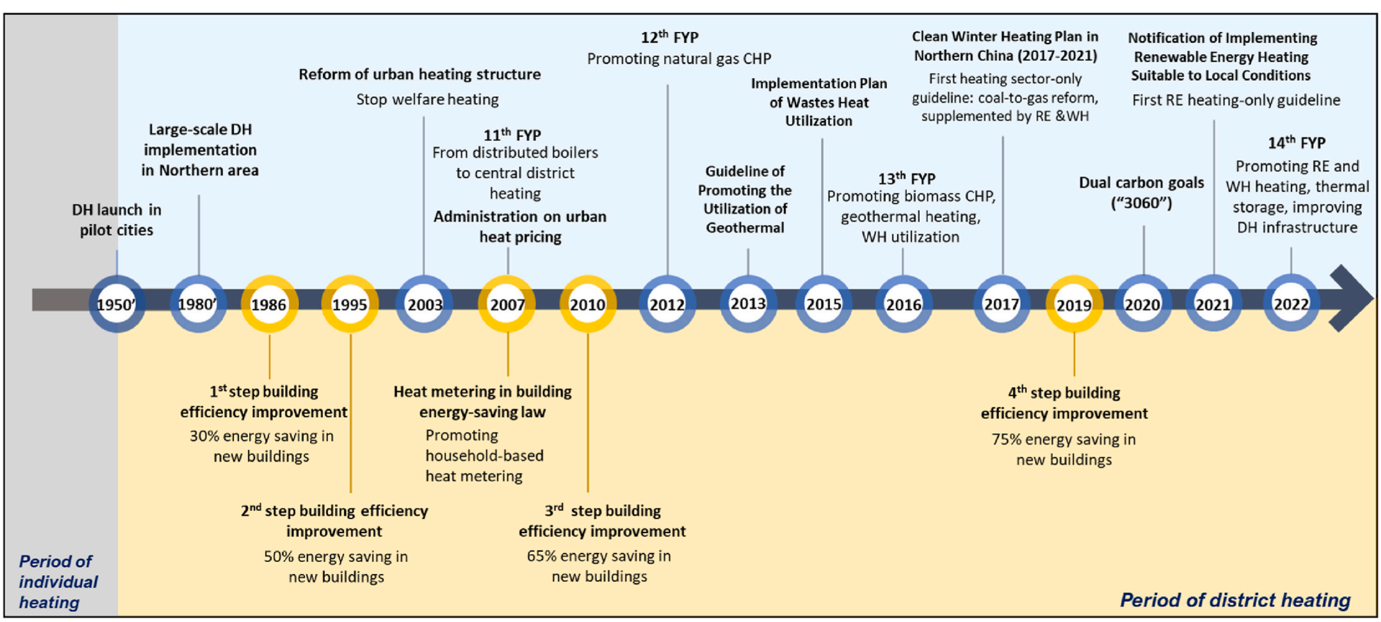


Fig. 1. Timeline of the development of district heating systems in China with main policy progresses in the heating sector (blue area) and building sector (yellow area). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

[1] The concept of fifth-generation district heating and cooling (5GDHC) is excluded from the discussion of this paper.

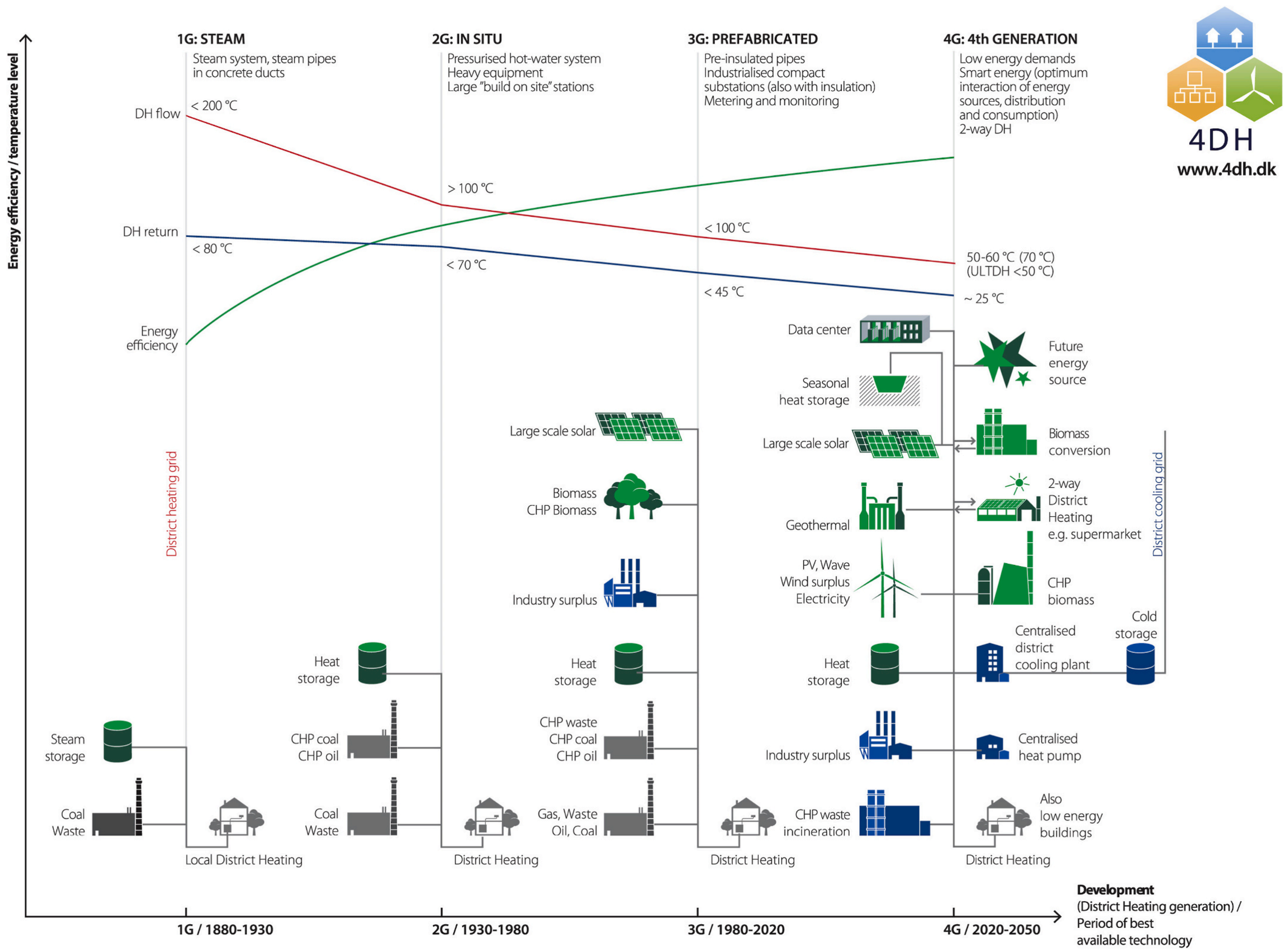


Fig. 2. Concept of the 4th Generation District Heating compared with the previous three generations [13].

hot-water systems, 4GDH is expected to facilitate the integration of low-temperature RE sources and the recovery of WH from e.g., data-centers and industries in combination with advanced technologies such as HPs and thermal storage (TS) into space heating while considering the efficiency improvement of the buildings as well as the reduced temperature in DH network [10]. The SES displays a coherent approach that integrates the different components of the energy system and exploits synergies through sector integration [12,14,15]. 4GDH can have an important role to play in such SES that combine the electricity, heating, industry, and transportation sectors in a way in which the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar energy.

The scientific aim of this review paper is to establish the status of the technical potential as well as the political strategies and barriers to implementing DH in China. The purpose is to create a platform for the discussion of gaps in current policies for the transition into 4GDH as an integrated part of SES in China.

1.3. Literature gap and contributions

Previous reviews of the Chinese DH systems [16–19] cannot adequately capture the fast changes in the DH systems in China in the recent decade. The latest study of scientific literature review on China's DH was published ten years ago, before 2013 [19], while the review of policy progress was published before 2017 and with a focus on the building sector [18]. The status and practices of the economy and restrictions of clean heating technologies in Northern China, in general, were summarised in Ref. [17] covering both individual and district heating, and an overview of the operational flexibility of DH systems was provided in Ref. [16]. However, some of the investigated clean heating technologies, specifically natural gas and low-emissions coal, are debatable in relation to their ability to contribute to reaching China's climate targets.

Aside from the review studies on the overall DH systems, there are also a wide range of comprehensive technology reviews focused on the respective heat resources and corresponding complementary technologies in China, including solar heating [20], geothermal heating [21], ground source heat pumps [22] and waste water sources HPs [23], WH recovery from the condensers of large turbine units [24] as well as large scale underground seasonal thermal energy storage [25]. However, to the best of the author's knowledge, a systematic review has not yet been made of the implementation of RE and WH in DH systems in a Chinese context from the perspectives of practices, policies, and scientific research. Such knowledge is essential for identifying research gaps and potential policy barriers to facilitating evidence-based decision making in the pursuit of sustainable and efficient DH systems in China.

This paper contributes to the literature by addressing the existing research gap by systematically reviewing and assessing a wide coverage of different subjects, encompassing the current status, policy landscape, and scientific literature on the integration of RE and WH in the DH systems in China. The goal of this paper is to help broaden the understanding of the current challenges and future directions in the field.

Given that the specific techniques have already been reviewed and undergone extensive examination in previous studies within the Chinese context [16–25], this paper will refrain from delving into the details of the related technologies. The cutting-edge advancements and experiences in the field from other countries, especially Denmark, are also utilised for discussion to enlighten the peer development of DH in the Chinese context. The focus of this paper is oriented toward future prospects in RE and WH heating as well as the technologies enabling this, such as HPs and TS. Therefore, the discussion in this paper excludes all types of fossil fuels, including natural gas, despite their current prominence in discussions within China.

The remainder of this paper is organised as follows: First, an overview of the status, potential and challenges of different renewable heat and waste heat analysedsources for DH are analysed in Section 2, based on data from international and local statistics in China. Furthermore, the analysis of the current policies and their impacts on the application of RE in DH is presented in Section 3. Section 4 reviews the scientific literature in international journals and Chinese journals. This leads to a discussion and perspectives in Section 5 on the technologies needed, the gaps in current policies as well as research for a transition towards 4GDH and an overall smart energy system in China. Finally, Section 6 concludes the paper.

2. Overview of the renewable energy and waste heat in district heating systems in China

The potential of decarbonising DH in China comes from WH recovery, biomass heating, geothermal energy, and solar thermal resources, which are available in different regions across the country. However, challenges of limited land as well as the geographic and temporal mismatch between these heat sources and the demanding area exist. This section first offers an overview of the current status, potential, and challenges of DH in China with a focus on RE and WH, which are analysed from both the demand and supply sides.

It is noted that due to the scarcity of data, detailed official statistics on DH systems in China are only partially available from the national government; however, data from other reliable non-official organisations in the field, mainly the Building Energy Research Center (BERC) at Tsinghua University and the China District Heating Association (CDHA), are adopted in this section as a supplementary.

2.1. Status of the current district heating system

The total fuel consumption for heating systems in China accounts for 20% of the nation's overall energy consumption [26]. As mentioned earlier, DH has a long history in Northern China for providing space heating in winter, aiming to maintain indoor temperatures at no less than 18 °C during the heating season, while domestic hot water mainly relies on individual solutions. China covers several different climate zones, which leads to variations in the duration of heating seasons across different regions, e.g., four months for North China and five to seven months for Northeast and Northwest China.

China is divided into five main heating zones according to the local climate conditions [27], namely severe cold, cold, hot summer cold winter, hot summer warm winter, and temperate, as shown in Fig. 3. The boundary of the DH area in China has been determined by a North-South heating line known as the "Qinling Mountains – Huaihe River" line. This line corresponds to the 0 °C isotherm of January in China [28]. DH is predominantly available in the severe cold and cold areas located in the northern part of the line, which is marked by white dashed lines in Fig. 3. These areas were nominated by the State as the location for the DH system installation in the 1950s with the aim to improve residential welfare.

The promotion of DH and the rapid development of urbanization in China has led to significant growth in DH coverage and gradually reached saturation in recent years, as shown in Fig. 4 [4,29]. In 2020, the total building heating area in northern China was 15.6 billion m^2, while the area covered by DH was about 9.88 billion m^2 [30]. The average heat loss rate in the DH pipeline network was around 20% in the same year [30]. The annual growth rate of the DH area has decreased from 16.3% in 2010 to 6.8% in 2021, with an average annual growth rate of 10%. By 2021, DH covered 18 provincial administrative regions, which are primarily in the Northern part of the country whereas DH is rarely provided in South and Southwest China, as shown in Fig. 4 (a).

The structure of the entire heating system in China, as depicted in Fig. 4 (b), shows that the DH system is predominantly reliant on coal as the primary heating fuel. Around 72% is provided by coal boilers and CHP. The data here include the heat supplies in all applications, including both individual heating and DH. The heat demand covered by RE resources (geothermal and biomass), industrial WH and electricity took up 8%. Although the precise data on the share of these technologies in the supply of DH are incomplete, it can be estimated that the share of WH and RE in DH is even lower than in the heating sector in general. The total district heating area in China during 2010–2021 is shown in Fig. 4 (c), where the cities predominant the DH areas.

2.2. Overview of the national heat demands

Identifying the heat demands is a critical step for the further investigation of the carbonization of the supply side. Considering the trend of future population, urbanization rate, and the building floor area, the current and future heat demands in 2035 and 2050 in the northern and southern urban areas of China, respectively, are estimated as shown in Fig. 5. The demand data is based on a study by BERC and more details can be found in Ref. [32].

Two scenarios, Reference Scenario and Fast-renovation Scenario, are employed here. The first scenario assumes that the existing non-energy-efficient buildings and corresponding DH networks will be renovated at the current speed, i.e., there will remain 23% and 15% low energy-efficient buildings in 2035 and 2050, respectively. In the second scenario, all the existing low energy-efficient buildings and DH networks will be renovated before 2035.

The total heat demand in China is expected to be approx. 4350–4950 PJ in 2035, while the demand will drop to around 4500–4800 PJ in 2050 due to energy efficiency improvements and a declining population. The northern part of China will make up more than 80% of the total heat demand. The total heat demand estimation of northern China is based on detailed analyses at the city and county level consisting of 1047 urban regions[3] using the ArcMap 10.3 software, which delivers the geographical distribution of heat demand in 2050 as shown in Fig. 6. Most cities in North China have a dense population and an intense heating demand with an average demand higher than 500 MW, while the urban regions in Northwest China are dispersed with an average heat demand of around 100 MW and only the capital of the provinces showing a relatively higher demand. It shall be noted that the predictive data for the heat demand in southern China remains a large uncertainty due to the fact that the heating roadmap in the region is still under discussion. Thus, this paper provides the total value of the southern heat demand instead of presenting a more detailed geographical distribution.

[3] According to the Chinese classification, there are five levels of administration: provincial, prefecture, county, township, and village. In 2017, there were 1340 county-level units in the 15 Northern provinces, which constitute the spatial entities in this study. After merging some of the municipal districts due to these circumstances, this study utilises 1047 urban units (UUs) representing the cities and county seats in Northern China, including 622 counties and 425 cities.

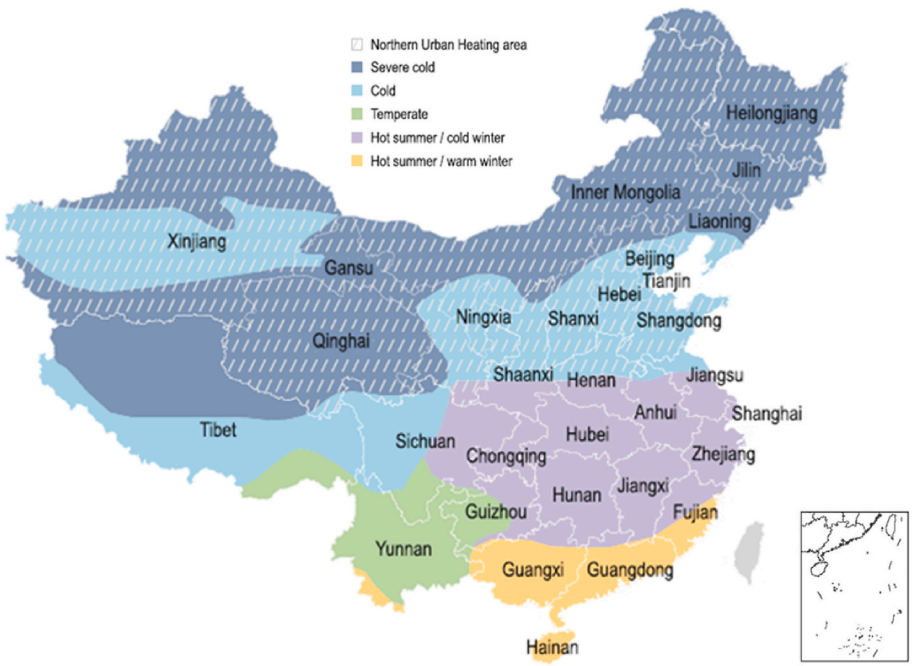


Fig. 3. Climate zones in mainland China. Note: reproduced based on Ref. [31].

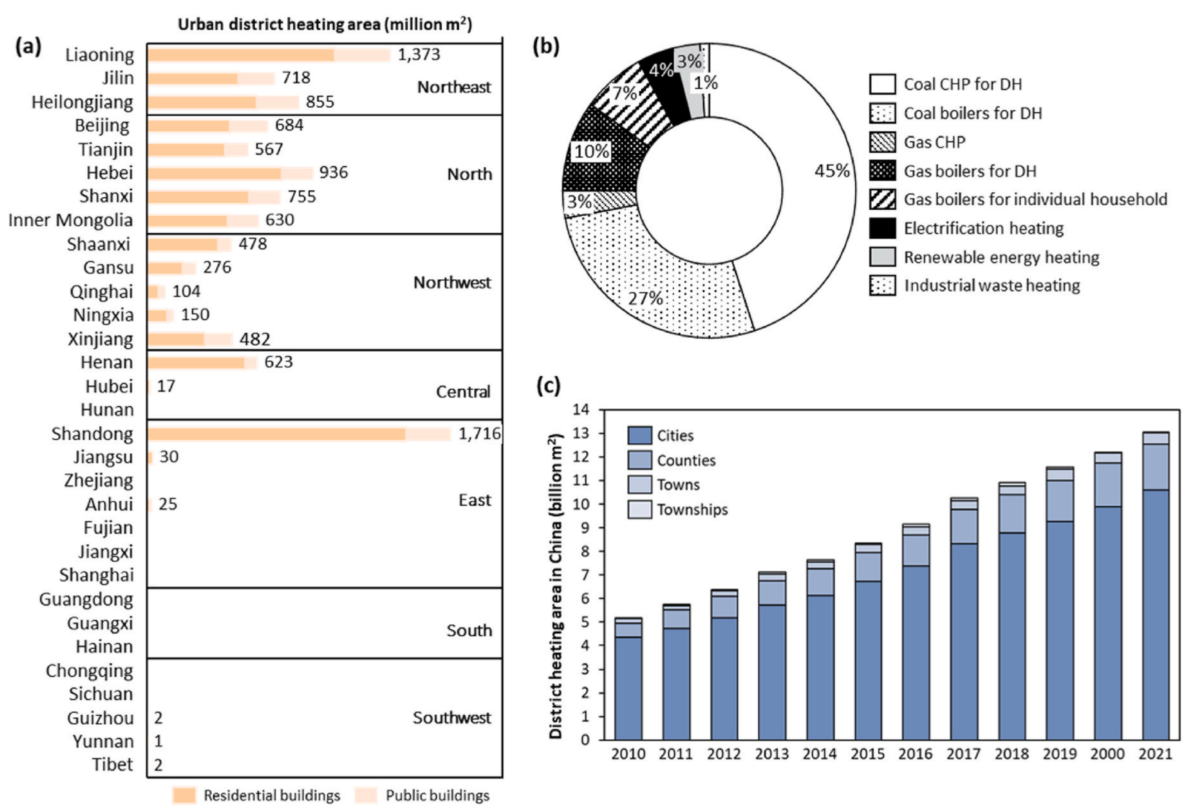


Fig. 4. Status of the district heating systems in mainland China. (a) Urban district heating areas in different provinces in China in 2021; (b) The structure of the heating systems in China by heat production technologies in 2021; (c) The total district heating area in China during 2010–2021.[21]

2.3. Status, potential and challenges of renewable energy and waste heat recovery in district heating systems

The heating sector can be decarbonised by combining the implementation of WH and RE in DH, renovation of buildings and energy efficiency improvement. This section provides an update on the status of the WH and RE technologies currently being developed in Chinese DH systems as well as the corresponding potential and challenges.

2.3.1. Waste heat recovery

WH refers to the heat generated as a by-product in the industrial or tertiary sector that can be recovered for multiple applications [33].

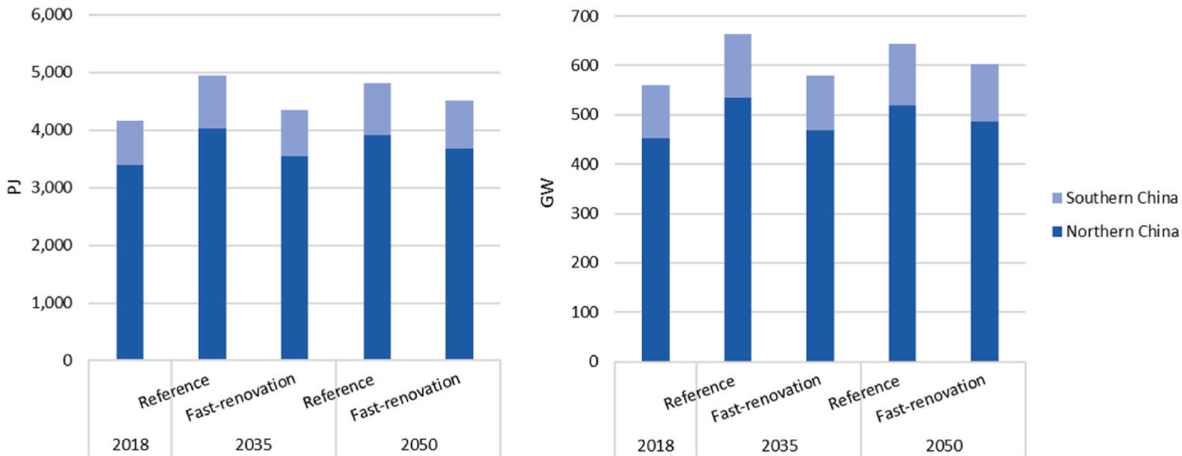


Fig. 5. The current and future heat demands in urban areas of China under different scenarios.

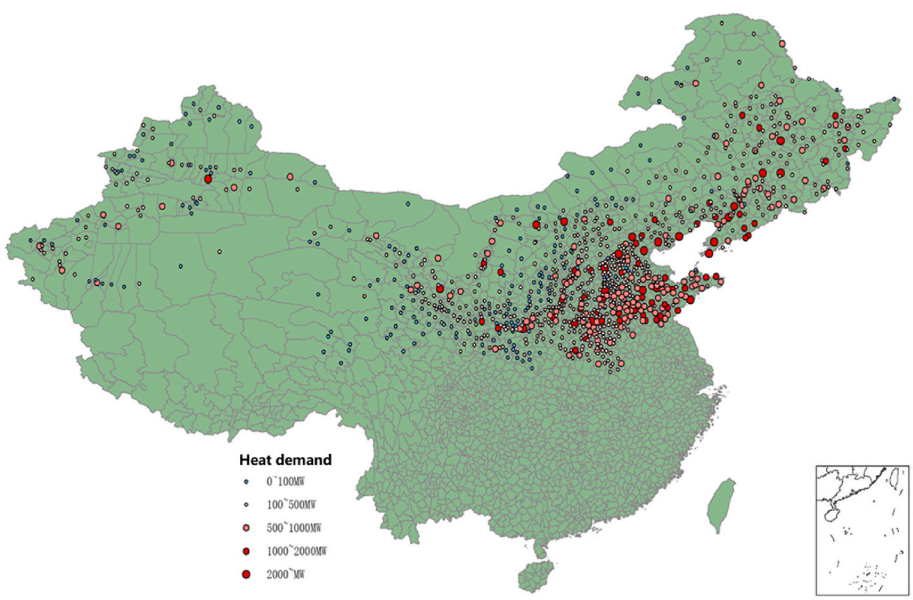


Fig. 6. The heat demand of 1047 urban regions in Northern China in 2050.

Depending on the temperature level of the WH source and the DH grid temperature, WH can be either directly useable in the DH system, if the temperature of the WH source is sufficiently high, or indirectly via HPs, if the inherent temperature level of the WH source is too low to allow for direct utilisation [8]. For example, HPs can be combined with the lower-temperature heat sources recovered from the changing decarbonised industrial sector [34]. The utilisation of WH can be an important resource in DH systems to decrease fuel consumption, e.g., coal consumption, for heat supply.

The technical potential of WH in China is presented in Fig. 7 according to the BERC [26]. The total WH that can be recovered during the winter season is around 7700 PJ, which is more than one-third of the total annual potential, i.e., approx. 19,800 PJ. The heat recovery from the existing condensing thermal power plants and the nuclear power plants consists of approx. 60% of the WH sources available in China. The third largest WH source is the energy-intensive industries that consume

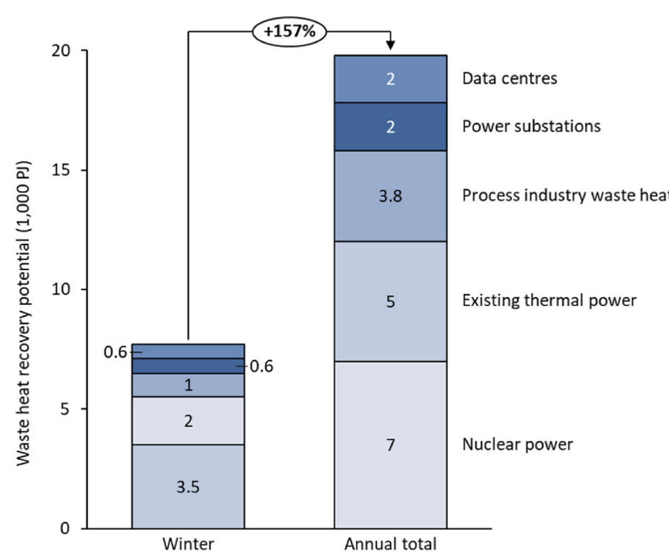


Fig. 7. Recovery potential of waste heat sources in China.

[2] In the statistics division of China, the urban area refers to the areas under the jurisdiction of cities and the areas of towns under the jurisdiction of counties, and the rural area refers to the areas of townships under the jurisdiction of counties.

abundant amounts of fossil fuels in their production process such as steel making, cement production and chemical industries. The total energy consumption of the industry sector accounted for 66.3% of the total energy consumption in China in 2021 [6]. And the rest of the WH potential comes from power transformation substations and datacentres.

The utilisation of WH in DH systems helps to improve overall energy efficiency. However, challenges remain in terms of the mismatch in time, location and temperatures between the supply and demand side. The heat output of the WH sources and the heat demand are inconsistent most of the time, which requires short-term and potentially seasonal thermal storage to balance the system. Also, the WH sources in China are usually located in the outskirts of the heat demand areas, as the energy-intensive industries have been strategically relocated to the suburbs along with the rapid urbanization in recent years. Therefore, long-distance, energy-efficient, and low-cost DH grids are critical to using the WH to a larger extent. Aside from the technological challenges, from the policy perspective, there is no specific regulatory authority in China to coordinate and optimise the utilisation of WH at the local level, which hinders the large-scale applications of WH. Also, there is uncertainty related to the use of WH, as the source of the WH might shut down or experience reduced activity resulting in a decrease in the WH available [35].

2.3.2. Biomass heating

Biomass heating is a mature technology in China compared with other renewable heating options. The main part of biomass heating is based on CHP and boilers, using agricultural and forestry biomass and biomass molded fuel (BMF). But waste incineration and biogas heating through the conversion process of biomass also play a role.

By 2019, the total heating area supplied via biomass technologies in China was about 480 million m^2, of which 70% was covered by biomass-fired CHP plants, 18.8% was by BMF boilers, and the rest was provided by biogas heating and biomass stoves [36]. The major DH-demanding areas in the Northeast, North and Central China mainly produce agricultural residues, while forestry residues are distributed in the Southwest and South China. More specifically, the CHP projects are mainly distributed in Shandong, Hebei, Liaoning, Heilongjiang, Jilin and Henan, while the BMF market is mostly in the Beijing-Tianjin-Hebei region, Shandong, the Pearl River Delta, and the central and eastern regions [37].

Following the same principles in Section 2.2, the BERC at Tsinghua University also investigated the heating potential of biomass resources and waste incineration in northern China. Biomass heating is expected to have a significant increase in the future, from the current level of 922 PJ in 2018 to a potential of 3058 PJ in 2050, while the potential of waste incineration is around 601 PJ in 2018 and may decrease to 565 PJ in 2050 due to waste recycling.

Despite the abundant potential, it should be considered that there is a limit to how much biomass can be used in the energy system if it is to be used at sustainable levels. Locally available sustainable biomass resources vary from area to area, but according to the estimation from the European Union, around 10–30 GJ biomass per capita can be considered a sustainable utilisation in the energy system [38]. The recent investigation on the maximum bioenergy potential in China varies from 41.21–58 EJ in the literature [39,40], which corresponds to 29~41GJ/capital. The major challenge for biomass heating is the competition between the energy sectors. The overall sustainability limit on biomass consumption for energy means that it is important to prioritize where in the energy system the need for using biomass is most relevant. Studies normally find these sectors to be industries and long-haul transport as they are hard to directly electrify [34,41–43], which also means that the biomass resources for the heating sector are limited.

2.3.3. Geothermal heating

China possesses abundant geothermal resources with recoverable reserves exceeding 20 EJ and has been the largest country in the world in terms of the scale of direct geothermal utilisation for many years. Geothermal heating has become the main force of growth in the heating market among all RE sources in recent years. By 2021, the geothermal heating and cooling area in China reached 1.33 billion m^2 [44]. The utilisation of shallow geothermal energy has witnessed a remarkable increase, while the development of medium-deep hydrothermal resources continues to expand mainly in Shandong, Hebei, and Henan. The exploration of hot-dry-rock geothermal has also started. In 2020, the installed capacity for hydrothermal heating, both with and without heat pumps (primarily for shallow geothermal systems), reached 14.2 GW and 26.5 GW, respectively. This resulted in an annual heat production of 197 PJ and 246 PJ, respectively [45].

The distribution of geothermal resources is uneven across the country with a clear pattern of irregularity and regional variation [46]. The distribution map of geothermal resources in China can be found in Ref. [47]. The geothermal resources are particularly well-suited for DH applications in China, as they offer a consistent source providing a reliable baseload supply. In addition, the distribution of geothermal resources in China is highly overlapped with northern areas in need of clean heating solutions, particularly in areas lacking coverage from the natural gas pipeline network [48].The medium-deep hydrothermal geothermal resources are promoted as the main clean heating options in these regions, including Beijing-Tianjin-Hebei, Shanxi, Shandong, Shaanxi, Henan, Qinghai, Heilongjiang, Jilin and Liaoning. To minimize the impacts on the soil underground, rock and groundwater, the applications of rejection with the same level as the production zone and heat exchange via a closed system are encouraged [49]. In particular, medium-depth geothermal heat pump systems have been proven to be a potentially efficient and applicable solution for cold regions with a lower need for space occupation, which is a key factor to be considered in the Chinese context [50,51].

Geothermal heating faces the challenge of being relatively costly to develop. Geothermal heating is very dependent on the local underground condition, which brings a high upfront cost in relation to pre-studies to investigate the underground potential for geothermal heat. Even after a proper pre-study, the deep geothermal projects also have a high degree of uncertainty which brings a high upfront CAPEX cost. Also, depending on the temperature levels of the underground and the DH grid, HPs might be needed to boost the temperature of the geothermal heat for proper utilisation in the DH system, which in turn increases the costs.

2.3.4. Solar heating

Solar energy has been a prominent source for DHW in China for decades. However, solar thermal energy has very few applications in space heating and industrial heating. Approximately 96% of applications cater to DHW, with only 4% serving space heating and industrial process heating needs [52]. In 2020, the solar heating area reached 16.5 million m2 in China [53]. China has an installed solar capacity of 20–110 $MW_{th.}$ for DH systems with an average heat capacity factor of about 0.7 kW_{th}/m^2 for its solar heating collectors. The largest solar DH system is implemented in Shijiazhuang in the Hebei province, while most of the smaller solar DH systems are situated in Tibet [54].

Solar radiation resources in China are generally abundant, although they show significant variation across regions due to distinct geographical conditions, as seen in Fig. 8 [55]. The lowest solar radiation areas are located in the Sichuan-Chongqing region with around 950 kWh/m^2, whereas the highest annual global radiation is 2330 kWh/m^2 in Tibet [56]. Solar energy has considerable potential in the severe cold and cold regions of China [57–59].

However, considerations such as space requirements and impact on landscapes can hinder the penetration of solar DH systems, particularly in densely populated urban areas where land costs are expensive, and there is a scarcity of suitable locations for the installation of solar collectors. Also, the seasonal variation of solar energy can limit the

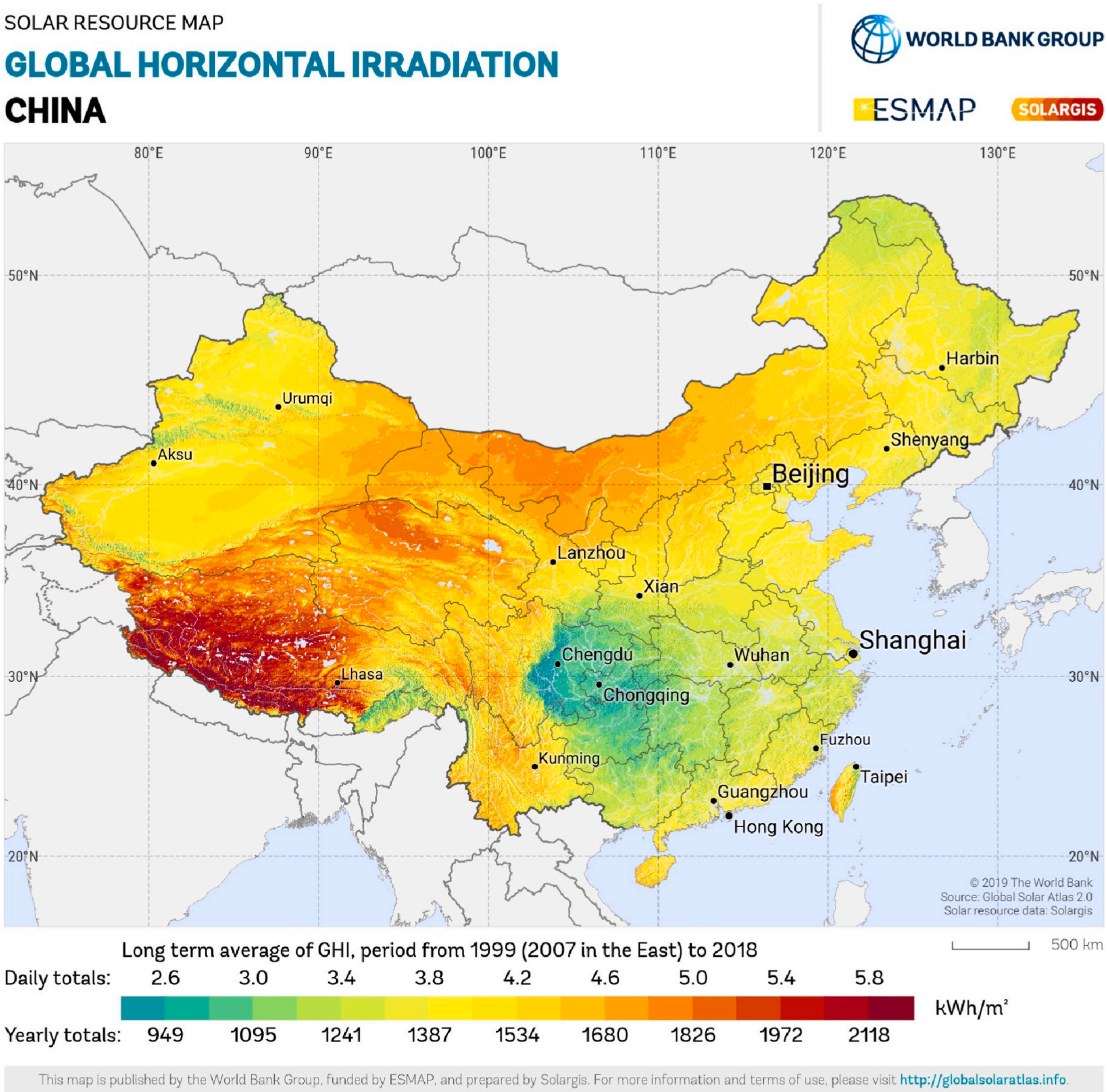


Fig. 8. Global horizontal irradiation in China. Note: Data for islands in South China Sea are not included here.

potential. Despite the option of increasing the potential by use of seasonal storage, the corresponding thermal loss still exists, which in turn increases the cost and potentially takes up space depending on the type utilised. Based on previous studies in Europe [60], the solar thermal share in the DH areas can be 6–12% of the total DH production with a 50% solar penetration rate, referring to the share of buildings that are connected to a solar thermal system.

2.3.5. Large-scale heat pumps

HPs are energy efficient heat generation technologies, which can extract heat from multiple sources, such as surrounding air, soil underground or nearby water sources, and upgrade to a desired temperature. Though HPs are also considered as enabling technologies for utilising WH and geothermal resources, the discussion of large-scale HPs here excludes these two resources, since they are discussed in previous sections.

When leveraging RE-based green electricity, the integration of large-scale HPs in the DH systems is expected to play a significant role in the decarbonisation of the heating sector [61]. Currently, quite a large proportion of large-scale HPs in China is powered by non-RE electricity. The capacity of the renewable power generator accounted for 42.5% of the total power capacity in China by 2020 [49]. In the severe cold region such as Northeast China, air-source HPs have relatively low efficiency due to the low ambient air temperature; thus, HPs based on geothermal and WH are more desirable. In Central and North China, large-scale HPs based on multiple sources are suitable depending on the local conditions [62].

Though large-scale HPs could contribute to the transformation of the heating sector with the decarbonisation of the electricity sector, the implementation of large-scale HPs poses significant challenges in many cities in the Chinese context. The high population and building density in urban areas present obstacles to the higher penetration of ground-source HPs, as the limited underground space is shared by all human activities and cannot be exclusively allocated to the DH network. The natural low-temperature heat sources are also insufficient to meet the heating demands of high-heat-density urban areas. These sources can typically provide heat to 20–30% of the buildings in urban areas in China [26]. Studies in Europe also indicate that there is a large potential for large-scale HPs in future DH systems covering up to 25–30% of the district heating production [63].

2.4. Summary and assessment of the balance between resource potential and heat demand

To sum up, the main potential for decarbonising DH in China comes from the heat recovery from thermal power plants. In addition to that, WH in other forms, biomass, geothermal energy, and solar thermal resources are also available in different regions across the country. However, challenges exist in terms of limited land in urban areas as well as the geographic and temporal mismatch between these heat sources and the demanding area.

However, industrial WH needs large-scale HPs or biomass during peak demand as these cannot be covered by geothermal or solar resources. Solar energy DH could play a role in southern China where the heat demand pattern is not known. Where there is potential for industrial WH (Northeast China), solar thermal energy is not compatible as summer demand would be covered and the heating season corresponds to the period when solar thermal resources are less abundant.

3. National policy and regulation mechanisms

In this section, a thorough analysis of the current national policies concerning RE and WH recovery in DH systems in China is presented, beginning with an overview of the national regulatory framework and followed by a comprehensive analysis of the different stages of policy development.

3.1. National regulatory framework of district heating

China's approach to regulating and developing its energy systems, including DH systems, is characterized by a top-down regulatory system. At the national level, the national ministries (e.g., NEA, NDRC, MOHURD, MEE, MOC, MOF, etc.[4]) are responsible for the overall development guidelines according to corresponding functions. The aim is to solve the common problems across the country. A series of development initiatives targeting different energy subsectors are issued by the respective national ministries every five years, called **Five-Year Plans (FYP)**. The latest plans are the **14th FYP** for the year 2021–2025. At the local level, the province government (autonomous regions and municipalities) compiles and implements the local clean heating plan in accordance with the requirements of the national plan and according to the local conditions of the region. At the corporate level, energy-related companies at all levels, encompassing electricity, oil and gas, and heating sectors, are required to break down and put into effect the goals set by the government.

3.2. National policies on district heating, renewable energy and waste heat recovery

As the primary heat supplier in northern China, DH has received increasing attention from the central government. Over the last two decades, a series of national policies, regulations, standards, and support measures relating to the heating sectors were developed as indicated earlier in Fig. 1. More details of the major national-level policies that cover DH-related components and corresponding key points are summarised in Table A1 in the Appendix. According to the level of support for RE and WH, the policy development of DH systems in China can be divided into three stages as follows.

Stage 1: Progressive development of the heating sector (pre-2017)

Prior to 2017, the regulations on the overall heating sector were typically covered in the national FYP for energy development. However, these regulations lacked a clear and comprehensive nationwide strategy for the heating sector. Starting from the 11th FYP and continuing through the 14th FYP, there was a shift in policy orientation from promoting CHP to the utilisation of cleaner heat sources including RE and WH. Additionally, specific policies related to the utilisation of geothermal and WH in the overall heating sector were introduced in 2012 and 2015, respectively, though they did not explicitly target DH. With regard to the building sector, three steps of building efficiency improvements were implemented from 1986 to 2010 which helped to reduce the unit energy consumption of the end-users.

Stage 2: Moderate development of RE and WH for heating (2017–2021)

Despite recent efforts to reduce coal consumption and promote sustainable growth, the heating sector in China attaches great importance to natural gas as an economic alternative to coal due to the fast replacement, rather than fully embracing RE and WH solutions. To address environmental issues brought by coal-based heating, the first national plan focusing only on the heating sector, "**Clean Winter Heating Plan in Northern China (2017–2021)**", was issued in 2017 [64]. The plan aims to realise 70% coverage of "clean heating" in northern China and reduce dispersed coal consumption by 2021 [65]. However, it should be noted that the concept of "clean heating" still includes natural gas and ultra-low-emission[5] coal. Natural gas was given high importance, whereas RE (geothermal, biomass, and solar energy) and electricity were regarded as supplementary mainly in the rural areas, where local conditions were suitable and there was a lack of gas infrastructure. Since the plan did not differentiate the DH target from the overall target of the heating sector, it remains uncertain how much RE and WH were integrated into the DH system.

In addition to the plan [64], other support policies for heating were issued in 2017 from the aspects of pricing and finance. For instance, the electricity and gas pricing policy for heating was improved to ensure the same electricity price for HP heating as for household electric heating, establishing a sound pricing mechanism of heating according to local conditions [66], and financial support was provided to pilot cities [67]. Furthermore, tax incentives were introduced for heating enterprises and residents. In addition, the 4th step of building efficiency improvement was also implemented in 2019, aiming at achieving 75% energy savings in the new buildings compared with the 1980s level.

Stage 3:RE and WH era towards dual carbon goals (post-2021)

Since China's pledge in 2020 to achieve its national dual carbon goals, the imperative of integrating a higher share of renewable energy into the entire national energy system has grown significantly. In response, a series of national support policies have been put forward. In early 2021, the first national strategy on RE heating was proposed – *"Notification of Implementing Renewable Energy Heating Suitable to Local Conditions"* [68]. It emphasized the promotion of renewable heating technologies, i.e., geothermal, biomass and solar thermal, in the heating sector as well as the corresponding policy support, and also defined the corresponding restrictive requirements considering environmental issues.

In the same year, another national guideline on geothermal energy was released – "*Several Opinions on Promoting the Development and Utilisation of Geothermal Energy*" [69], which set mid-to-long term targets for geothermal heating, i.e., achieving a 50% increase in the geothermal heating and cooling area in 2025 compared to 2020, and then double the area in 2035 compared to 2025. Additionally, the Opinions [69] referred to meeting the growing heating demand in southern China for the first time. More specifically, it promoted the utilisation of geothermal energy

[4] Abbreviations of the related national ministries are listed as follows. NEA: National Energy Administration; NDRC: National Development and Reform Commission; MOHURD: Ministry of Housing and Urban-Rural Development; MEE: Ministry of Ecology and Environment; MOC: Ministry of Construction; MOF: Ministry of Finance.

[5] Ultra-low-emission refers to the emission concentrations of smoke, sulphur dioxide, and nitrogen oxides, which shall not be higher than 10, 35, and 50 mg/m^3 respectively under the condition of 6% oxygen content as a reference level.

in the alpine regions of Yunnan and Guizhou and water-source HPs in the middle and lower reaches of the Yangtze River.

Subsequently, the latest national plans of the 14th FYP were issued in 2022, encompassing a broader range of aspects related to DH. For instance, "*The 14th FYP for the Modern Energy System*" [49], which outlined the comprehensive energy development strategy, addressed various aspects of DH. This included the promotion of CHP transformation and electric heating, the utilisation of WH from industrial and nuclear power plants, the incorporation of geothermal heating where conditions allowed, smart network operation coordination with both power and gas grids, and the implementation of clean heating electricity and heat pricing.

Detailed support for RE in the heating sector was elaborated more in "*The 14th FYP for Renewable Energy Development*" [49], which further covered biomass heating and heating infrastructure. For instance, it emphasized the upgrading of biomass power generation to cogeneration and encouraged the use of large and medium-sized biomass boilers for DH in urban areas. Moreover, "*The 14th FYP for the Development of New Energy Storage*" [70] introduced, for the first time, the pivotal enabling technology of thermal storage for a range of temporal resolutions, from daily to seasonal. Furthermore, "*The 14th FYP for National Urban Infrastructure Construction*" [30], addressed the enhancement of the urban DH network, including reducing heat loss in existing networks, minimizing building energy consumption, and expediting the renovation of ageing pipes and substations.

4. Scientific literature review on district heating in China

This section reviews the scientific literature to provide a comprehensive understanding of the research on the DH system in China from both internatioal sources and Chinese domestic sources.

4.1. Approach of literature review

Five steps are adopted to carry out the literature search and review, as shown in Fig. 9. The focus is put on the studies published in scientific journals from both international and Chinese local publishers to track the cutting-edge topics on the DH systems in China. Two major databases are employed, i.e., Scopus for international journal articles and China National Knowledge Infrastructure (CNKI) for the Chinese domestic journal articles. For the latter, note that only the articles published in the Core Chinese academic journals are included for a more professional screening.

Table 1 lists the detailed scope information used for the initial literature search process in Step 1. To make sure the articles are closely within the subject of this paper, i.e., DH system in China, an article screening process is necessary as presented in Step 3. In Step 4, an expanded search is conducted by adding RE into the search key words so as to find the remaining articles that are not found in the first round.

There is a variety of subtopics in the DH-related literature, including both review articles and research articles. To better understand the purposes, forms, and focus areas of these studies, the research articles are divided into four main categories: component-focused, district heating system-focused, energy system-focused, and policy focused. Table 2 shows the detailed descriptions of each category. The difference between component-focused and district heating system-focused is whether the article investigates more than one component. For instance, research that investigates the technical issue of thermal storage will fall into the category of component-focused, while research that optimises the solar DH system with thermal storage will be included in the category of system-focused.

Table 2
Description of the classification of journal articles.

Article categories		Descriptions
Review or survey articles		Review and analyse research previously published or provide survey results of the status of the DH system in China.
Research articles	Component-focused	Studies only focus on the heating sector and investigate a single component of the DH system, e.g., building, DH pipe network, heat generation utilities (CHP, boilers, HPs, etc.), thermal storage, heat sources (fossil fuel, WH, biomass, geothermal, solar thermal, wind).
	District heating system-focused	DH system-level study that only focuses on the heating sector and includes multiple system components.
	Energy system-focused	Studies consider the multiple sector synergy in the energy system instead of the single heating sector.
	Policy-focused	Studies focus on the discussion of heating policy, regulation, or institution related issues.

4.2. Review of the scientific literature in international journals

A total of 268 scientific articles related to the DH system in China were published in international journals during 2010–2022. Most of the authors are from Chinese universities and research institutes. A lack of review study is found that summarises all kinds of RE applications in the DH system of China.

Fig. 10 (a) shows the number of journal articles published each year, illustrating an increasing interest in the DH system in China during the past decades. The slight decline in papers published in 2021 and 2022 might be attributed to the effects of COVID-19. Component- and DH system-focused articles constitute the largest share in each year. The number of energy system- and policy-focused articles has grown since 2017, when the 'Clean Winter Heating Plan in Northern China (2017–2021)' was issued by the central government, which drew significant academic attention. Fig. 10 (b) shows the number of research articles classified by the main topics identified. Various topics are found for the DH system regarding technical, environmental, social, and policy aspects. Note that articles with hybrid topics may count multiple times in the respective classification. It is found that the top five topics are the operation optimisation, design, or reliability analysis of the DH network [71–73], HPs [74–76], CHP plants [77–79], WH utilisation [80–82] and policy aspects [83–85] (see Fig. 10).

From the perspective of heat sources, coal was the most widely used fuel in conventional CHP plants in the last decades, which caused heavy air pollution in Northern China [86]. To improve the air quality and accomplish the climate target, China has been looking for alternatives to coal in recent years and has issued a series of policies. Due to this, studies on the heating transition of "coal to gas" [85,87,88] and "coal--to-electricity" [89,90] emerged after 2017. However, inadequate domestic gas reserves and insufficient infrastructure resulted in gas

Table 1
Scope of the literature searches.

Data sources	Language	Keywords	Range	Article type	Period
Scopus	English	"China" and "District heating, Central heating or Clean heating"	Title, abstract, or author-specified keywords	Scientific journal article	2010–2022
CNKI- Core Journals	Chinese	"区域供热" or "集中供热"			

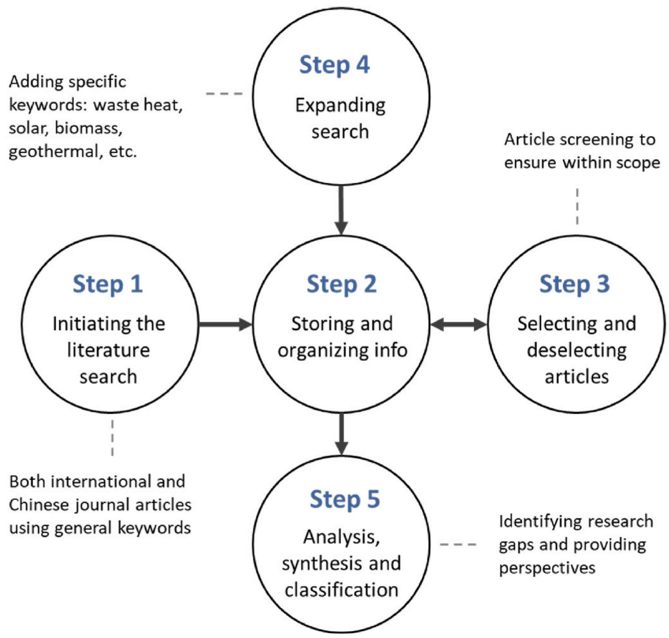


Fig. 9. Flowchart of the literature search process.

shortage during the winter heating season as well as other problems.

In relation to a further decarbonisation of the heating sector, academic interests are reflected in the increasing focus on other alternatives of heat sources. The interests according to which the number of articles are sorted are WH utilisation, wind integration, biomass, solar thermal, and geothermal. WH is regarded as one of the most promising ways [91,92]. Most literature investigated the implementation of recovering WH from CHP [93,94], thermal power plants [95] and nuclear power plants [96] with absorption HPs, from industries [80,82] such as iron and steel production [97,98], and very few analysed the possibility of the datacentres [99,100].

To reduce the problem of wind power curtailment in northern China, some research [101] introduced power-to-heat devices, including HP and electric boilers in the existing DH system, which is commonly in combination with TS [102,103]. Biomass heating is considered as a cleaner alternative instead of the coal used for heating in rural areas [104]. Studies investigated the positive effects of biomass boilers [105] and high-efficiency biomass stoves [106] to replace the traditional low-efficiency household heating stoves. For solar thermal, despite the limited application for space heating in China due to a significant obstacle of land availability, the literature still shows interests in solar DH systems, which are commonly installed with the assistance of seasonal TES [107–110] and air-or ground-source HP [107,111] to guarantee system reliability and cost feasibility. Geothermal heat is considered an underutilised resource for DH in China due to inadequate awareness, high upfront cost, and technical barriers. Existing research on the utilisation of geothermal heat in the DH system mainly focused on investment strategy [112,113], technical evaluation [114], and related environmental and economic analyses [115].

In addition, increasing academic interests are found in the debate of whether Southern China should apply DH [28,116]. Compared to the north area which is dominated by a DH system, in the south area, the efficiency and thermal comfort are much lower, but the price is higher [117]. Evidence found that promoting the DH market in appropriate areas in South China where the conditions are suitable may improve residential welfare and indirectly reduce energy consumption and financial burdens [28], which will bring new opportunities for RE heating in the southern area.

Looking into the energy system-based articles, research has been carried out on the issue of reducing wind curtailment in the North [118–120], and planning the future heat roadmap in China [121]. Interests in the design and operation of integrated energy systems [122–126] have been growing in the past five years, including the DH system as the key element. However, most research only studied the synergy between the electricity and heating sector.

The major gaps lie in the fact that very few studies investigate 4GDH or low-temperature DH in China. Tong et al. [127] estimated the energy-saving potential for a heating/cooling system in 20 cities in two Chinese provinces, which highlighted the importance of utilising low-grade WH from industries through 4GDH. Yuan et al. [61] found that large-scale HPs can be one of the feasible options to decarbonise DH in the Beijing-Tianjin-Hebei region. Fu et al. [128] designed a DH system using low-grade thermal energy for large cities, large WH sources, and high heating densities.

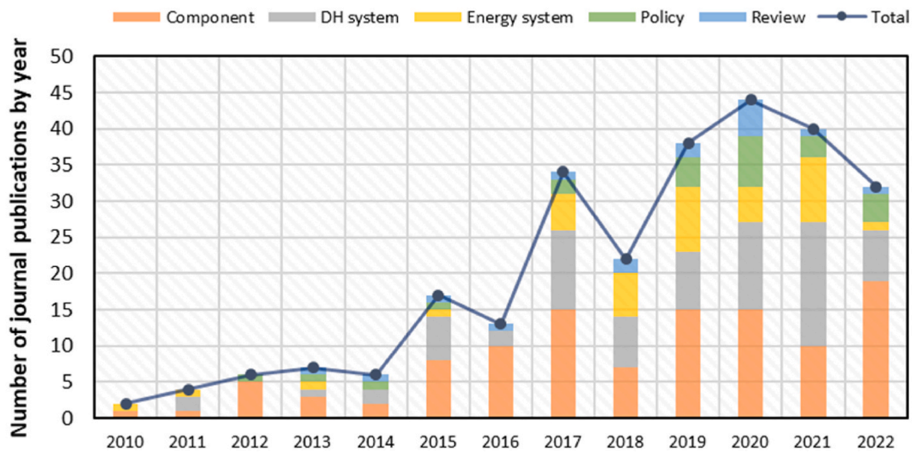
4.3. Review of the scientific literature in Chinese journals

To broaden the understanding of the DH research interests in local journals, a review of the academic articles published in Chinese journals was conducted, which identified a total of 285 scientific articles published about DH. Different from international publications, a considerable number of the authors publishing in domestic journals are from the private sector.

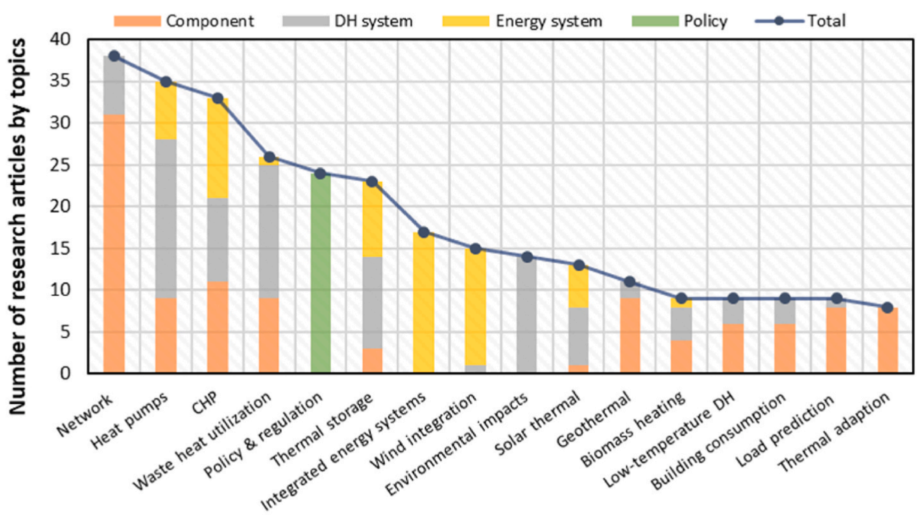
Fig. 11 (a) shows the number of journal articles published each year during 2010–2022, which illustrates a similar trend as in international literature. Component- and DH system-focused articles were the two dominant aspects before 2017, while the number of energy system-focused articles began to increase afterwards. Fig. 11 (b) shows the number of research articles classified by the main topics identified. It is found that the most frequently focused topic is the DH network, including both theoretical analysis, field research and case studies. This is followed by the three main topics of CHP, building consumption and HPs. By contrast, there are relatively fewer studies published in local journals on the topics of WH, solar thermal, biomass heating, and other RE heating. One of the major reasons behind this is that most researchers from academia prefer to publish cutting-edge studies in international journals, rather than domestic journals, to have a greater scientific impact.

Compared with the findings of international publications, there are similar insights from domestic articles in terms of WH utilisation, wind, biomass, solar, and geothermal. As for WH, most literature investigated the implementation of recovering WH from power plants [129–132] and industries [133–135], while very few analysed the utilisation of WH from recycled water [136]. To reduce the amount of wind curtailment in northern China, some research discussed the integration of the heating system and the power supply system [137], and the introduction of electric heating equipment in the DH system, especially the heating systems designed with thermal storage devices [138]. As for biomass heating, since the direct combustion of biomass has led to severe air pollution, both biomass gas [139] and biomass briquettes [140] have been introduced to utilise rural surplus biomass in urban DH systems. In relation to the utilisation of solar thermal, the literature on solar DH systems recently started to focus on seasonal TES [141]. Besides, there are some examples of existing research [142,143] focusing on the performances of the DH system combining with geothermal energy devices. However, in northern China, geothermal energy is mostly used for decentralised heating, and only accounts for a small proportion of DH.

Looking into the energy system-based articles, most research only investigated the synergy between the electricity and heating sector, e.g., reducing the wind curtailment in the North [144,145], promoting electric heating with thermal storage [146,147], as well as the comprehensive management of DH heating systems and power supply systems [148]. However, the other sectors of the energy system have not been considered.



(a)



(b)

Fig. 10. Number of articles about district heating in China published in international journals during 2010–2022. (a) Number of articles by year; (b) Number of articles by main topics.

5. Discussion and perspectives

5.1. Policy implications for integrating WH and RE in DH systems

Despite some guiding instructions that have been issued to promote the integration of low-temperature RE and WH in the DH systems, they are still in their infancy. Heating transition is a long-term, arduous task with high market demand. Existing policies are faced with a variety of challenges, which are summarised from the following aspects.

(1) **The definition of "clean heating" sources is subject to debate.**

The current pricing and support policy encompasses all sources of so-called "clean heating", including natural gas and low-emission coal. RE heating lacks a competitive advantage when compared to fossil fuels due to higher investment and operating costs. Ensuring profitability for heat supply enterprises while providing affordable heat to energy users pose a challenge. It is necessary to introduce various instruments at the national and local levels to establish a level playing field.

(2) **A long-term planning scheme is needed for WH and RE in DH.**

Currently, the nation heavily relies on natural gas during the initial stage of the heating transition. However, RE has become an unavoidable choice to meet the national carbon neutrality goal by 2060. The current RE target is insufficient and must move away from fossil "Clean Energy" –natural gas and coal. Additionally, raising awareness about the best available RE technologies is essential. Technical assistance programmes and streamlined authorization procedures for RE are required to achieve the 2060 target.

(3) **A deeper understanding of WH sources is required.**

The current policies mainly support WH sources from thermal and nuclear power plants as well as energy-intensive industries such as iron and steel. Despite the mentioned conventional WH sources of abundant potential for the Chinese DH system, there are more potential sources that can also be quite relevant. For example, excess heat from data-centres [150], metro stations, food retails, wastewater treatment plants,

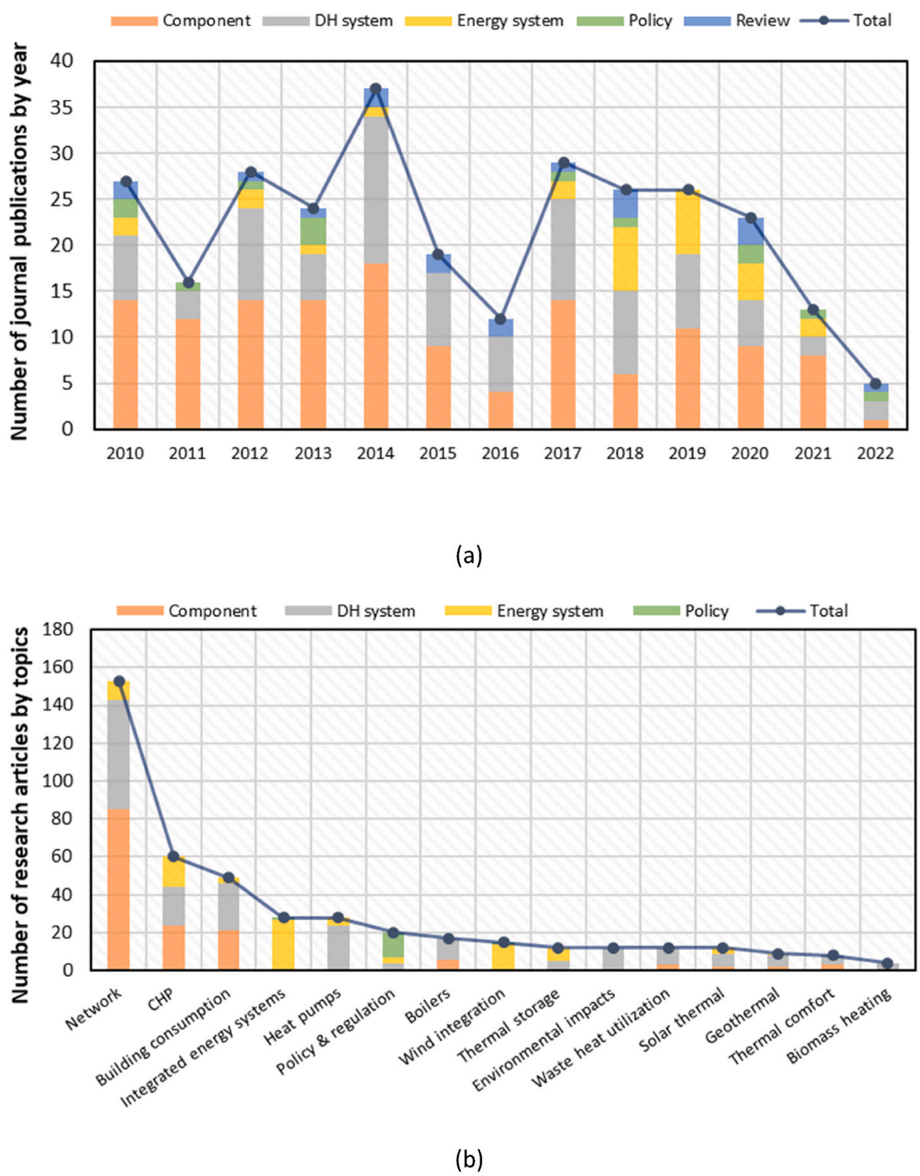


Fig. 11. Number of journal articles on district heating in China published in Chinese journals during 2010–2022. (a) Number of articles by year; (b) Number of articles by topics.

supermarkets as well as power-to-X (PtX) plants [8,151].

(4) **More concrete goals are needed for WH and RE in DH.**

Both the national and local level strategies lack clearly defined goals regarding the share of RE and WH in the overall heating structure and different types of heating systems, i.e., existing, expanded, and new DH systems. The existing goals for the entire heating sector fail to specify the share within the DH system. In addition, the level of integration and the priority of the various competitive heat resources RE vs. WH shall also be considered carefully, which requires further knowledge on the long-term energy planning considering the synergies among various energy sectors under the Smart Energy Systems concept as well as the efficiency improvement of both DH networks and buildings.

(5) **Supporting policies on integrating RE and WH in the heating sector in general are also needed.**

The current focus on integrating RE into the national energy system in China predominantly centres around electricity in general, while heating has not received sufficient attention and supportive policies in this regard compared to electricity. For instance, the policy on energy consumption points out that the electricity consumption from RE sources of each province will only be evaluated based on energy intensity, but will exclude the assessment of the total amount of consumption. Given the fundamental role of renewable electricity in achieving climate targets, while it is inevitable to highlight the deployment of RE in the electricity sector, it is still important to know that the national policy shall not overlook the capacity of the heating sector in terms of decarbonisation using RE and WH. from a system perspective.

(6) **Greater attention should be given to southern areas in China.**

The national heating development plan and financial support measures exclusively focus on areas located north of the North-South heating line. Expansion opportunities could be available throughout China, without being limited by zoning. There is significant potential for RE and WH in the hot summer and cold winter regions of southern China. Detailed mapping is needed to identify heat demand and supply resources in Southern China, supporting decision-making at the local, regional, and national levels.

(7) **More efforts are required on the reform of heat metering and charging.**

Though the introduction of the meter-based heat charging system as a replacement of the building floor area-based charging system has been proposed in China for many years, less progress is achieved. In 2022, nine ministries issued [149] "*Establish and Improve the Implementation Plan of Carbon Peak and Carbon Neutral Standard Measurement System*", which put forward essential standards that can be used in various sectors at all levels, including the energy sector. However, the description of the standard and the measurement system in relation to the heating system, both DH and household individual heating, is lacking in this implementation plan.

5.2. Research gaps and future directions

Based on the evidence from both international and domestic journals in China, it is founded that the overall DH systems in China have been well and widely studied. The research interests have been growing in recent years in terms of the various kinds of RE and WH sources. Nevertheless, some key gaps are still found and can potentially be the direction for further studies.

First and foremost, there is considerable potential for further promoting the adoption of 4GDH in China, which could improve the energy efficiency of the Chinese DH systems by allowing more efficient use of, e.g., HPs and low-temperature WH as well as reducing DH grid losses [8–10]. Considering the dual carbon goals in China, it becomes crucial to reduce energy intensity and enhance overall energy efficiency. The extensive literature on European countries like Denmark [8], Norway [155], Latvia [156] and so on has affirmed the benefits of 4GDH in terms of sector coupling, energy conservation, facilitating renewable energy integration, and environmental advantages. Encouragement should be given to bolster research efforts in the field of 4GDH in China.

Moreover, to the best of the author's knowledge, the current investigations on sector coupling have primarily focused on the integration between the electricity and heating sectors. However, there is a lack of studies conducted under the context of Smart Energy Systems [12,14], which encompasses all sectors of the energy system, including electricity, heating, industry, and transportation. This would enable the utilisation of low-temperature WH from the other sectors, such as the excess heat from the PtX plants that produce sustainable methanol and ammonia for the industry and transportation sectors.

The potential of these plants is still uncertain as the WH potential and temperature levels depend on the type of technology used and their geographical proximity to the DH grids. However, existing studies have already demonstrated the potential; e.g., a study for Denmark finds that WH from these sources could deliver more than 5% of the national DH production of Denmark [9]. Replicating the exact level of WH utilisation from other countries in China can be challenging due to variations in urban scale, land availability, types, and distribution of WH sources, as well as climate conditions. Nevertheless, the methodologies and concepts employed can provide valuable references for future research conducted in the Chinese context.

Also, the current focus on WH integration primarily revolves energy-intensive industries and power plants. This trend is also evident in national policies, as discussed in Section 3.2. Notably, there are only two publications addressing WH recovery from data centres [99,100]. To gain a comprehensive understanding of WH utilisation in Chinese DH, it is crucial to explore the potential and implementation of various low-temperature WH sources, e.g., supermarkets, metro stations and wastewater treatment plants, which warrants further investigation within the academic domain [8,157,158]. These sources become more relevant for DH as the grid temperatures are reduced, and they provide a higher temperature energy source for HPs than, e.g., air or seawater, resulting in a more efficient energy system.

Also, more importantly, despite the fact that a business scale has not been realized at present, the WH recovery from cutting-edge power-to-X (PtX) technologies is an abundant and valuable asset for the future high-share RE-based energy system [43]. The production of green hydrogen and green liquid fuel (e.g., methanol and ammonia) and gas are foreseen to be the trend to decarbonise the hard-to-abate sectors, especially industries [34,41] and transportation [152,153] in the future. With the boosting domestic hydrogen industry in China outlined in the National Hydrogen Industry Development Plan (2021–2035) [154], the WH recovery potential from electrolysers is expected to be on the way. Despite the uncertainty on the level of WH utilisation, which is contingent on the type of electrolysers chosen, it is anticipated that relevant studies from both academia and industries will help bridge the gap and capture emerging trends.

Some of the other gaps are, for example, further research to map the heat demands and assess the WH and RE potentials specifically in southern China. A thorough techno-economic energy system analysis is necessary to establish an informed foundation for developing DH planning across the entire country. These studies will provide valuable insights into the potential heat sources, including WH and RE integration, enabling more effective and efficient DH planning and implementation strategies.

6. Conclusions

This study provides a systematic review and assessment of the current status, policy framework, and scientific literature concerning the integration of RE and WH in DH systems in China. It is found out that, DH is currently the primary approach to fulfil the heating demands in the urban regions of Northern China. Despite the considerable RE and WH potential in China, the prevailing DH system relies on coal, resulting in environmental and health concerns. The primary technical obstacles include the uneven geographical distribution of RE and WH sources nationwide, the temporal mismatch between heat production and demanding points, and the potential challenges associated with further expanding the DH network in certain southern areas.

A comprehensive policy review revealed that the policy advancements in China concerning RE and WH in DH systems can be categorized into three stages: pre-2017, 2017–2021, and post-2021, according to the timeline. The emphasis on RE and WH in the heating sector, particularly from a policy perspective, began following the announcement of China's dual carbon goals in 2020. Prior to this, the focus had long been on phasing out coal without presenting ambitious targets for the integration of RE and WH. Also, despite still under the developmental stage, there is growing attention on the southern regions of China, particularly central and southwest China, which have been excluded from the national heating plan traditionally due to relatively lower demand compared to northern regions. The findings from the policy review highlight the importance of urging to enhance the policy support and to set concrete goals for the integration of RE and WH in DH systems. Instead of only focusing on the single heating or power sector, achieving the dual carbon goals necessitates the collaboration among all sectors of the energy landscape in society to create a long-term national energy plan so as to maximize efficiency through synergies among sectors, which is also the key element of the Smart Energy Systems concept.

To offer a thorough understanding from a scientific standpoint and to track emerging trends as well as the research gaps, a comprehensive literature review was carried out from 2010 to 2022 specifically focusing on the topic of DH in China. The review identified 268 and 285 academic articles published in international journals and domestic journals written in Chinese, respectively. The results show that the understanding of WH sources is primarily focused on the energy-intensive industries and heat recovery from thermal power stations, while only limited attention has been paid to the significant future WH potential from the emerging energy conversion processes such as biogas plants and PtX plants. Besides, great potential was identified for the further exploration of the 4th generation district heating and smart energy systems in the Chinese context to enhance local knowledge. Also, in response to the existing technical and policy challenges, a more holistic approach to identifying the local resources and heat demands around the nation, especially the southern China, is necessary to be able to make relevant decisions to move forward towards carbon neutrality.

CRediT authorship contribution statement

Meng Yuan: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Brian Vad Mathiesen:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Noémi Schneider:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Jianjun Xia:** Data curation, Writing – review & editing. **Wen Zheng:** Data curation, Formal analysis, Visualization, Writing – original draft. **Peter Sorknæs:** Funding acquisition, Writing – review & editing. **Henrik Lund:** Writing – review & editing. **Lipeng Zhang:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The work presented in this paper is supported by the Sino-Danish Strategic Sector Cooperation for Clean Heating in China; IEA-DHC Annex TS5 "Integration of Renewable Energy Sources into District Heating and Cooling Systems" and TS7 "Industry-DHC Symbiosis" funded by the Energy Technology Development and Demonstration Programme (EUDP) under no. 134223–497128 and no. 64020–2026; and REWARDHeat - Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks funded by the European Union Horizon 2020 research and innovation programme under grant agreement 857811. The study was first presented at the 18th International Symposium on District Heating and Cooling (DHC2023) in Beijing in September 2023, and this paper is an extensive version of the original conference paper. The authors would especially like to thank Mette Reiche Sørensen for her help in proofreading.

Appendix A

Table A1Major national policies, regulations, and supporting frameworks on district heating in China.

Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
2003	Eight ministries (MOC, NDRC, etc.)	Guiding Opinions on the Pilot Reform of the Urban Heating Structure	Stopping welfare heating and implementing heat commercialisation						✓	✓
2007	NDRC	The 11th Five-Year Plan for Energy Development (2006–2010)	Promoting CHP; Switch from distributed boilers to centralised heating; 40% urban heating area covered by DH system	✓						
2007	Central Government	Energy Conservation Law of the People's Republic of China	Implementing household heat metering for DH building step-by-step						✓	
2010	MOHURD	Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ 26–2010)	The new residential buildings with heating demand are required to save 65% energy based on 1980 to 1981 level.			✓				
2012	NDRC	The 12th Five-Year Plan for Energy Development (2011–2015)	Promoting of gas co-generation	✓						
2013	NEA, MOHURD, MOF, MLR	Guiding Opinions on Promoting the Development and Utilisation	Promoting geothermal heating where resources are available		✓					

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
		of Geothermal Energy								
2015	NDRC	Implementation Plan of Waste Heat Utilisation	2020 target: utilising low-grade waste heat resources for space heating for more than 2 billion m^2 and reducing coal for heating by more than 50 million tons.		✓					
2016	NDRC	Energy Supply and Consumption Revolution Strategy (2016–2030)	Promoting biomass heating and implementing geothermal where resource conditions are suitable.		✓					
2016	NEA	The 13th Five-Year Plan for Energy Development (2016–2020)	Promoting renewable energy utilisation in rural areas.		✓					
2016	NDRC	The 13th Five-Year Plan for Renewable Energy Development (2016–2020)	2020 target: solar heating collector area 800 million m^2, geothermal heating 1172 PJ, and biomass heating 440 PJ. Various types of renewable energy heating and civil fuels will replace a total of 3296 PJ.		✓					
2016	NEA	The 13th Five-Year Plan for Solar Energy Development (2016–2020)	2020 target: solar heating collector area 800 million m^2.		✓					
2016	NDRC	Administrative Measure for Combined Heat and Power Plants	Encouraging utilisation of clean and renewable energy for heating, including excess heat, excess pressure, biomass, geothermal, solar energy, and natural gas. Promoting the application of IEH and heat pumps.	✓	✓					
2017	NDRC	The 13th Five-Year Plan for Geothermal Energy Development (2016–2020)	2020 target: total space heating and cooling area by geothermal 1.6 billion m^2.		✓					
2017	NDRC, NEA	Guiding Opinions on Promoting the Development of Biomass-based Heat Supply	2020 target: biomass CHP 12 million KW, BMF 30 million tons, biogas 10 billion m^3, total bioenergy heating area 1 billion m^2. 2035 target: biomass CHP 25 million KW, BMF 50 million tons, biogas 25 billion		✓					

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
			m^3, total bioenergy heating area 2 billion m^2.							
2017	MOHURD	The 13th Five-Year Plan for Buildings Energy Saving and Green Building Development	Expanding the scale of renewable energy building applications.			✓				
2017	NDRC, NEA, MOF, MEE, MOHURD, SASAC, AQSIQ, CBRC, CSRC, LSCMC	Clean Winter Heating Plan in Northern China (2017–2021)	2021 overall target: clean heating area in north China reaches 70%, replacing bulk coal 0.15 billion tons. • Geothermal heating area (billion m^2): shallow geothermal 0.5 and hydrothermal 0.5. • Biomass heating area (billion m^2): total 2.1, including biomass CHP 1, urban household waste CHP 0.5, BMF 0.5, and biogas 0.1). • Solar heating area: 50 million m^2. • IWH heating area: 0.2 billion m^2. • New areas of natural gas heating: 1.8 billion m^2 during 2017–2021 in "2 + 26″ cities [a]. • Electricity heating area (billion m^2): total 1.5, including distributed heating 0.7, electric boilers 0.3, and heat pumps 0.5. • Clean coal district heating area: 11 billion m^2.	✓	✓					
2017	MOF, MOHURD, MEE, NEA	Notification of Implementing Central Financial Support for Pilots of Clean Heating in Northern China	Financial support for 43 clean heating pilot cities with 0.5–1 billion RMB/city/year.							✓
2017	NDRC	Opinions on Pricing Policy of Clean Heating in Northern China	• Improving electricity and gas pricing policies to							✓

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
			support "coal-to-electricity" and "coal-to-gas" reform • Establish a sound price mechanism of heating according to local conditions							
2018	NEA	Launching Country-level Clean Heating Demonstration Project of Biomass Cogeneration in "100 Towns"	Launching 136 demonstration projects in 20 provinces. • Installed CHP capacity:3.8 million KW. • Annual consumption of agricultural and forestry waste and household waste: 36 million tons. • Supply residential heating area: 90 million m^2, and Industrial heating: 69 million GJ.	✓	✓					
2018	MOHURD	Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ26-2018)	The new residential buildings with heating demand are required to save 75% energy based on 1980 to 1981 level.			✓				
2021	NEA	Notification of Implementing Renewable Energy Heating Suitable to Local Conditions	Provides guiding instructions on promoting renewable energy heating based on six aspects: • Scientific-based planning • Suitable local conditions • Promoting pilot demonstration projects • Guaranteeing supportive policies • Strengthening R&D support for key technologies • Improving the government management system		✓					
2021	NEA	Several Opinions on Promoting the Development and Utilisation of Geothermal Energy	Overall target in geothermal heating: • 2025 target: 50% increase in geothermal heating (cooling) area compared to 2020		✓					

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
			• 2035 target: double the geothermal heating (cooling) area and the installed capacity of geothermal power generation compared to 2025. Promote the utilisation of shallow geothermal heating. • Region of Beijing-Tianjin-Hebei-Shanxi-Shandong-Henan and the Yangtze River Basin: promote geothermal heating and cooling considering local demands. • Yunnan and Guizhou: using geothermal energy to meet the increasing heating demand in Southern China • Adopting surface water source, ground source, and groundwater source heat pumps where suitable. Promote the medium-depth geothermal heating in Beijing-Tianjin-Hebei, Shanxi, Shandong, Shaanxi, Henan, Qinghai, Heilongjiang, Jilin, Liaoning and other regions, considering the situation of the sources and the market demands.							
2022 29 Jan	NRDC, NEA	The 14th Five-Year Plan for the Development of New Energy Storage	• Boost the research and development of key technology and equipment of thermal (cold) energy storage. • Promote short-medium term high-efficiency thermal energy storage, including daily,				✓			

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
			weekly, and seasonal.							
2022 29 Jan	NRDC, NEA	The 14th Five-Year Plan for the Modern Energy System	• Promote CHP transformation and comprehensive utilisation of industrial WH and pressure in Northern region. Gradually phase out small coal boilers and dispersed coal within the coverage of the DH network. • Promote new electric heating equipment such as air source heat pumps, water source heat pumps, and thermal storage electric boilers according to local conditions. • Promote the comprehensive utilisation of nuclear energy in clean heating, industrial heating, seawater desalination and other fields. • Develop geothermal heating and cooling where suitable. • Build an intelligent and efficient energy operation system and explore coordinated scheduling of multiple energy systems, i.e., electricity, heat, and natural gas. • Implement clean heating electricity price, gas price, heat price and other policies.	✓	✓		✓			✓
2022	NRDC, NEA	Medium and long-term plan for hydrogen industry development (2021–2035)	Promote the integration of the hydrogen, electricity, and thermal energy system for a modern energy supply system that is multi-complementary and integrated.				✓			

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
2022 May	NRDC, NEA	Implementation plan for promoting the high-quality development of new energy in the new era	• Encourage public institutions to install PV or solar thermal utilisation facilities in existing buildings. • Promote clean heating in rural areas and clean agricultural production. Promote biomass, geothermal, and solar heating according to local conditions. Replace dispersed coal with new energy on the basis of ensuring safe and stable energy supply.		✓					
2022 June	NDRC, NEA, MOF,MNR, MEE, MOHURD, MOA, CMA, NFGA	The 14th Five-Year Plan for Renewable Energy Development	2025 target: Non-electric renewable energy utilisation reaches more than 60 million tonnes of coal equivalent, including geothermal and biomass heating, biomass fuel, and solar thermal energy utilisation. • Upgrade biomass power generation to cogeneration and provide DH for densely populated villages as well as small-medium-size industrial parks according to local conditions. Encourage the use of large-medium-size biomass boilers for DH in cities and towns. Promote the household molding fuel heating stoves in rural areas in the non-key region for air pollution control. • Promote medium and deep geothermal heating in the northern region depending on the resources		✓		✓			

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
			and market demands. Promote the use of shallow geothermal energy in the North China Plain and the Yangtze River Economic Belt which have both heating and cooling needs, by prioritizing the use of ground source heat pumps, then the recycled water source heat pumps, moderately develop surface water source heat pumps. Promote the development and utilisation of geothermal energy in southern alpine regions such as Yunnan and Guizhou. • Promote biomass, geothermal, solar, and electric heating in northern rural area according to local conditions. • Coordinate the planning, construction, and renovation of the heating infrastructure, and establish a heating system in which RE and conventional energy are complementary and cascaded. Improve the compatibility of the DH pipe network with the integration of RE such as geothermal energy. • Develop district comprehensive energy services based on the smart power grid, gas grid and DH network.							

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
2022 June	MEE, NDRC, MIIT, MOHURD, MOT,MOA, NEA	Implementation Plan for the Synergy Efficiency Improvement in Pollution and Carbon Reduction	• Promote the simultaneous implementation of building energy-saving renovation and clean heating in northern regions. • Give priority to supporting key areas of air pollution control to use RE such as solar energy, geothermal, and biomass to meet the building demands of heating, cooling, and domestic hot water. • Promote thermal energy utilisation technologies such as sludge biogas cogeneration in sewage treatment plants and water source heat pumps.		✓	✓				
2022 July	MOHURD, NDRC	Implementation Plan for Carbon Peaking in Urban and Rural Construction	• Targets for building efficiency improvement: In 2025, new buildings in urban area shall fully implement green building standards. The star-rated green buildings will reach more than 30%, and all newly built government-invested public welfare buildings and large public buildings shall be rated more than one star. In 2030, the main body of newly built residential buildings in severe cold and cold regions shall meet the energy saving requirements of 83%, and that for regions of hot summer and cold winter, hot summer and warm winter, and mild areas is 75%. The new			✓	✓		✓	✓

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
			public buildings shall meet the requirements of 78% energy savings. Encourage the construction of zero-carbon buildings and near-zero energy buildings. • Targets for DH network efficiency: implement renovation for DH pipe network for more than 30 years. By 2030, the heat loss of the DH pipe network will be reduced by 5% compared with 2020. • Promote the application of solar thermal buildings in areas rich in solar energy resources and in buildings with stable DHW demand. • Promote the application of geothermal and biomass heating as well as heat pump technologies. • Comprehensive utilisation the WH from heat and power cogeneration, industries, and nuclear power according to the actual conditions of each region. • Guide ultra-low energy building in cold regions no longer connect to municipal DH. Promote RE heating in rural area. • Accelerate heating metering and pricing according to the amount of heat supplied.							
2022 July	MOHURD, NDRC	The 14th Five-Year Plan for National Urban	• Reduce the heat loss of the DH pipe network and the energy	✓	✓	✓				

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Year	Ministry	Title	Key points	Conventional heat sources	RE & WH sources	Building efficiency	DH system renovation, expansion, & operation	Thermal storage	Metering	Pricing & financing
		Infrastructure Construction	consumption per unit building area. • Accelerate the renovation of the old DH pipe networks and substations. • Promote low-carbon heat resources, including co-generation, RE heating, industrial WH, natural gas and electricity heating.							
2022 June	MOST, NDRC, MIIT, MEE, MOHURD, MOT, CAS, CAE, NEA	Implementation Plan for Science and Technology to Support Carbon Peaking and Carbon Neutrality (2022–2030)	Research development for network connecting of new energy, thermal power and industrial WH, and long-distance DH technology. Develop new technologies for co-generation, co-supply and inter-seasonal co-storage of water and heat for the utilisation of WH from nuclear power plants in the northern coastal areas.		✓					

Note: NEA: National Energy Administration; NDRC: National Development and Reform Commission; MOHURD: Ministry of Housing and Urban-Rural Development; MEE: Ministry of Ecology and Environment; MOC: Ministry of Construction; MOF: Ministry of Finance; MNR: Ministry of Natural Resources; MOA: Ministry of Agriculture and Rural Affairs; CMA: China Meteorological Administration; NFGA: National Forestry and Grassland Administration; MIIT: Ministry of Industry and Information Technology; MOT: Ministry of Transport; MOST: Ministry of Science and Technology; CAS: Chinese Academy of Sciences; CAE: Chinese Academy of Engineering; SASAC: State-owned Assets Supervision and Administration Commission of the State Council; AQSIQ: General Administration of Quality Supervision, Inspection and Quarantine; CBRC: China Banking Regulatory Commission; CSRC: China Securities Regulatory Commission; LSCMC: The Logistic Support Department of the Central Military Commission.

[a] The "2 + 26" cities are the important cities located at the air pollution transmission channel of the Beijing-Tianjin-Hebei region, which include Beijing, Tianjin, 8 cities in Hebei Province (i.e., Shijiazhuang, Tangshan, Langfang, Baoding, Cangzhou, Hengshui, Xingtai, Handan), 4 cities in Shanxi Province (i.e., Taiyuan, Yangquan, Changzhi, Jincheng), 7 cities in Shandong Province (i.e., Jinan, Zibo, Jining, Dezhou, Liaocheng, Binzhou, Heze), and 7 cities of Henan Province (i.e., Zhengzhou, Kaifeng, Anyang, Hebi, Xinxiang, Jiaozuo, and Puyang).

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