Diversifying Heat Sources in China's Urban District Heating Systems Will Reduce Risk of Carbon Lock-in

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Abstract

China's clean heating policy since 2017 has notably improved air quality. However, the share of non-fossil sources in China's urban district heating systems remains low, and many new coal-fired combined heat and power (CHP) plants are being built. Strategic choices for district heating technologies are necessary for China to reach peak carbon emissions by 2030 and achieve carbon neutrality by 2060. Here we find that replacing polluting coal technologies with new and improved coal-fired CHP plants will lead to significant carbon lock-in and hinder decommissioning of associated coal-fired electricity generation. Expanding the use of industrial waste heat and air/ground-source heat pumps can avoid the need for new CHP construction and reduce carbon emissions by 27% from 2020 to 2030. Such a transition will unevenly increase heating costs depending on nearby availability of CHP and waste heat resources. Our findings inform implementation of the government's recent proposals to decarbonize district heating.

Introduction

Mitigating carbon emissions from heating buildings is a critical part of the global energy transition[1]. District heating systems, widely used in China, Russia, and Europe, distribute heat from a central location through insulated pipes to buildings throughout a city. District heating is promising for decarbonizing heating as it can integrate diverse low-carbon heat sources[2]. However, the full potential of district heating's decarbonization remains largely untapped. In 2020, fossil fuels accounted for 90% of global district heat production, contributing to nearly 4% of global CO_2 emissions[3]. Meeting global climate goals requires a substantial increase in the use of non-fossil energy sources, including industrial waste heat and large heat pumps powered by decarbonized electricity, in district networks[3].

Northern China hosts the world's largest district heating systems, consuming more energy than the entire UK and contributing ~1.5% of global CO_2 emissions[4]. Until 2016, China's district heating predominantly relied on inefficient polluting coal boilers and small-scale combined heat and power (CHP) plants. In addition to carbon emissions, these facilities contributed to severe air pollution, adversely affecting public health[5]. In response to the severe air pollution, the Chinese government launched a nationwide clean heating campaign in 2017[6]. A primary objective of the campaign was to replace polluting coal boilers and small-scale CHP plants with various clean district heating technologies, including large and efficient CHP plants (equipped with air pollutant emission control systems), natural gas boilers, and various non-fossil heating technologies. As a result, urban district heating demand met by large CHP plants increased to 54% in 2021, greatly contributing to the notable improvements in air quality observed in China in recent years[7,8]. However, the share of non-fossil sources in China's district heating systems remains low (~10% in 2021)[8], falling short of the 27% non-fossil heating goals set by the clean heating campaign for 2021[9].

For China to peak carbon emissions by 2030, reducing emissions from district heating will be crucial particularly in industrial cities where carbon emissions continue to rise[10]. Spurred by the announcement of the 2060 carbon neutrality goal, the Chinese government recently announced several clean heating policy proposals aimed at decarbonizing district heat, including increasing heat electrification and deploying low-carbon district heating technologies (Supplemental Table 1). Meeting the carbon neutrality goal will require an extraordinary near-term effort to expand low-carbon heat sources in China's district heating networks so that non-CHP sources contribute nearly two-thirds of total district heating by 2030[11]. Some studies highlighted the benefits of increasing the use of coal-fired CHP resources but did not consider associated carbon lock-in risks[12,13]. No previous studies, to the best our knowledge, have systematically evaluated the cost and emission implications of district heating options in China (Supplementary Note 1).

Here we examine the cost and emission implications of various possible near-term (2020-2030) district heating investment scenarios based on the assessment of 15 currently available district heating technologies. These investment scenarios range from a business-as-usual scenario ("high-coal"), representing practices prior to the carbon neutrality announcement, to an ambitious decarbonization scenario ("low-coal"), consistent with the full implementation of recent clean heating policy proposals. We find that the business-as-usual approach, i.e., replacing polluting coal technologies with existing and new coal-fired CHP plants, while resulting in cost savings, poses a risk of carbon lock-in and hinders the decarbonization of the power sector. In contrast, we find that expanding the adoption of industrial waste heat and air/ground-source heat pumps can facilitate achievement of the new heating policy proposals and avoid the need for new CHP plant construction, leading to a 27% emission reduction from 2020 to 2030. Such transition will increase the national total annualized costs per unit heat by 9% from 2020 to 2030, while unevenly affecting cities depending on the nearby availability of CHP heating sources and industrial waste heat.

District heating technologies

We assess CO_2 emissions, costs, and availability of various district heating technologies, including five fossil fuel technologies and ten non-fossil technologies (Figure 1 and Supplemental Table 2). Currently widely used coal-based technologies, i.e., coal boilers and CHP-extraction, have low costs but high CO_2 emissions. Improved coal-fired CHP technology utilizes large absorption heat pumps to recover waste heat from the power plants' cooling system (Supplementary Note 2), resulting in substantial reductions in both costs and emissions compared to current coal-based technologies. We find that the improved CHP technology has CO_2 emission factors only slightly higher than those of natural gas boilers and most grid-based options that use the 2020 power mix.

Replacing coal-based technologies with non-fossil alternatives faces challenges due to limited resources and higher costs. Most alternatives to coal-fired CHP, including those using heat recovery from nuclear or chemical plants, municipal solid waste, biomass, or wastewater, have limited resource availability. These technologies collectively can only meet a small fraction (<10%) of the total district heating demand. Among the options suitable for large-scale implementation, recovering waste heat from steel plants using large grid-based electric heat pumps shows the greatest promise. This technology has costs comparable to current coal-based technologies with significantly lower emissions as of 2020. Further emission reductions are possible with grid decarbonization. Air/ground-source heat pumps are also widely applicable and have operating costs similar to coal boilers; however, their capital costs are high. Hence, trade-offs exist among various district heating options.

Chinese district heating systems in 2030

To represent various levels of penetration of non-fossil heating technologies combined with existing and new CHP deployment in 2030, we develop three district heating investment scenarios, including high-coal, mid-coal, and low-coal (Table 1). All three scenarios aim to replace polluting coal boilers and small coal CHP plants with other options that satisfy the ~30% increased district heating demand expected in 2030 relative to 2020[11,14]. All three scenarios assume the optimal use of existing CHP resources from existing coal-fired power plants as proposed by existing policies (Supplemental Table 1).

New heat sources are necessary to meet 2030 heating demand. The high-coal scenario represents the business-as-usual approach used prior to the carbon neutrality announcement and involves the construction of many new coal CHP plants. The mid-coal scenario combines new coal construction with adoption of cost-effective recovery of industrial waste heat from steel plants, chemical plants and nuclear power plants. In contrast, the low-coal scenario represents a highly ambitious near-term action consistent with the full implementation of recent clean heating policy proposals. This scenario prohibits new coal CHP plant construction and reduces the capacity factors of existing coal-fired power plants to align with the 2°C climate goal (Methods). The low-coal scenario therefore necessitates the extensive integration of industrial waste heat and the implementation of air/ground-source heat pumps.

Total carbon emissions from district heating will increase by 10% in the high-coal scenario but will decrease by 3% and 27% in the mid-coal and low-coal scenarios in 2030, respectively, compared to 2020 levels (Figure 2b). Notably, the low-coal scenario reduces carbon emissions per unit heat by a third between 2020 and 2030. This reduction results from the widespread deployment of low-carbon electric technologies and accelerated decarbonization of the power grid.

Total heating costs per unit heat will decrease from 2020 to 2030 in the high-coal and mid-coal scenarios because of the replacement of inefficient coal boilers with CHP plants, while heating costs will rise in the low coal scenario, mainly due to the significant capital and operating costs of electric heat pumps. For the low-coal scenario, we estimate that a total capital investment of about 1 trillion yuan (~$140 billion) between 2020 to 2030 is required to enable the implementation of low-carbon district heating technologies. To provide context, in 2022 alone, China invested nearly 4 trillion yuan (~$546 billion) on clean energy including solar, wind, electric vehicles, and batteries[15]. In addition, we find that in the low-coal scenario operating costs per unit heat will increase by 12% in 2030 in the compared to 2020 levels (Figure 2d). In Chinese district heating markets, operating costs are annually paid by households, while a significant portion of upfront capital costs are covered by fees and taxes associated with home purchases as well as government subsidies[16]. Thus, the increase in household annual heating costs in the low-coal scenario are likely to be manageable, considering that household incomes are projected to rise from 2020 to 2030 in China[11].

The abatement costs of CO_2 emissions in 2030 between the high-coal to low-coal scenarios will be ~500 yuan per ton CO_2, and from the mid-coal to low-coal scenarios will be ~600 yuan per ton CO_2. These abatement costs are lower than the social cost of carbon (i.e., the economic damages that would result from one additional ton of CO_2 emissions) currently estimated at ~1200 yuan per ton CO_2[17]. Carbon prices in China's carbon emissions trading markets were ～70 yuan per ton CO_2 in 2023 and are projected to increase to 150-300 yuan per ton CO_2 by 2030[18]. The current and projected 2030 carbon prices are thus still insufficient to achieve the full implementation of recent clean heating policy proposals.

Carbon lock-in risks with new coal CHP investments

The district heating investment approach used prior to the 2060 carbon neutrality goal announcement, as represented by our high-coal scenario, involves the construction of many new coal CHP plants. This approach, while leading to cost savings compared to a low-coal scenario, will result in an increase in total carbon emissions from 2020 to 2030 in most northern Chinese cities, making the achievement of China's 2030 carbon emissions peak target challenging. Moreover, new and improved CHP plants require substantial investments and are built to last for decades. Consequently, these plants may lock in a reliance on coal and continue to generate emissions for decades, hindering the transition to alternative, low-carbon heating technologies and the achievement of China's 2060 carbon neutrality target.

In addition, CHP plants generate heat and electricity simultaneously. Utilizing CHP plants for residential district heating requires that these plants continue to operate to provide heat even if the electricity can be obtained from non-fossil sources. This creates challenges for integrating variable renewable energy into the power grid and minimizing renewable energy curtailment. We find that in 2020, existing CHP plants lock in ~440 TWh of coal-fired electricity generation during the heating season. This is equivalent to ~10% of Chinese coal power generation or ~5% of global coal power generation.

If the new clean heating proposals are not implemented, coal CHP capacity will expand and operate in accordance with our high-coal scenario. As a result, existing and new CHP power plants will cumulatively lock in ~19,000 TWh coal-fired electricity and produce nearly 30 Gt emissions from 2020 to 2060, assuming historical operational parameters (i.e., CHP plant lifetime = 30 years, heat-to-power ratio = 1.5) (Figure 3). For comparison, GCAM-China, a widely used integrated assessment model, determines that from 2020 onward the maximum allowable Chinese coal-fired electricity generation that is compatible with the 1.5° and the well-below 2°C targets are ~37,000 and ~63,000 TWh, respectively. Therefore, in the high-coal scenario, the locked-in coal-fired electricity generation from CHP plants during the heating season alone could represent ~50% of the 1.5°C budget and ~30% of the 2°C budget (Supplemental Figure 1).

Under the high-coal scenario, adopting improved CHP technologies with higher district heat production efficiency and a higher heat-to-power ratio offers a reduction of 4.5 Gt CO_2 emissions. Early retirement of CHP plants, for example, shortening the operational lifespan to 20 years, achieves another 4 Gt CO_2 emission reduction. However, early retirement may encounter significant challenges. The low operating costs of CHP plants makes it difficult to replace them with non-fossil technologies. Early retirement leads to stranded assets and drives up levelized costs of heat, possibly leaving coal-asset owners unable to recover their initial investments (Supplemental Figure 2).

The most effective way to reduce carbon lock-in is to avoid building new CHP plants and utilize non-fossil alternatives. Committed CO_2 emissions drop to 17-23 Gt in the mid-coal scenario and only 10 Gt in the low-coal scenario. The reduction of locked-in coal-fired electricity generation also facilitates more integration of variable renewable energy, supporting the decarbonization of electric district heating technologies.

Since 2020, local governments in China have approved a significant number of new coal power plants including both CHP and electricity-only power plants (Supplemental Figure 3). We examine the progress of new coal power projects across northern China using data from the Global Coal Plant Tracker database[19] and identify those that are or will be (partially) constructed to meet the demand for residential district heating. We estimate that a total of ~74 GW of new coal CHP projects, motived by residential heating demand, are either constructed, under construction, permitted or announced between Jan 2020 and June 2023. Many of these new projects still intend to utilize the currently widespread CHP technology instead of adopting improved technology which utilizes heat pumps to increase the efficiency of district heat production.

We compare these new coal CHP pipeline plants with the necessary new coal CHP capacity in 2030 in our high-, mid-, and low-coal scenarios (Figure 4). We estimate that 140-250 GW, 90-160 GW, and 0 additional GW of new coal CHP capacity is required to meet heating demand in the high-, mid-, and low-coal scenarios, respectively. The range of estimates reflects variations in assumptions regarding the capacity factors and heat-to-power ratios of new CHP plants (Methods). Notably, new coal CHP capacity in the pipeline in provinces including Shanxi, Inner Mongolia, and Ningxia already surpasses the projected necessary residential district heating needs for 2030. Our results suggest that some of these new CHP plants can be replaced by improving the use of CHP resources from existing coal-fired power plants. For newly commissioned CHP plants, adopting the improved CHP technology and planning for early retirement (or carbon capture retrofit) will be important to minimize future emissions.

Strategies for a low-carbon district heating transition

Diversifying heat sources in China's urban district heating systems by 2030 is critical to secure the climate goals. Based on our findings from the low-coal scenario, we outline a city-level strategy to avoid new coal CHP construction and meet the rising demand for district heating between 2020 and 2030. This strategy represents the preferred option to fully implement the recent clean heating policy proposals to promote the use of non-fossil technologies in district heating. The strategy varies across cities primarily based on the availability of existing coal CHP resources and industrial waste heat. Therefore, we categorize the ~300 cities into three main groups according to their greatest heating resource availability: "Abundant CHP", "Abundant Industrial Waste Heat" and "Limited Heating Resources" (Figure 5a).

More than half of the cities fall under the "Abundant CHP" group. For these cities, improving the use of existing CHP resources to replace polluting coal technologies enables a gradual shift to lower-carbon technologies. We find that existing CHP plants and existing pipelines can only meet ~26% of the national urban district heat demand in 2030 due to retirements of existing CHP plants and a reduction in capacity factors between 2020 and 2030 to facilitate power sector decarbonization (Methods). However, with improvement measures, existing power plant resources can meet ~41% of the urban district heating demand in 2030. These improvement measures include converting existing electricity-only power plants into CHP plants (~50 power plants), installing large absorption heat pumps to enhance district heat production efficiency (~110 power plants), and constructing new heat transport pipelines (~110 new city-plant pipelines) (Figure 5b). These new pipelines are longer, typically ranging from 15-70 km, compared to most existing plant-city pipelines (<20 km). Total CO_2 emissions, total and operating costs per unit heat in most "Abundant CHP" cities will remain similar to 2020 levels in 2030, despite an average 30% increase in district heating demand.

The "Abundant Industrial Waste Heat" group of cities presents a promising opportunity for a swift transition to low-carbon heating technologies by 2030. These cities are predominantly located in industry-heavy provinces, including Shandong, Liaoning and Jilin. Maximizing the economic use of industrial waste heat requires retrofitting ~50 steel plants, two nuclear power plants, a few chemical plants, and constructing ~55 associated new plant-city pipelines (Figure 5b). We estimate that integrating industrial waste heat into district heating will lead to a substantial >50% reduction in CO_2 emissions relative to 2020 levels in most cities, greatly helping these industrial cities in meeting the 2030 CO_2 emissions peak target. Moreover, total costs per unit heat in most cities will remain similar to 2020 levels in 2030, while operating costs will increase by an average of ~20% (Supplemental Figure 4).

The "Limited Heating Resources" group, with limited access to CHP resources and industrial waste heat, faces challenges in adopting low-carbon technologies by 2030. If new coal CHP construction is prohibited, extensive deployment of air/ground-source heat pumps is necessary by 2030 to meet heating demand. This deployment will significantly cut CO_2 emissions by on average 65% compared to 2020 levels (Supplemental Figure 4). However, it will also significantly raise both total and operating costs per unit heat by more than half. This cost increase is a significant challenge because these cities are largely located in economically disadvantaged regions with high existing household heating burdens (due to cold climates and low incomes), particularly in Heilongjiang, Jilin and Liaoning provinces[5,11]. These results highlight that targeted subsidies are needed to facilitate the low-carbon heating transition in these cities.

Another option, which we find to be a less favorable choice compared to heat pumps, is to expand the use of natural gas boilers and natural gas CHP plants as a bridge fuel to displace coal. We estimate that, compared with deploying air/ground-source heat pumps, using efficient natural gas technologies leads to slightly smaller emissions reductions with slightly lower total costs and higher operating costs in 2030 (Supplemental Figure 5). Such expansion of natural gas heating will require more than doubling the district heating sector's natural gas consumption from 2020 to 2030, potentially increasing the risk of energy insecurity due to China's heavy reliance on imported natural gas[20]. Moreover, natural gas CHP plants will also lock in CO_2 emissions from both district heat production and electricity production, similar to coal CHP that we have discussed. Our emission calculations do not include natural gas leakages. Previous studies show that natural gas may even have a similar carbon intensity to coal with a high leakage rate[21]. These results indicate that the adoption of air/ground-source heat pumps to replace coal technologies, instead of natural gas, on a large scale should be preferred.

Discussion

Our findings highlight the substantial impact of near-term investments in district heating systems on China's decarbonization trajectory. The high-coal approach used prior to the carbon neutrality target announcement continues to result in the construction of new CHP plants, leading to carbon lock-in and hindering the decarbonization of the power sector. The Chinese government recently announced several proposes to decarbonize the district heating sector (Supplemental Table 1), which is critical for China to secure its climate goals. Our findings inform implementation of these clean heating policy proposals.

We also highlight a crucial but often overlooked challenge in reducing coal power generation: the reliance on coal-fired CHP facilities for district heating. While previous studies have explored ways to decrease coal power generation by ramping up renewables and storage[22,23], few have addressed the decarbonization of CHP systems in the context of simultaneously meeting both heat and power demands. This is particularly important because relying on coal-fired CHP for district heating hinders decommissioning associated electricity generation.

Instead of using CHP, an alternative is to deploy low-carbon heating technologies, particularly recovering industrial waste heat and using air/ground-source heat pumps while decarbonizing the power grid. In our low-coal scenario, electric technologies, including waste heat recovery with large electric heat pumps and air/ground-source heat pumps, will meet 34% of total district heating demand in 2030. This substantial electrification necessitates a significant expansion of clean power infrastructure, requiring an additional ~200 TWh of electricity generation during the heating season (Supplemental Figure 6). To provide context, China is on track to build an additional 700 GW of utility-scale wind and solar capacity by 2030[24,25] and we estimate that these new sources will generate ~500 TWh of electricity during the heating season. The associated operational challenges of renewable grid integration are not fully captured by our annual supply-demand matching approach[1,26]. However, such limitations will not impact our main conclusions as renewable integration only has marginal effects on power grid costs by 2030[27–29].

Our analysis primarily focuses on the impacts of near-term (2020-2030) investments in district heating systems due to their direct and immediate policy implications. However, the path to achieving carbon neutrality in China's district heating systems by 2060 remains unclear. An important uncertainty pertains to the future availability of waste heat sources for district heating systems. For example, the availability of waste heat may decrease if a steel plant decarbonizes by shifting from a blast furnace to an electric arc furnace. Conversely, waste heat from data centers is expected to rise due to the growing demand for computing resources[30]. Another important challenge is to ensure power grid reliability with high district heat electrification, which leads to a substantial increase in winter electricity demand[26]. Promising solutions include long-duration energy storage[31,32], dual-fuel systems[1], and demand-side flexibility[33], but detailed assessments are needed. Previous studies have also suggested deploying CHP systems with carbon capture and storage on a large scale to decarbonize district heating[14,34]. However, the feasibility, costs, environmental implications, and impact on power grid flexibility need to be carefully examined.

While this study primarily addresses the supply-side transition to low-carbon options, improving demand-side energy efficiency is also very important. Substantial potential for energy efficiency improvements exists across northern China. Currently, ~20% of district heat production is lost due to overheating and network losses, and about 40% of urban residential buildings lack adequate insulation[4]. Improving energy efficiency can lower energy consumption and peak loads, reducing the need for extensive infrastructure upgrades and associated costs and emissions[26]. Moreover, improving energy efficiency enables more efficient use of electric heat pumps for district heating by lowering required water temperatures in heating networks[35].

Our analysis only includes technical and engineering costs and does not account for the "soft costs" associated with political and social challenges[36]. Soft costs are often higher for emerging low-carbon technologies, as they lack an established market presence[4]. Government policies are necessary to enable the adoption of low-carbon alternatives to displace coal-fired CHP technologies. This could involve implementing mandates such as renewable heating portfolio standards or mandatory building codes, as well as offering subsidies to low-carbon technologies and establishing government procurement policies.

Methods

Infrastructure database

We compile an infrastructure database of China's coal-fired power plants, steel plants, chemical plants, nuclear power plants and urban district heating systems, utilizing data sources including Global Coal Plant Tracker (Jun 2023)[19], Global Steel Plant Tracker (March 2022)[37], recent peer-reviewed literature[38], industry reports, and Chinese Urban Infrastructure Statistical Yearbooks[39]. We do not consider the utilization of waste heat from cement plants because most of China's cement plants cease production during the heating season. This regulatory measure is implemented to mitigate air pollution in winter and tackle overcapacity issue in the cement sector. For coal-fired power plants, we use publicly accessible project information and company homepages of power plants to identify whether a power plant is CHP plant and, if so, which cities it is or will be supplying district heat to. Our infrastructure database includes detailed information including capacities, status, technologies, locations, vintage years for ~1000 coal-fired power plants, ~170 steel plants, ~150 chemical plants, and 2 nuclear power plants ("Hongyanhe" in Liaoning and "Haiyang" in Shandong) in northern China (Supplemental Figure 7).

This database also includes locations, district heating capacity, and district heating demand for ~300 cities (including both city proper areas of prefecture-level cities and county-level cities) in 15 provinces in northern China, using data from 2020 Chinese Urban Infrastructure Statistical Yearbooks. China's district heating systems are predominantly located in the northern regions of the country, where the climate is colder and heating demand is higher. We determine the specific location of each city by first identifying the "urban grid cells" with a population density of >1000 persons/km^2 using a Chinese population gridded map[40]. We use the center points of these "urban grid cells" as the geographic coordinates (latitude and longitude) for each city. We estimate urban district heating demand for each city in 2030 based on projected future population[40] and per capita district heating demand[14] (Supplementary Notes 3).

We also collect data on the amount of municipal solid waste (MSW) and wastewater treatment at the city level in 2020 from Chinese Urban Infrastructure Statistical Yearbooks[39]. We use the biomass resource map developed by Wang et al. (2023)[41] to calculate the potential for district heating generation from burning agricultural and forestry residues (Supplementary Notes 3).

Carbon emissions calculation

We calculate carbon emissions using the specific emission factors for each district heating technology. The CHP extraction and CHP absorption heat pump systems operate using coal-produced hot steam, and their carbon intensity is determined by the steam's emission factors and heat production efficiency (Supplemental Figures 8-9 and Supplemental Table 3 for details). CO_2 emission factors of combustion heating technologies, including coal boilers, natural gas boilers, MSW incineration, and biomass boilers are obtained from previous studies[5,42] (Supplementary Note 3 and Supplemental Tables 4-5). For grid-based electric technologies, we estimate the carbon intensity of grid-based electricity in 2020 and 2030 using data from the IEA's stated policy and sustainable development scenarios, as well as proposed provincial renewable portfolio goals[43] (Supplemental Table 6).

District heat production potential calculation

We estimate the plant-level district heat production potential (*DHPP*) for coal-fired power plants, steel plants, chemical plants, nuclear power plants. For coal-fired power plants, the CHP extraction technology and CHP absorption heat pump technology require extracting hot steam from the turbine, and the amount of steam that can be extracted is limited by the amount of electricity generated[32]. For these two technologies, we calculate the district heat production potential based on unit capacity (*C*), capacity factors (*CF*), local heating days (*HD*), and maximum heat-to-power ratios (*HtPR*) as outlined in equation (1) (Supplemental Table 7). Unit-level maximum heat-to-power ratios are calculated based on unit capacity and cooling methods (Supplemental Table 8)[12]. The extraction-condensing method has a *HtPR* of 1.3-1.6, while the absorption heat pump method has a higher *HtPR* of ~1.8 due to waste heat recovery. We also use equation (1) to calculate district heat production potential for nuclear power plants. The maximum heat-to-power of nuclear power plants is 1.6[44].

$$DHPP = C \times CF \times \frac{HD}{365} \times HtPR \qquad (1)$$

Electric compression heat pumps can also recover waste heat from coal-fired power plants, steel plants, and chemical plants. For coal-fired power plants, we estimate the amount of recoverable waste heat (*RWH*) in the condenser based on power generation and power cycle efficiency (η) using equation (2). The percentage of total energy input contained in the condenser is represented as α (Supplemental Table 9)[6]. For steel and chemical plants, we estimate the amount of *RWH* based on plant-level production capacity, utilization factors, and waste heat generation per industrial product (Supplemental Table 10). We then estimate district heat production potential using the coefficient of performance (*COP*) of the large electric heat pump technology[45], as outlined in equation (3).

$$RWH = (C \times CF \times \frac{HD}{365}) \times \frac{1}{\eta} \times \alpha \qquad (2)$$

$$DHPP = RWH \times \frac{COP}{COP-1} \qquad (3)$$

For local low-carbon heating resources (MSW, wastewater, and biomass), we estimate their city-level district heat production potential based on the amount of MSW, urban wastewater, and crop/forestry residues (Supplementary Note 3).

Matching industrial plants with cities

Heat produced in industrial plants (including coal-fired power plants, steel plants, chemical plants, nuclear power plants) needs to be transported to cities through long-distance pipelines. We first pair existing coal-fired CHP plants with cities that are already connected by existing heat transport pipelines. We also propose possible construction of new heat transport pipelines from industrial plants to cities. These proposals are based on an optimization algorithm for the fixed charge transportation problem (FCTP)[46], as described in equations (4)-(6).

$$z(F) = min \sum_i \sum_j (pc \cdot d_{ij} y_{ij} + fc \cdot x_{ij} + tc \cdot d_{ij} x_{ij}) \qquad (4)$$

$$s.t. \sum_j x_{ij} \le a_i, \sum_i x_{ij} - l d_{ij} y_{ij} = b_j, \sum_i x_{ij} - l d_{ij} y_{ij} \ge 0 \qquad (5)$$

$$x_{ij} \le m_{ij} y_{ij},\ \ m_{ij} = min\{a_i, b_j\},,\ \ x_{ij} \ge 0,\ \ y_{ij} \in \{0,1\},, y_{ij} = 1 \text{ for existing linkages} \qquad (6)$$

The objective of this FCTP is to minimize the annual total costs, including a fixed cost (pipeline costs, $pc \cdot d_{ij} y_{ij}$) and two types of operating costs (fuel costs $fc \cdot x_{ij}$ and heat transport costs $tc \cdot d_{ij} x_{ij}$). Each industrial plant has a district heat production potential a_i and each city requires a certain quantity b_j of district heat from the industrial plants. x_{ij} and y_{ij} are decision variables in the optimization problem. x_{ij} represents the quantity of district heat sent from industrial plant *i* to city j. y_{ij} is a 0-1 variable that equals 1 if there is a heat transport pipeline from industrial plant *i* to city j. y_{ij} is set to 1 for existing linkages. d_{ij} is the distance between industrial plant *i* and city j, and l denotes the annual heat loss factor, in the unit of GJ/km. pc, fc and tc represent annualized pipeline unit costs (in the unit of yuan/km), operating unit costs (yuan/GJ), and heat transport unit costs (yuan/(km·GJ)), respectively.

In the case where district heating demand exceeds the supply from existing industrial facilities, we add a dummy plant with high penalty fuel costs to balance the model. Cities receiving heat from the dummy plant implies that their demand cannot be satisfied by existing industrial facilities alone, and additional heating sources (e.g., new coal CHP, air/ground-source heat pumps) are required.

We exclude the consideration of interprovincial heat transport pipelines (except the Beijing-Tianjin-Hebei region) due to the significant political challenges involved, such as challenges in acquiring land and obtaining permits and approvals. We treat the Beijing-Tianjin-Hebei region as one province because currently coal-fired CHP plants in Hebei are used to meet district heating demand in Tianjin and Beijing. We assume this practice will continue through 2030.We exclude the proposed pipelines that exceed 150 km in length due to high construction cost and heat loss during transport[47].

District heat cost calculation

We evaluate operating costs and annualized total costs per unit heat (annualized upfront capital costs plus operating costs per unit heat) of various district heating technologies. The annualized total costs per unit heat (ATC) of a district heating technology in year *t* can be calculated as equation (7):

$$ATC_t = (\frac{I}{AF} + OC_t)/H_t \qquad (7)$$

where *I* denotes the initial investment costs (Supplemental Table 11) and *AF* denotes the annuity factor. The discount rate is set at 7% in our analysis. OC_t denotes annual operating costs (including fuel costs, operating and maintenance costs, and heat transport costs) in year *t*. H_t represents the amount of heat delivered to the city (excluding heat loss if involving heat transport) in year *t*. See details in Supplementary Note 3. Our estimates of emissions, availability, costs of various district heating technologies are generally consistent with previous literature[11–13](Supplementary Note 1).

Power sector scenarios

Most existing large coal power plants in China, particularly CHP plants, are expected to continue operating at their current capacity factors during the heating season until the end of their historical lifespan (~30 years) in a business-as-usual scenario. However, to meet well below 2°C climate goals, a rapid reduction in coal use in power generation is necessary[48]. Therefore, we design two power sector decarbonization scenarios to represent possible power sector decarbonization between 2020 and 2030: (1) a Business-As-Usual (BAU) scenario, which assumes that coal power plants operate at their 2019 capacity factors until the end of their historical lifespan of 30 years. We assume that the share of non-fossil sources in China's total power generation will increase from ~35% in 2020 to ~45% in 2030, according to China's proposed renewable portfolio standards, and (2) an Accelerated Power Sector Decarbonization scenario, which represents an ambitious climate policy that the same power plants continue to operate but their capacity factors are reduced by ~18% from 2020 to 2030 to align with the well-below 2°C-consistent decarbonization pathway. This also aligns with current policies that require coal-fired power plants to become more flexible to integrate renewable energy sources. We assume that the share of non-fossil sources in China's total power generation will increase to ~67% in 2030 based on IEA's estimates (Supplemental Table 6).

We determine the maximum allowable Chinese coal-fired electricity generation from 2020 onward that is compatible with the 1.5°C (modeled as a ~50% chance to reach the 1.5°C climate goal) and well below 2°C targets (modeled as a ~66% chance to reach the 2°C climate goal), using an integrated assessment model, GCAM-China (China-focused version of the Global Change Analysis Model). The simulated well below 2°C-consistent mitigation pathways show that China will achieve carbon neutrality by 2070 and that China's unabated conventional coal power generation will peak in 2020 and be phased out by 2055. While China's pledge to peak CO_2 emissions by 2030 and reach carbon neutrality by 2060 can be seen as compatible with the 2°C climate goal in the long run, its current coal power policies indicate that coal power generation will not peak until 2030[49]. Therefore, our 2°C-consistent coal power phasedown scenarios represent a more ambitious near-term climate effort. The details of these power sector decarbonization scenarios are described in a previous study[50].

District heating investment scenarios

We develop three district heating scenarios (high-coal, mid-coal, and low-coal) to represent various possible near-term investment in China's district heating systems between 2020 to 2030 (summarized in **Table 1**). These scenarios range from a business-as-usual scenario (high-coal), reflecting practices prior to the carbon neutrality announcement, to an ambitious decarbonization scenario (low-coal), consistent with the full implementation of recent clean heating policy proposals. The mid-coal scenario represents a partial implementation of these proposals, utilizing the most cost-effective industrial waste heat for district heating. We assume that existing polluting coal boilers and smaller coal CHP plants (constructed before 2016) must be replaced by 2030 to tackle air pollution, aligning with national and regional environmental policies (Supplemental Table 1).

We assume the proportion of natural gas boilers will remain similar from 2020 to 2030 as existing natural gas infrastructure is expected to continue being utilized in 2030 and China's natural gas consumption is likely to see a moderate increase in the near term. Utilizing natural gas boilers for backup heating can help address grid challenges associated with increased electrification in district heating[1].

New investments in district heating technologies are needed to replace polluting coal technologies and meet the rising demand from 2020 to 2030. We begin with assuming that 20/50/80% of available local low-carbon heating resources (MSW, wastewater, biomass) will be used in 2030 in the high/mid/low-coal scenarios. However, these resources can only cover a small part (usually <10%) of heating needs in most cities.

We then explore using existing coal CHP resources and industrial waste heat to meet the remaining demand. Industrial waste heat is not considered in the high-coal scenario. All three scenarios assume the optimal use of existing CHP resources from existing coal-fired power plants commissioned before 2020, as proposed by existing policies (Supplemental Table 1). Using the optimization algorithm described above, we identify the most cost-effective linkages between industrial plants (coal-fired power plants, steel plants, chemical plants, and nuclear plants) and cities. Any linkages with total heating costs lower than air/ground-source heat pumps are considered as "constructed" by 2030. For each coal-fired power plant-city linkage, we calculate costs for three possible technologies (extraction, absorption heat pumps, waste heat recovery using electric heat pumps) and select the lowest-cost option. Waste heat recovery using electric heat pumps is more expensive than the other two technologies due to high electricity prices.

For the remaining heating demand, new CHP plants are assumed to be constructed in the high- and mid-coal scenarios, and air/ground-source heat pumps are deployed in the low-coal scenario. In the latter case, the lowest-cost options from air- or ground-source heat pumps are chosen for each province. Our analysis mainly considers the adoption of large, community-level air/ground-source heat pumps to produce heat that would be circulated through an existing district heating system.

To engage the ongoing debate in China regarding the potential benefits of expanding the use of natural gas heating, we also design a supplementary low-coal-natural-gas-heating scenario. In this scenario, everything remains the same as the low-coal scenario, except for the use of efficient natural gas CHP plants (with absorption heat pumps to recover waste heat), instead of air/ground-source heat pumps, to meet the remaining demand unmet by existing heating resources. This scenario represents recent proposals to use natural gas as a bridge fuel to displace coal in cities with limited low-carbon heating resources[51].

In our high/mid-coal scenarios for district heating, where new coal CHP is allowed, we assume that the power sector will decarbonize following the BAU power sector scenario. In the low-coal scenario where new coal CHP is prohibited, we assume that the power sector will decarbonize following the Accelerated Power Sector Decarbonization scenario.

The transition to low-carbon district heating will affect carbon emissions and costs differently across regions, mainly due to the availability of existing coal CHP resources and industrial waste heat. To illustrate this, we categorized ~300 cities with existing district heating systems based on their greatest heating resource availability. Cities where existing district heating resources (including existing coal CHP, industrial waste heat, MSW, wastewater, and biomass) cannot meet >50% of the 2030 heating demand are in the "Limited Heating Resources" group. The remaining cities are categorized by their main heating resource: "Abundant CHP", and "Abundant Industrial Waste Heat". Smaller cities which have relatively modest heating demand and can rely on local low-carbon heating sources such as MSW, wastewater, and biomass, are grouped into the "Local Low-Carbon" category. Beijing primarily uses natural gas for heating.

New coal CHP capacity

We calculate the necessary new coal CHP capacity ($Cap_{newCHP,p}$) in province p from 2020 to 2030 in the high/mid/low-coal scenarios using equation (8):

$$Cap_{newCHP,p} = \frac{H_{newCHP,p}}{HD_p \cdot 24 \cdot CF_{new} \cdot HtPR_{new}} \qquad (8)$$

where $H_{newCHP,p}$ represents the heating demand that must be met by new coal CHP in 2030 in the high/mid/low-coal scenarios. In the low-coal scenario, $H_{newCHP,p}$ is zero. HD_p is the number of heating days in each province. CF_{new} denotes the capacity factor for new CHP plants, which we assume to be 0.4-0.6 in our analysis[11]. $HtPR_{new}$ is the heat-to-power ratio for new CHP plants, which we assume to be between 1.5 (currently widely used extraction technology) and 1.8 (the state-of-the-art improved CHP technology) in our analysis[52].

CHP Carbon lock-in

We estimate the locked-in coal-fired electricity generation associated with district heat production from CHP plants, as well as the committed emissions from existing and new CHP power plants from 2020 to 2060. This estimation is based on unit capacity factors, lifetime, heat-to-power ratios, and the required district heating generation from new CHP plants. This calculation focuses solely on emissions associated with district heat generation thus excluding CHP plant emissions occurring during the non-heating season. See details in Supplementary Note 3. We also estimate the impact of CHP plant lifetime, CHP technology choices and other factors on the levelized costs of heat for the new CHP plant (Supplemental Figure 3).

Data Availability

Datasets of coal-fired coal power plants, steel plants, nuclear plants were obtained from the Global Energy Monitor (https://globalenergymonitor.org/)[19] and recent peer-reviewed literature[38]. Urban district heating data were retrieved from Chinese Urban Infrastructure Statistical Yearbooks[39]. All data generated and analyzed in this study are available within the Supplementary Information and Supplementary Data files.

Code Availability

GCAM-China is an open-source model publicly available at https://github.com/JGCRI/gcam-core/releases and a previous paper[50]. The plant-city matching algorithm is conducted using PuLP 2.7.0, a linear programming model written in Python, available at https://pypi.org/project/PuLP/.

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Author Contributions Statement

S.L. and D.L.M. conceived the idea for this project and designed the research. S.L. performed the research. Y.G. and F. W, contributed to method design and analysis. Y.G., H.L., and R.C. contributed data. S.L. and D.L.M. wrote the manuscript with feedback from all other authors.

Competing Interests Statement

The authors declare no competing interests.

Tables

Table 1. Scenario design for China's district heating systems in 2030.

	High-coal scenario	**Mid-coal scenario**	**Low-coal scenario**
Coal boilers/small CHP	Phased out	Phased out	Phased out
Natural gas boilers	Same share as in 2020	Same share as in 2020	Same share as in 2020
Existing coal CHP resources	Optimal use of existing CHP resources	Optimal use of existing CHP resources	Optimal use of existing CHP resources
Coal power capacity factors	Continue to operate at 2019 capacity factors	Continue to operate at 2019 capacity factors	Reduced to meet the 2°C climate goal (avg ~18%)
Power sector decarbonization scenario	Business-As-Usual scenario	Business-As-Usual scenario	Accelerated Power Sector Decarbonization scenario
Local low carbon heating sources (MSW, biomass, wastewater)	20% of total potential	50% of total potential	80% of total potential
Industrial waste heat (steel, chemical, nuclear)	Not considered	Used if cheaper than air/ground-source heat pumps	Used if cheaper than air/ground-source heat pumps
Air/ground-source heat pumps	Not considered	Not considered	Used to meet remaining heating demand
New coal power plant construction	Allowed	Allowed	Not allowed
Resulting coal CHP share in 2030	~81%	~67%	~41%

Figure Legends/Captions

Figure 1. Carbon emissions and costs for 15 district heating technologies. a-c, carbon emissions per unit heat (**a**) in 2020, (**b**) in 2030 under the Business-as-usual (BAU) electricity generation scenario (**c**) in 2030 under the Accelerated Power Sector Decarbonization scenario. **d**, annualized total costs (annualized capital costs plus operating costs) per unit heat in 2020. **e,** operating cost per unit heat in 2020.

For coal boilers (T1), natural gas boilers (T4), natural gas CHP with absorption heat pumps (T5), and biomass boilers (T7), segments show the typical range of their costs and emissions, which vary mainly due to combustion efficiency and fuel costs.

For technologies involving long-distance plant-city heat transport (T2, T3, T8, T9, T10, and T11), each point represents a plant-city linkage, and box plots depict data distribution with central lines as medians, and boxes for data quartiles. Emissions and costs vary mainly because of plant sizes, plants' remaining lifetimes, plant-city distances, local grid carbon intensities, and local residential electricity prices.

For MSW incineration (T6), wastewater-source heat pumps (T12), air-source heat pumps (T13), ground-source heat pumps (T14), and electric resistance boilers (T15), each point shows costs/emissions in a province, with variations mainly due to different MSW composition, residential electricity prices, grid carbon intensities, and heat pump efficiency among provinces.

Abbreviations: CHP, combined heat and power; MSW, municipal solid waste; WHR, waste heat recovery with electric heat pumps.

Figure 2. District heating generation, costs, and emissions, by sources, in 2020 and three scenarios projected for 2030. a, district heating generation. **b**, district heating CO_2 emissions. Average CO_2 emissions per unit heat are shown in parentheses. **c**, district heating total costs (annualized capital costs plus operating costs). Average heating total costs per unit heat are shown in parentheses. **d**, district heating operating costs. Average operating costs per unit heat are shown in parentheses.
Abbreviations: CHP, combined heat and power; MSW, municipal solid waste; WHR, waste heat recovery with electric heat pumps.

Figure 3. Locked-in coal-fired electricity generation and committed CO_2 emissions from existing and new combined heat and power (CHP) plants during the heating season in high/mid/low-coal scenarios from 2020 to 2060. a, locked-in coal-fired electricity generation. **b**, committed CO_2 emissions.

Figure 4. Required new coal combined heat and power (CHP) capacity in the low/mid/high coal scenarios by 2030 (bars) and new coal CHP capacity in the pipeline (triangles) as of Jun 2023 in northern China. The range of required new coal estimates reflects variations in assumptions regarding seasonal power capacity factors and heat-to-power ratios of new CHP plants (low value: capacity factor = 0.6, heat-to-power ratio = 1.8; high value: capacity factor = 0.4, heat-to-power ratio = 1.5). No new coal CHP occurs under the low coal scenario. We do not consider CHP projects that have been recently shelved, mothballed, or cancelled. We also do not include those CHP plants used only for industrial heat. **BTH:** Beijing-Tianjin-Hebei region. We treat the BTH region as one province because currently coal-fired CHP plants in Hebei are used to meet district heating demand in Tianjin and Beijing. We assume this practice will continue through 2030.

Figure 5. Geographic map of city groups and required infrastructure investments in the low-coal scenario. a, Geographic map of city groups in northern China. Cities are categorized into three groups according to their greatest heating resource availability: "Abundant CHP" (172 cities, representing 62% of total district heating demands in northern China), "Abundant Industrial Waste Heat" (29 cities, 12% of total) and "Limited Heating Resources" (68 cities, 20% of total). Additionally, 28 smaller cities (1% of total) can rely on local low-carbon heating sources (MSW, wastewater, biomass) due to their relatively modest heating demand. Beijing relies on natural gas for heating demand. **b,** cities, industrial facilities (CHP power plants, steel plants, nuclear plants, and chemical plants), existing and new city-plant heat transport pipelines in 2030 in the low-coal scenario. **Abbreviations:** CHP, combined heat and power; MSW, municipal solid waste.

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