Low-carbon Heating in Inner Mongolia

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Address
GIZ Office East Asia Sunflower Tower 1100
37 Maizidian Street, Chaoyang District
100125 Beijing, PR China

E climatechangechina@giz.de
I www.climatecooperation.cn

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Project Director
Paul Recknagel

Authors
Anna Nilsson (NewClimate Institute), Jamie Wong (NewClimate Institute), Takeshi Kuramochi (NewClimate Institute), Frauke Röser (NewClimate Institute)

Responsible Coordinator
Chen Yixing

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Summary

Phasing out fossil fuels in Inner Mongolia's heating sector is a requirement to meet the central government's climate objectives. Achieving the Chinese national goals of peaking emissions by 2030 and carbon neutrality by 2060 ("30/60 goals") will require the energy systems of all provinces and sectors to transform away from fossil fuels to the wide penetration of renewables. Such transformation will require careful and timely planning to allow for the development and commercialisation of appropriate technology and to avoid locking in fossil fuel reliant technologies and infrastructure. As one of the coldest Chinese provinces and endowed with rich coal resources, the heating sector of Inner Mongolia is energy intensive and a large CO_2 emitter, Following population growth, urbanisation and increasing living standards, residential heat demand in Inner Mongolia is growing more rapidly compared to any other Chinese province. Yet, Inner Mongolia is among the provinces with the highest renewables potential. Using that potential with already available and emerging heating technologies could be an opportunity for the province to avoid carbon lock-in of long-life fossil fuel-based heating infrastructure while delivering additional sustainable development benefits.

Inner Mongolia's provincial climate policy related to the heating sector promotes fossil fuel-based technologies and thus may jeopardise the achievement of climate targets. Chinese climate governance grants substantial liberty to provincial governments to design and implement policies. Provinces are ultimately responsible to meet climate targets set by the central government. The key provincial policy related to climate change and emissions mitigation in Inner Mongolia is the 14th five-year plan (14FYP) on climate change, which promotes the deployment of a wide set of "clean heating" technologies and fuels. However, the definition of clean heating in public policy documents includes a wide range of fuels and technologies, including fossil fuel-based technologies, with varying mitigation potentials. The promotion of such technologies jeopardises the achievement of the 30/60 goals by locking in carbon and delaying the integration of renewables.

The direct use of solar thermal, electric heat pumps, and hybrid versions of those could deliver zero emissions heat at large scale in Inner Mongolian urban and rural contexts. The most suitable decarbonisation technologies for heating vary across regions and depend on context specific factors such as available energy resources, climatic conditions/heat demand, and available infrastructure. The mapping exercise of available zero-emission heating technologies for the Inner Mongolian context, conducted as part of this research, suggests that the direct use of renewable heat, i.e., solar thermal, and electric heating in the form of heat pumps, as well as hybrid systems combining the two of those, could provide zero-carbon heat in the most energy efficient way, and at a large scale. Their high energy efficiency could contribute to low operational costs. However, high upfront costs remain a key barrier. Those technologies could feed into already existing district heating networks as well as decentralised heating.

The total number of low-carbon heating projects in Inner Mongolia is decreasing, and there is a general lack of pilot and demonstration projects of heat pumps and hybrid systems. Because those technologies are relatively novel, they have not yet been widely tested and deployed in Inner Mongolia or other extremely cold climates. In Inner Mongolia, we estimate that low-carbon heating options based on the technologies included in our mapping exercise have been initiated since 2010, out of which the majority were solar thermal district heating projects. The number of projects has declined in recent years, and there is a lack of projects focusing on heat pumps and hybrid systems.

There is a need for increased support for piloting and demonstration, clearer promotion of decarbonisation technologies and a stronger anchoring in the short and long-term provincial public policy. To achieve the 30/60 targets in a smooth and efficient manner, it is important to consider the mitigation potential of technologies as well as the lifetime of the technology and infrastructure and potential to reach full decarbonisation. To fully decarbonise the Inner Mongolian heating sector, a complete shift to renewables, mainly solar thermal and electric heating-based solutions, will be required. For their timely implementation and rollout, new technologies need to be piloted and demonstrated. Thus, full decarbonisation technologies could be more clearly highlighted and prioritised in official policy documents, while more support and guidance for their piloting and demonstration is needed. To avoid carbon lock-in, the long-term perspective should be considered, even in near-term policy documents. The development of a vision and strategy for the Inner Mongolian heating sector could give investors, policymakers, and other stakeholders a clearer idea of what is needed for the transformation, as well as provide useful inputs to the planning of other sectors such as the power sector.

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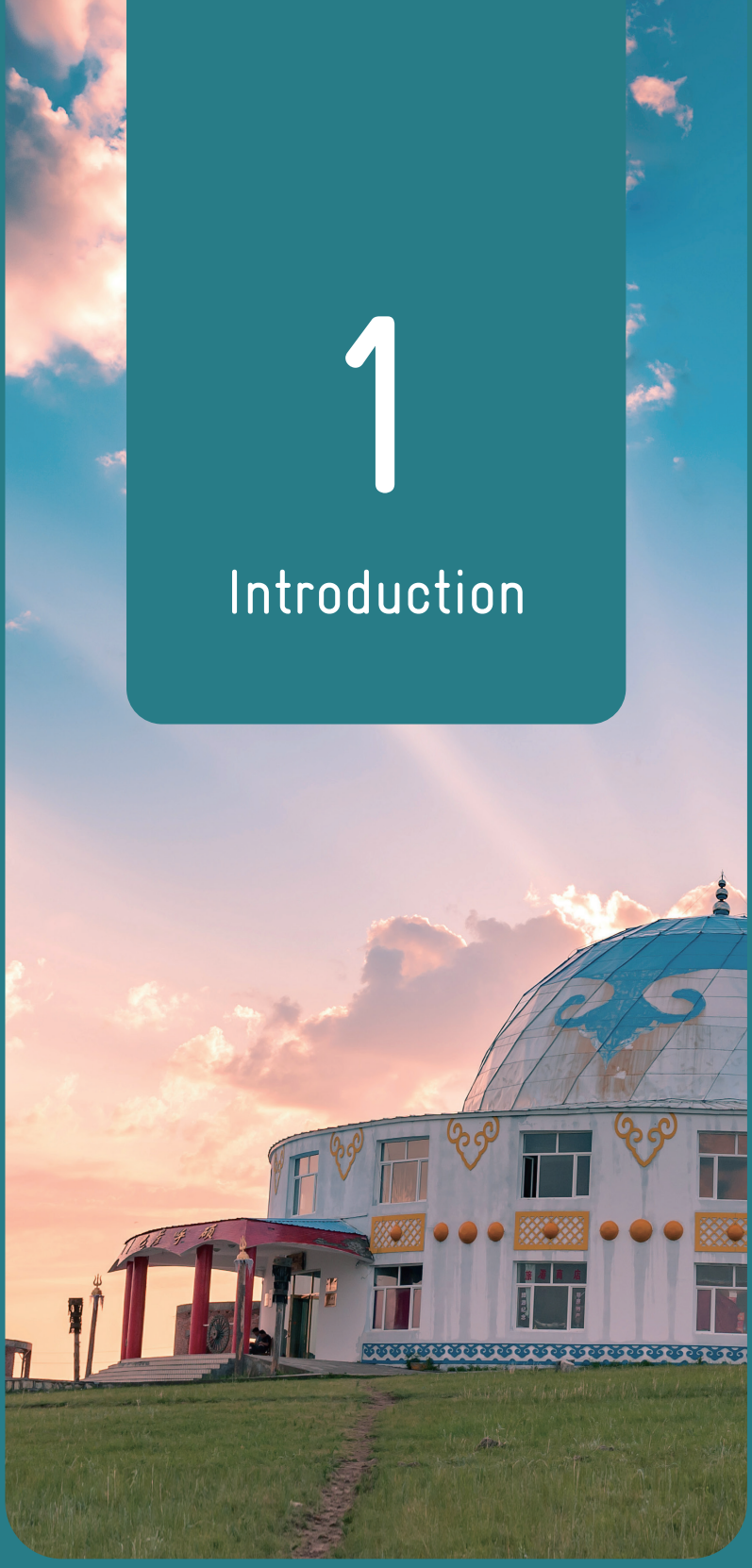
Acronyms and abbreviations

ASHP	Air-source heat pump
CHP	Combined heat and power
DH	District heating
FYP	Five-year plan
GSHP	Ground-source heat pump
k	kilo
LCOH	Levelised cost of heating
M	Mega
T	Tera
W	Watt
Wh	Watt-hour

1

Introduction



1 Introduction

1.1 Background and objectives

Considering China's climate objectives of peaking emissions before 2030 and achieving carbon neutrality by 2060 (hereafter the "30/60 goals"), provinces will play a crucial role as national targets are translated into provincial ones. In Chinese climate governance, provinces are ultimately responsible for achieving climate goals and have substantial autonomy in designing and implementing policies do so (Nilsson, Smit and Kuramochi, 2021).

Achieving carbon neutrality in the long term will require deep emission cuts across all sectors (Shukla et al., 2022). CO_2 emissions in the Chinese building sector increased by roughly 200% between 2000 and 2017, corresponding to about 17%-21% of national CO_2 emissions (Li, Qiu and Wu, 2021). The most rapid growth was observed in Inner Mongolia Autonomous Region (hereafter "Inner Mongolia") where emissions grew by 12.02% per year on average, compared to 11.95% in the second fastest growing province (Heilongjiang). The steep growth in emissions in Inner Mongolia can partly be linked to the severe climatic conditions in the region which experiences long and harsh winters with temperatures typically below 0°C during 6 months of the year and dropping to as low as to -40°C in the coldest days (ADB, 2017).

Inner Mongolia faces challenges, but also opportunities, to reduce emissions from its building sector. To comply with the long-term goal of reaching carbon neutrality by 2060, the way heat is generated needs to fundamentally change. The province's rich coal reserves (second biggest coal producer in China (Bloomberg News, 2022)) have been, and continue to be, the main energy source for heat and electricity in the province, which is also the most emissions intensive source of energy. In addition to the generation of CO_2 and other GHGs, it also results in increasing levels of air pollutants, leaving the human and animal populations at risk of severe diseases and premature death. To achieve carbon neutrality, the heating supply mix must therefore, initially, diversify to integrate more renewables, and in the long term completely phase out unabated coal and other fossil fuels through the wide deployment of renewable energy-based technologies.

Apart from rich fossil reserves, Inner Mongolia is endowed with vast renewable energy resources, and already produces most renewable energy among Chinese provinces. The integration of those renewables, however, is slowed down by the current set up of the energy system which is heavily reliant on coal-fired combined heat and power (CHP), leading to high levels of renewables curtailments (Wang *et al.*, 2020).

The pathway to transforming Inner Mongolia's heating sector could take various forms using various technology portfolios with different implications for other sectors and in particular the power sector. A number of renewable energy-based space heating technologies applicable in cold climates are already commercially available, while others are still emerging. Many of those technologies are directly or indirectly based on electrification, meaning that their application would need to be coupled with a decarbonisation of the power supply to reach zero emissions. The most suitable technology portfolio will be dependent on various context specific aspects such as renewable energy resources and the type of existing infrastructure and buildings and is likely to differ across urban and rural areas.

In this study, we aim to provide an overview of the Inner Mongolian residential and commercial space heating sector and potential pathways to achieving the 30/60 goals. We provide an overview and analysis of existing national and provincial climate policy related to the heating sector. We also perform a mapping exercise of potential decarbonization heating technologies and their suitability in the Inner Mongolian context. Those are compared to the Inner Mongolia government's vision for the heating sector and ongoing efforts in this regard. Based on that, we identify challenges and opportunities related to technological potential, synergies and tradeoffs including aspects such as energy security, affordability and implications for the power sector. As such, we do not attempt to identify the optimal technology mix for Inner Mongolia's heating sector as we do not perform any type of optimization modelling or quantification of any kind. The findings of this study can, however, serve as a basis for further research and modelling exercises, as well as input to policy development and the formulation of provincial heating decarbonisation plans and similar.

Scope of the study

This study considers the Inner Mongolian residential and commercial space heating sector. Due to the differences in heat and temperature demands and thus also technological requirements, industrial heat is not covered.

Even though the reduction of demand for heat through measures such as energy efficiency are vital to the transition (further discussed in (Chang, Zhu and Shang, 2017) (Shao, Zheng and Jin, 2020) (Li et al., 2021) (Zhang et al., 2021), the scope of this study is limited to the heating supply side.

In terms of CO_2 emissions, we evaluate technologies based on scope 1 and 2 emissions (i.e., direct onsite CO_2 emissions from fuel combustion and indirect emissions from electricity and heat generation).

1.2 Brief overview of current heating in Inner Mongolia

Emissions in the Chinese building sector increased from 668 $MtCO_2e$ in 2000 to 2.04 billion tCO_2e in 2017, corresponding to about 17%-21% of national emissions. The increase was mainly driven by growing GDP per capita, population growth, an increasing living area per capita, urbanisation and growing energy intensity. The most rapid emissions growth was observed in Inner Mongolia. Following Beijing, the energy intensity per square meter in Inner Mongolia is the second highest in China (249 kWh/m^2 compared to 270 kWh/m^2 in Beijing) (Huo *et al.*, 2019). The high energy intensity combined with the fact that coal is the main heating fuel in the province contributes to a high coal consumption which more than doubled between 2006 and 2010 (from 3.23 billion tce in 2006 to 8.71 tce in 2010) (Huo *et al.*, 2021).

The residential sector is the second largest contributor to CO_2 emissions in the province after the industry sector. Because the northern region of China is home to the country's largest industrial base, emissions from industry are high and amounted to 63% of total CO_2 emissions (135 Mt CO_2) in 2017 (Wang, Li and Zhao, 2021). Hence, despite the relatively high emissions intensity per square meter in the residential and service sectors, the overall share of emissions remains relatively low at about 12% (26 Mt CO_2) in 2017 Figure 1.

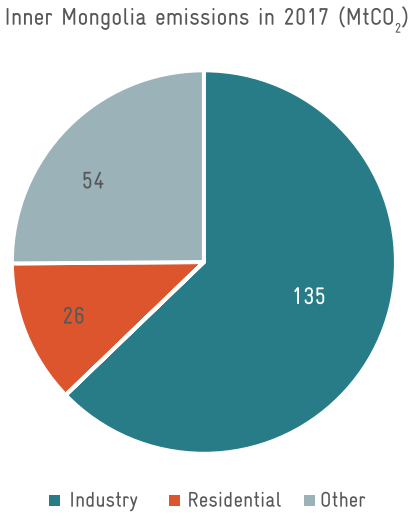


Figure 1. Inner Mongolia CO_2 emissions in 2017 by sector. Other includes agriculture, construction, transport, retail and others. Source: (Wang, Li and Zhao, 2021)

1.2.1 Urban areas

Inner Mongolia's urban population has historically increased steadily, rising from 42% in 2000 to 67% in 2020 (Inner Mongolia Autonomous Bureau of Statistics, 2021), and is projected to continue to rise further (Inner Mongolia provincial government, no date). The scope and access

to district heating systems have also increased rapidly in recent years with an average annual rate of 12% between 2011 and 2018 (Figure 3) and are now well established in the Inner Mongolian urban context; All 22 cities and 69 county seats currently have a complete district heating system with an average penetration rate of 86% within the cities/county seats in 2017 (Zhang *et al.*, 2019). The majority of district heating systems are based on coal fired CHP. Buildings not connected to district heating are typically heated with coal boilers and, to a small extent, heat pumps. Overall, coal boilers and coal fed CHP provide the majority of heating services (99%), as presented in Figure 2.

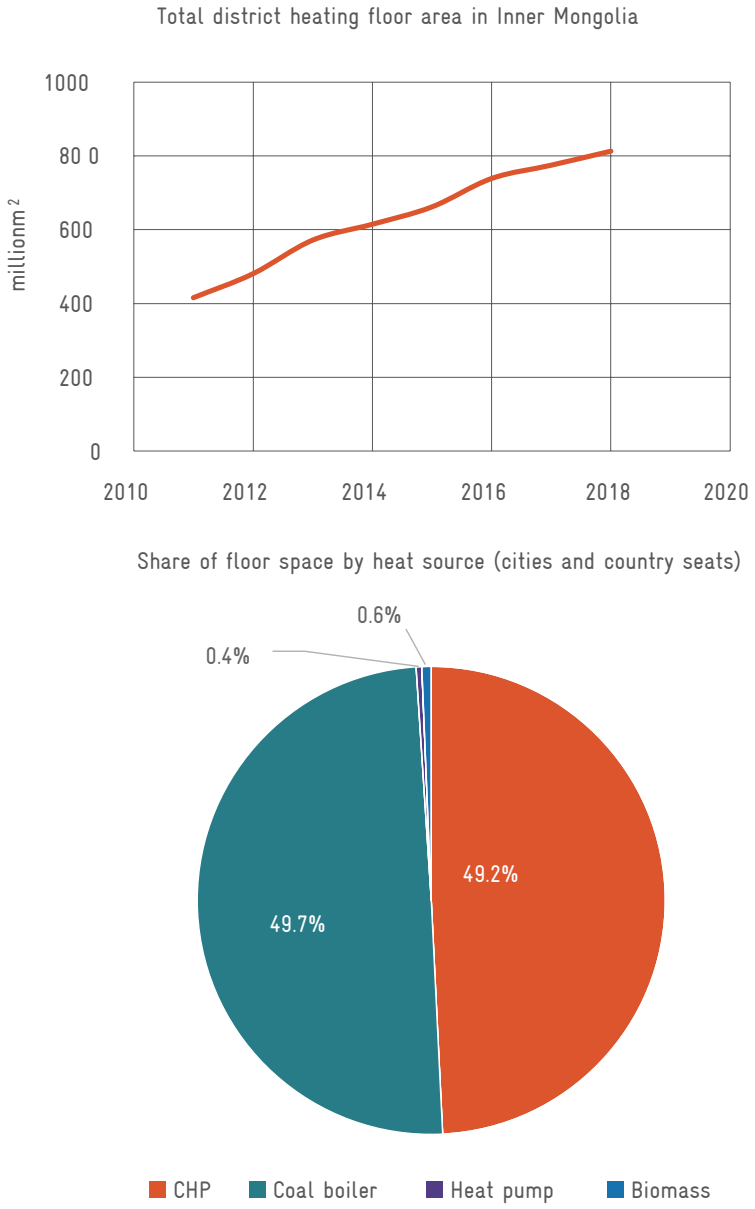


Figure 2. Up: total floor area in Inner Mongolia heated with district heating.
Down: the relative shares floor areas in cities and county seats by heat supply source. Source: (Zhang et al., 2019).

1.2.2 Rural areas

Inner Mongolia's rural population accounted for about 33% of the total population in 2019 (Inner Mongolia Autonomous Bureau of Statistics, 2021) and is decreasing as a result of increased urbanisation. Unlike the urban sector where industry is the main energy consumer, energy consumption from buildings in the rural sector make up the vast majority of total rural energy consumption (80% in northern China) (Zhang, 2017).

Most of the rural population relies on decentralised raw coal burning for residential heating due to the lack of access to a district heating network and the relatively low price and high heat value of raw coal (Zhang *et al.*, 2019; Wang *et al.*, 2020). The burning of raw coal for heating is a major contributor to CO_2 emissions and air pollution, particularly in the winters when the air quality typically gets substantially worse compared to in the summers when less or no heating is required (Wang *et al.*, 2020).

The small share of households in the rural sector that use electricity to generate heat is dominated by direct electric (resistive) heating. Even though there are other electrical alternatives with significantly higher efficiency (see section 2), the low capital cost and ease of instalment of resistive heaters make it the preferred option (Wang *et al.*, 2020).

1.3 National and subnational plans for low-carbon heating

Climate governance in China is similarly structured as other policy areas in the country and grants substantial authority to lower levels of governments. As for other policy areas, climate targets are established by the central government which are subsequently distributed to provincial governments. It is then largely up to the provincial governments to formulate and implement policies to achieve those targets (Nilsson, Smit and Kuramochi, 2021). Nevertheless, national policies have a large influence on the provincial policies as they set the boundaries and provide the general direction.

1.3.1 National plans

(Xiong and Hassan, 2022) provides a comprehensive overview of the development of clean heating policy in China over the last 20 years and is used as the main source of information for this subsection.

Clean heating has been a growing area of interest in Chinese policymaking since around the year 2000 as a result of rising demand for heat and increasing air pollution. In 2013, quantitative renewable heating targets were included in the 12th Five-Year Renewable Energy Development Plan for the first time.

The electric heating policies introduced from 2015 aimed to address the health impacts from inefficient, highly polluting coal-fired boilers that are predominantly used in rural areas by replacing raw coal burning with electric heating. An action plan for clean and efficient coal was issued in 2015 by the National Energy Administration, which prohibited the use of coal with high ash and sulphur content. In 2016 NDRC published instructions for substituting coal-fired boilers with electric heaters with the goal of reducing coal consumption for heating by 130 Mt in rural areas between 2016 and 2020 (Wang *et al.*, 2020).

The publishing of the "Plan for Clean Heating in Northern China (2017-2021)" formally defined which energy sources are considered clean, namely clean coal[1], natural gas, industrial waste heat, geothermal energy, biomass, solar energy, electricity, and nuclear energy. Even though that definition still includes fossil energy sources, renewable heating was for the first time established as the main source of clean heating, as opposed to having a supplementary role which had been the case in previous policies. The policy also set out quantitative targets to achieve a 50% clean heating rate by 2019, and 70% by 2021 (Xiong and Hassan, 2022). The 2021 target was exceeded and reached 73.6% in mid-2022 in Northern China (Xu and Ge, 2023). Minimum clean heating rates are set for urban areas (100%), county seats and urban-rural junction (80%), and rural areas (60%). The plan stipulates that each region must formulate its own heating plans based on available resources and existing infrastructure (Zhang *et al.*, 2019).

In 2021, a new policy "Notice on advancing the development of renewable heating according to local conditions" was formulated which focuses on several key aspects such as specific renewable heating goals compatible with climate objectives, the promotion of pilot and

1 Including high efficiency combustion of coal, coal transformation technologies, integrated gasification combined cycle, and carbon capture and storage (Chen and Xu, 2010)

demonstration of renewable-based heating technologies, policy support for renewable heat, and improving the government management system for the promotion of renewable heat. Instead of increasing demand and air pollution issues, the main driver behind this policy was climate change, indicating a shift towards including renewable heat as a key strategy to reach the climate targets (Xiong and Hassan, 2022).

1.3.2 Provincial plans

To achieve a lower coal consumption for heat according to the Plan for Clean Heating in Northern China, some local authorities in Northern China developed "Coal to Electricity Transformation" and a "Coal to Gas Transformation" objectives (Huang, Fan and Furbo, 2019). Less attention was given to the direct use of renewables, e.g., solar thermal. The Coal to Electricity Transformation focused on the replacement of coal-fired boilers with ASHPs and GSHPs and thus targeted decentralised heating rather than centralised heating. The Coal to Gas Transformation targeted both centralised and decentralised heating with gas-based cogeneration, gas-fired boilers and household gas boilers. As a result, the gas consumption increased and led to national gas shortages in 2017 and spiking gas prices.

The main policy document related to climate change in Inner Mongolia is the provincial five-year-plan (FYP) on climate change. Similarly to national FYPs, provinces also develop their own FYPs. Nov. 2021, the Inner Mongolian government released its 14 FYP on climate change which outlines its development vision, further highlighting the role of natural gas.

Table 1 provides an overview of the aims and targets in the FYP on climate change related to the heating sector, divided into those related to the energy sector and those related to the heating and/or buildings sector. In the latter category, both heating supply and demand are considered, however, since the demand side is not a central part of this study, the list of measures and targets is not exhaustive here.

Table 1. Non-comprehensive overview of aims and targets related to heating in the Inner Mongolia 14FYP on Climate Change

Energy sector (related to heating)	
Promote the gasification of Inner Mongolia	Aims • Increased exploration and development of natural gas • Accelerated construction of gas transmission infrastructure • Encourage the use of multi-gas sources with the aim to stimulate the demand for gas in areas not covered by pipeline infrastructure Targets • Natural gas production to reach 33.3 billion cubic meters by 2025 • Natural gas pipeline coverage of more than 66% in the flag counties (cities and districts) by 2025
New energy[2]	Aims • Promote its development • Development of wind and PV power at a large scale Targets • New energy becomes the main energy source for power generation by 2025 and the share of new energy in installed capacities exceeds 45% • The resulting CO2 emission reduction is 200 Mt per year • Share of coal in total energy consumption is reduced to less than 75% by 2025 and the share of non-fossil energy increases to 18%

2 In relation to heating, CHP plants, natural gas, electric heating, industrial waste heat, and other renewable resources including geothermal, biomass, and solar power are considered clean fuels and technologies under the plan (Zhang et al., 2019).

Heating/buildings sector	
Heating supply	Aims • Improve the level of clean heating in urban and rural areas • Increase efforts to eliminate small coal-fired boilers • Strongly promote centralized CHP (cogeneration) heating • According to local conditions, promote natural gas, electricity and renewable energy heating, and continue expanding industrial waste heat • Enable the connection of multiple heat sources by increasing the construction and renovation of pipeline networks • Promote clean heating in rural areas, including air-source heat pumps, passive solar heating, and other technologies Targets • The rate of clean heating in the district heating network to reach above 80% by 2025
Heat demand	Aims • Improved management of energy efficiency in public and office buildings • Increase energy-saving renovation of public and office buildings Targets • The energy consumption per unit of floor space for centralized heating is reduced by more than 10% annually by 2025 • The renovation of heating pipelines older than 20 years is gradually completed by 2025

Inner Mongolia's 14FYP on climate change is largely in line with available literature exploring clean heating pathways for Inner Mongolia. Both (Zhang *et al.*, 2019) and (Tang *et al.*, 2021) foresees a large role for CHP with contributions from other technologies in the transition to clean heating. However, those studies are not constrained to a full decarbonisation of the sector, but rather to the government's definition of clean heating[1]. Even if the plan is meant to look at the aims of a five-year period, investment decisions in that period can have important implications on the achievement of long-term objectives. It is therefore important to take that into consideration in near-term plans. Based on that, we developed a number of recommendations to improve future plans' alignment with a 1.5°C compatible future:

- Improve transparency on the mitigation potential of clean heating technologies and fuels

  To further minimize the risk of carbon lock-in effects, the definition of clean heating could be grouped into "fossil based" and "non fossil based" (or "not possible to fully decarbonise" and "possible to fully decarbonise") to differentiate between the potential and emissions intensity of different technologies more clearly. That could also result in a raised awareness around various heating technologies and their emissions intensities.

- Set out quantitative targets for the heating supply side

  While the plan sets out more concrete actions on the demand side (i.e., energy efficiency), clear targets are generally missing on the supply side. In particular, quantitative targets for renewable based and emerging technologies could send clear signals to the industry and other relevant stakeholders. Further, it would also allow for the continuous tracking of progress against those targets.

- Highlight role of linking short-term objectives with the medium- and long-term perspective

  The plan highlights the importance of peaking action plan development by the provincial government as well as all leagues and cities. But little attention is paid to the link between peaking and long-term carbon neutrality. The peaking plan could have substantial implications on the achievement of long-term goals. Therefore, highlighting its role in future FYPs could increase alignment between short, medium and long-term objectives.

Based on this background, we investigate potential decarbonisation technologies and their suitability in the Inner Mongolian context in the next section.

2

Sustainable Heating: Comparison of Technology Options

2 Sustainable Heating: Comparison of Technology Options

2.1 Comparison based on key criteria

Several studies have attempted to find optimal heating portfolios and pathways to mitigate emissions in the Inner Mongolia space heating sector. However, they have largely focused on achieving clean heating according to the official definition, which includes fossil fuels such as "clean coal" and natural gas (Tang *et al.*, 2021) (Zhang *et al.*, 2019). Therefore, the studies result in an expansion and high shares of fossil fuels in the heating system, which might not be aligned with a long-term pathway compatible with the climate neutrality target.

In this report we conduct a technology mapping exercise with the aim to identify suitable low-carbon heating technologies for Inner Mongolia. We base this evaluation on the following criteria:

- Mitigation potential

  Because the ultimate goal of the technology shift is to contribute to a pathway compatible with reaching the 2030/2060 objectives, we assess to what extent the technology can mitigate CO_2 emissions and consider those able to achieve zero CO_2 emissions compatible with meeting the long-term neutrality targets. In doing so, we consider scope 1 and 2 emissions, but not the lifecycle emissions of the specific technologies.

- Energy efficiency/energy consumption

  Even though there is a wide range of technologies which could deliver zero emissions, they consume varying levels of energy to deliver the required amount of heat to the consumer. The level of energy consumption has implications on operating costs and the wider electricity system. For instance, even if an electric heating technology can be decarbonised by ensuring that the electricity supply is clean, a technology which consumes high amounts of electricity will contribute to an increased burden on the electricity sector and its decarbonisation. Further, a technology with higher energy consumption will lead to higher operating costs for the consumer.

- Suitability in extreme cold climates

  Due to the extreme cold conditions in Inner Mongolia during the winter months, it is important to assess how well the technology can deliver heat in such climates.

- Costs

  We assess the cost of the technologies, both in terms of initial investment cost, as well as levelised cost of heating (LCOH) which represents the average annual cost of building and operating a heating plant over the course of the plant's expected lifetime. Due to data limitations, we are not able to present those data for all technologies. In this case, the data refers to the cost in other parts of the world rather than specific for China.

The selection of the technologies is based on existing literature analysing low-carbon heating technologies in extreme cold climates including (Nilsson *et al.*, 2022). We group them by key energy carrier (i.e., electricity, direct use of renewables, hybrid systems, and other). As such, we only consider heating technologies based on non-fossil energy carriers. Indeed, an electric heating technology could indirectly be using fossil fuels if the electricity is generated from fossil fuels, but it could also be fully decarbonised by ensuring that the electricity is generated from clean sources and is thus included. Conversely, we exclude technologies which are inherently reliant on fossil fuels and consequently could lead to fossil lock-in effects. The selection of technologies and their comparison is presented in Table 2. A more detailed technical description of the technologies is available in (Nilsson *et al.*, 2022).

Table 2. Overview of decarbonisation heating technologies.

Technology	Mitigation potential	Energy efficiency	Costs	Suitability TO extreme low temperatures	Urban/rural
Electric					
Resistive heating	Depending on the carbon intensity of the electricity generation. If the electricity supply is decarbonised, the mitigation potential can reach 100%	100%[3]	Initial investment: ~1,000 RMB per household in Inner Mongolia (average) (Zhou et al., 2021) Operational costs: ~2,300 (urban) and ~6,300 (rural) RMB per household and year in Inner Mongolia (Zhou et al., 2021). May become higher (highly dependent on the local electricity price). LCOH: Not available	Yes	Does not require much space and easy to install. Suitable in both urban and rural contexts.
Air-source heat pump (ASHP)	Depending on the carbon intensity of the electricity generation. If the electricity supply is decarbonised, the mitigation potential can reach 100%	Coefficient of Performance (COP) of 1.9-2.8 at -7°C Approaches 1 at very low temperatures (Eichhammer et al., 2019)	Initial investment: high, yet lowest among heat pumps (855-1630 EUR/kW_{th}[4]) ~10,000 (urban), 23,000 (rural) RMB per household in Inner Mongolia (average) (Zhou et al., 2021) Operational costs: ~2,000 (urban), ~5,800 (rural) RMB per year and household in Inner Mongolia (Zhou et al., 2021) LCOH: Not available	Limited. COP>1, but some challenges with frost	Low space requirements and therefore suitable also in densely populated areas.
Ground-source heat pump (GSHP)	Depending on the carbon intensity of the electricity generation. If the electricity supply is decarbonised, the mitigation potential can reach 100%	COP of 3-4.5 at -7°C COP of 2.7-3.9 at -40°C (Eichhammer et al., 2019)	Initial investment: high (1350-2200 EUR/ kW_{th}) Operational costs: low (no data available) LCOH: Not available	Limited. Efficiency decreases as ground source temperature decreases	Requires space. Horizontal GSHPs require more space than vertical GSHPs. Less suitable in dense building areas.
Direct use of renewables					
Solar thermal	100%	N/A	Initial investment: High. Depend on the collector field area. The cost per m^2 generally decreases with an increasing area and is estimated to about 845-1970 RMB/m^2 in China (ADB, 2019). Operational costs: Low (no data available) LCOH: Not available	Evacuated tube collectors are particularly suitable	Requires space. Large scale solar farms can feed into district heating network.
Geothermal	100%	N/A	Initial investment: High Operational costs: Low LCOH: Not available		Most suitable when the heating destination is close to the geothermal heating source

3 Meaning that all energy in the electricity input is converted to useful heat. This figure, however, does not take into account efficiency losses in the generation of the electricity.

4 Depending on the system size and the efficiency of the building stock.

Technology	Mitigation potential	Energy efficiency	Costs	Suitability TO extreme low temperatures	Urban/rural
Hybrid systems					
Solar assisted ASHP/GSHP	Depending on the carbon intensity of the electricity generation. If the electricity supply is decarbonised, the mitigation potential can reach 100%	High. Generally increases the efficiency of the heat pump as well as of the complete system	Initial investment: High Operational costs: Low (no data available) LCOH: - SAASHP: 0.26 RMB/kWh in Hohhot (Huang, 2019)[5] - SAGSHP: 0.18 USD/kWh in Harbin (Shah, Aye and Rismanchi, 2020) 0.25 RMB/kWh in Hohhot (Huang, 2019)[5]	Yes. Hybrid system mitigates risks of ASHP frosting issues and temperature soil imbalance for GSHPs.	The solar thermal collectors require space, as do GSHPs. Can still be suitable in urban areas when installed at large-scale.
Other					
Green hydrogen	100%	Low (efficiency losses in production, storage, transport, and end-use)	Initial investment: high. Infrastructure for production, storage, transport. Green hydrogen: Medium to high depending on climatic conditions. Operating costs: Medium-high[6] LCOH: 0.53 EUR/kWh (Mongolia) (Nilsson et al., 2021)	Yes	Could be more suitable where available pipeline infrastructure is available
Biomass and wastes	Depending on the sustainability of the biomass	75-85% (Trojanowski et al., 2019)	Initial investment: 425 CNY/kW (for biomass processing plant and boiler) (Zhang et al., 2019) System dependent (gasification plant higher cost, incineration and co-firing lower cost) Operating costs: Dependent on the price of biomass LCOH: Not available	Yes	Could be suitable in both urban and rural contexts
Industrial waste heat	Depending on the original source of the heat	Not available	Initial investment: No technology costs as waste heat from already existing plants is used. Investments in waste heat distribution infrastructure would be required Operating costs: Zero-low LCOH: Not available	Require heating distribution system and buildings to be compatible with low supply temperatures in order to maximise the utilisation	Suitable to feed into district heating systems near industrial activities. More likely available in urban contexts

5 Lowest LCOH based on optimised solar fraction.

6 Will be highly dependent on the cost of green hydrogen.

2.2 Decarbonisation options

2.2.1 Evaluation of low-carbon technology options based on criteria and local energy resource availability

Based on the criteria analysis and the availability of local energy resources, we evaluate the suitability of the different decarbonisation options for the heat supply in a qualitative manner. We find that the direct use of renewables and electrification through the use of heat pumps has the strongest potential to supply significant amounts of heat in the most efficient and sustainable manner.

Electric- and renewable-based heating technologies

Inner Mongolia has vast renewable energy resources which make it suitable to both electrification and the direct use of renewable heat. Inner Mongolia is one of the provinces in China with most abundant variable renewable energy resources (i.e., wind and solar) (Myllyvirta and Zhang, 2022). In terms of onshore wind potential, Inner Mongolia has the highest potential in the country (strongest in the western part of the province) with a potential of about 2.7 billion kW based on 2020 data (Wang *et al.*, 2022). In terms of PV power potential, Inner Mongolia has the second highest potential among provinces (also strongest in the western part of the province), after Xinjiang.

Among provinces, Inner Mongolia has set the highest 14FYP target to expand its renewable energy power capacity and aims to generate more than 50% of its power from renewables by 2030 (Bloomberg News, 2022; Myllyvirta and Zhang, 2022). In 2019, the share of non-fossil energy in the power generation mix was 14% (Downie, 2021).

The gradual integration of renewables to the power mix will increase the mitigation potential of electrified heating with the potential to reach net zero emissions. As the decarbonisation of the electricity grid will be a gradual process, using electric heating technologies fed with grid electricity will still generate emissions as long as fossil fuels are used in the electricity generation mix. Electric heating technologies using grid electricity will thus gradually generate less CO_2 emissions as the share of renewables to the grid increases. As such, the installation of electric heating technologies does not contribute to carbon lock-in as they are not inherently dependent on fossil fuels. Installations can also be combined with the deployment of renewable energy corresponding to the demand of the electric heating technology, and thus be considered a zero-emissions system.

Heating technologies with higher energy efficiency will put less pressure on the power sector while also generating less emissions. The more energy efficient an electric heating technology is, the less emissions are generated while the electricity supply is still in the process of being decarbonised. More efficient technologies also require less deployment of renewable power generation. Among the electrified technologies listed in Table 2, the GSHP can achieve the highest level of energy efficiency ie. COP of 2.7-4.5 depending on the environment temperature), followed by ASHP (100-280% depending on the environment temperature). The least efficient electrified heating technology is resistive heating which can achieve a maximum efficiency of 100%. Significant energy savings could thus be made by shifting to heat pumps. Heat pumps are able to operate in extreme cold climates, but with a decreased efficiency as the environment temperature decreases.

Because GSHPs extract energy from the ground which has a relatively stable temperature, their efficiency is higher than ASHPs. However, as the GSHP extracts energy over time, the ground temperature will gradually decrease unless heat is reinjected to the ground. The GSHP may also face constraints in terms of space availability. As ASHPs are extracting energy from the air, their efficiency significantly decreases as the atmospheric temperature drops. However, ASHPs are less constrained by space availability.

The relatively high solar irradiation and cold climate makes Inner Mongolia particularly well suited for the direct use of renewable heat (i.e., solar thermal heating) which is a zero-emissions heating technology. Solar thermal heating can deliver heat at very low operating

costs as the energy is "free". The deployment of solar thermal, however, requires availability to large areas of land which need to be further investigated on a case to case basis. Further, even though solar thermal could contribute to large shares of the heating demand of a building, other technologies likely need to be included in the technology mix for a robust system that can satisfy the heating demand at all times.

Hybrid heat pump and solar thermal systems can provide the highest energy efficiency and a robust heat supply system. The combination of electrified heating and solar thermal heating in hybrid systems could provide several benefits by increasing the stability of the system, lowering operating costs, and reducing emissions. By, for instance, combining GSHPs with solar thermal, excess solar heat can be reinjected to the ground to serve as an energy storage unit as well as increase the efficiency of the system. Doing so can help the system to maximise the use of direct renewable heat while minimising the electricity consumption. Several Chinese studies have concluded that SAHPs provide highest environmental and economic benefits compared to other heating technologies (Lin *et al.*, 2022).

Indirect electrification through the use of green hydrogen is not economically viable. The use of green hydrogen for heating, which is indirectly an electrified technology as the production of green hydrogen is reliant on clean electricity, could technically deliver zero-carbon heat, but due to the low total energy efficiency of the full process, including the production of green hydrogen and its transportation and distribution, it is not economically feasible. Previous studies have shown that, even in regions which can produce low-cost clean electricity, using green hydrogen for heating is not economically attractive compared to other low-carbon heating options. As shown in Table 2, the LCOH of green hydrogen in Mongolia which has similar climatic conditions as in Inner Mongolia, is significantly higher than other technologies considered in this study.

Geothermal resources

There is not sufficient publicly available research and/or data to assess the potential of geothermal heating in Inner Mongolia. Although China has plentiful geothermal resources, they are unevenly distributed across the country. Limited available research indicates that the available resources are low-temperature and best suited for agriculture (Liu *et al.*, 2021). Even though geothermal heat also could deliver zero carbon heat to district heating networks, the available information on those resources in Inner Mongolia are insufficient and need to be further investigated.

Biomass and wastes

Inner Mongolia also has significant biomass potential available for heating, mainly from livestock excrement, straw, and branches (Zhang *et al.*, 2019). The total annual heating potential of crop residues and livestock excrement has been estimated at 222 TWh. However, a significant share of that biomass is already used in the papermaking industry. The same study estimates that about 6-10% of the district heating supply in 2025 could be generated with biomass. Transportation costs are high for biomass feedstocks and so the resource should be used onsite. Biomass resources are therefore an option for heating in Inner Mongolia's rural eastern and western agricultural areas where resources are most abundant. In terms of municipal wastes, those are estimated to be able to deliver about 5-8% of cities heat demand.

Due to the limited supply of sustainable biomass and the competitiveness for it in other sectors, it is not expected to play a large role in decarbonising the heat supply in Inner Mongolia. Because the combustion of biomass still generates CO_2 emissions, it can only be considered carbon neutral if the biomass used is sustainable. Further, the available supply of sustainable biomass is limited, and it is likely to be needed to reduce emissions in other sectors where few decarbonisation options are available. Examples include using biomass for high heat generation in industrial processes, or to produce carbon-neutral fuels. Based on the abovementioned limitations, we do not consider biomass as a feasible option to deliver significant amounts of low-carbon heat in Inner Mongolia.

Industrial waste heat

Industrial waste heat is not expected to play a central part in the decarbonisation of the Inner Mongolian heating sector but should still be considered as part of the low-carbon district heating mix. As one of the country's industrial hubs, Inner Mongolia hosts many

industrial plants generating waste heat which could be used for residential space heating. Specific industries include iron and steel, cement, coking and petroleum, and chemicals. (Zhang *et al.*, 2019) estimates that about 4-5% of the district heating heat supply in 2025 could be supplied with industrial waste heat. The most practical and efficient way of using the waste heat is by feeding it to a local district heating network. Its use is therefore most suitable in urban areas with a district heating network which is in the proximity to the industrial plant. However, since the waste heat typically has lower temperatures than supply temperature of the existing district heating networks, the waste heat can only be fully utilised when then district heating network is upgraded to allow for lower supply temperatures.

Creating revenue streams from industrial waste heat should not disincentivise the decarbonisation of industrial heat generation. Industrial waste heat could be a useful way of supplying extra heat to the district heating network without requiring any additional primary energy. Because heating with waste heat does not require any additional primary fuels, it does not generate any direct emissions. However, emissions are still generated if fossil fuels are combusted to generate the heat in the industrial plants in the first place. To achieve carbon neutrality across all sectors in the long-term, also those operations will need to be decarbonised. That could for instance require industrial plants to shift to other technologies which do not generate as much waste heat (e.g., the steel industry). It is therefore important to make sure that potential revenue streams created by selling waste heat do not disincentivise industrial companies to switch to low-carbon technologies.

Considerations on the various aspects of cost of electrified heating technologies

The operational cost of different heating technologies can have a major impact on its cost competitiveness. When comparing the cost of heating technologies, it is important to take both the upfront (investment) and operational costs into account. Only comparing upfront costs can give a skewed picture as operational costs make a substantial influence on the overall competitiveness and varies significantly across technologies. The wide range of energy efficiency levels across heating technologies combined with volatile energy prices can result in large differences in operational costs. Therefore, the most efficient way of comparing upfront and operational cost would be through the levelized cost of heating (LCOH) as it accounts for upfront costs, maintenance costs, and fuel costs over the lifetime of the technology. But since estimates on the LCOH of the technologies discussed in this study is not yet publicly available in the literature for Inner Mongolia or China, we are not able to use that as an indicator for comparison.

The high energy efficiency of heat pumps makes them cost competitive to most other heating technologies. Comparing upfront and operational costs of the technologies identified as most suitable in this section, a few conclusions can be made. Upfront costs of heat pumps and solar thermal are generally high, while those of resistive heating are low. Operational costs, however, tend to be very low for heat pumps and solar thermal, and high for resistive heating. Figure 3 and Figure 4 show the upfront and operational costs of ASHPs, resistive heaters, and natural gas boilers in Inner Mongolia. The lower operational cost of heat pumps is mainly the result of their high energy efficiency, making them cost competitive to other fossil fuel-based technologies such as natural gas (Zhou et al., 2021). Even though we do not have any estimates on the operational costs of GSHPs, they are expected to be even lower than those of ASHPs as they have a higher efficiency and thus consume less electricity (Table 2). When combining heat pumps with solar thermal which uses “free” solar energy, operational costs can be reduced even further.

Heating costs are typically higher in rural Inner Mongolia where the population could benefit substantially economically from a shift to more efficient heating if given financial support for upfront costs. In general, costs are higher in rural than in urban areas because of the larger average size of houses in rural areas and their generally lower energy efficiency (Zhou et al., 2021). Reducing the capital costs in rural areas may thus become a policy challenge (e.g., through the implementation of subsidies or other financial support). Bringing down operational costs could be partially realised through demand side measures improving building energy efficiency, but also through policies incentivizing the adoption of more efficient technologies such as heat pumps.

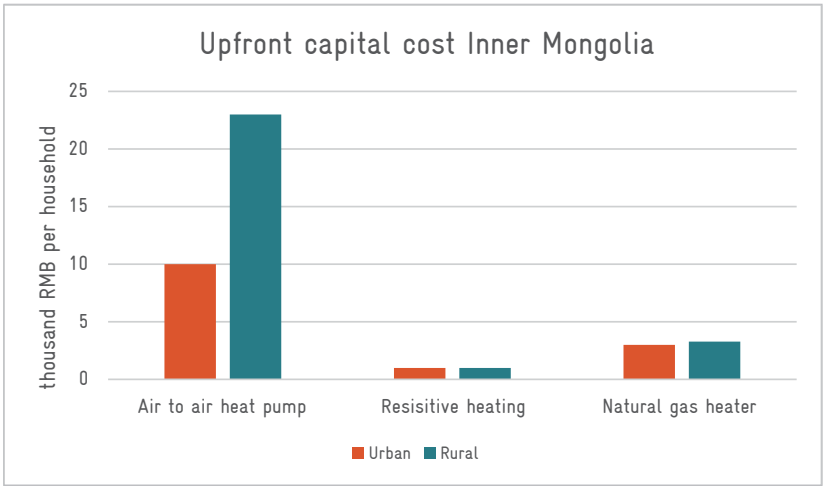


Figure 3. Upfront capital cost of selected heating technologies in Inner Mongolia. The estimates include installation costs. Data source: (Zhou et al., 2021).

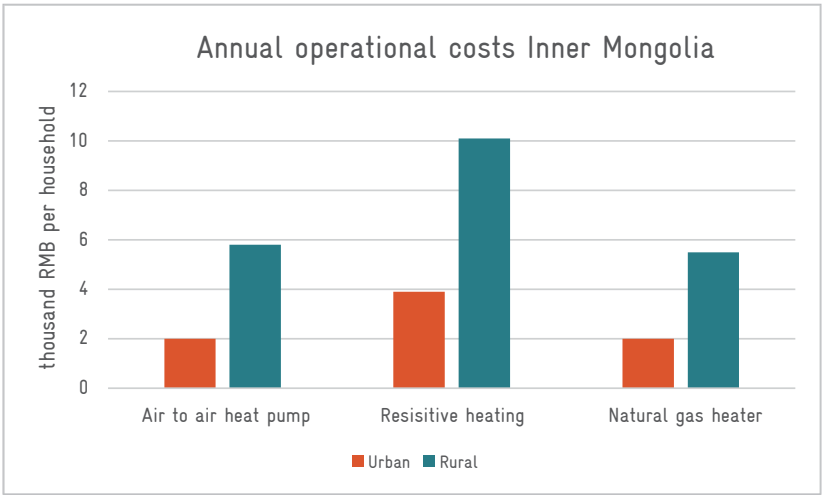


Figure 4. Annual operational costs of selected heating technologies in Inner Mongolia. Data source: (Zhou et al., 2021).

2.2.2 Potential technology set-ups in urban and rural areas

Based on the evaluation of the various potential decarbonisation technologies and the current set-up of the heating generation, transmission and distribution infrastructure in Inner Mongolia, we evaluate suitable options in urban and rural areas of the province.

Make use of existing district heating infrastructure in urban areas while gradually phasing out fossil-based heat production

The installation of largescale electricity- and renewable-based heating could gradually be connected to district heating networks as CHP is phased down. Considering that the majority of urban households are already connected to a district heating network, phasing out fossil fuels in the centralised heating system while keeping the district heating network would allow the continuous efficient use of the existing transmissions and distribution infrastructure while decarbonising the heat supply. Largescale heat pumps and solar thermal collectors could, for instance, be connected to the district heating network. By gradually increasing the deployment of such technologies, fossil fuel-based CHP could be phased down and phased out in the long term by diversifying the heat supply using additional heat sources such as industrial waste heat. **Importantly, however, district heating networks must be made compatible with the integration of renewable heating technologies** which typically has a lower supply temperature compared to fossil fuel-based heating technologies in order to allow for a wide integration of renewable-based heat. Further, such technology switch will also require substantial land area.

New investments in natural gas are likely to lock in fossil fuels and is not necessary as there are other options available. A coal-to-gas transition as promoted in the FYP on climate change in Inner Mongolia would mean investments in and building out of new infrastructure with economic lifetimes going beyond 2060 when carbon neutrality is planned to be achieved. In order to stay in line with the Paris Agreement, investments in CHP must be in line with an overall transition to full decarbonisation in the long-term (Marquardt and Kachi, 2021). While converting CHP plants from being coal to gas-based could reduce CO_2-emissions, investing in upstream gas production and gas infrastructure risk locking in the use of fossil gas while investments in natural gas-based electricity production risks delaying renewable energy power development by prioritising natural gas-based electricity production (Marquardt and Kachi, 2021). Further, methane leakages from the production of natural gas risks offsetting CO_2-savings. Considering that there are commercially available heating technologies which do not risk locking-in fossil fuels into the system (i.e., electricity and solar-based heating) and which could be integrated to district heating systems, switching to natural gas-based systems therefore appear an unnecessary and risky step.

Opportunity for rural communities to leapfrog to renewable and electricity-based heat while avoiding energy poverty

Rural households of Inner Mongolia are more vulnerable to high operating costs and thus also energy poverty. The governmental coal-to-gas and coal-to-electricity promotion in northern China has led to disproportionately higher energy poverty in the rural areas, mainly due to lower insulation levels, higher heat demand, lower average income levels and volatile energy prices (Huang, Fan and Furbo, 2019; Xie *et al.*, 2022). Progress made in clean heating[7] in recent years has also uncovered a number of issues, including high heating costs and gas supply shortages (Xu and Ge, 2020). Based on that, the local availability of energy resources can largely influence the economic sustainability of heating. Similarly, highly energy efficient heating technologies can contribute to lower operating costs and should be prioritised in policy planning in rural areas to avoid disproportional economic burden. Previous studies have found that, from a sustainable development theory perspective which considers the social, economic and ecologic perspective, geothermal energy used with heat pumps and wind energy are most suitable in rural Inner Mongolia and suggests that heat pump should be promoted (Xu and Ge, 2023). Hence, even without considering the climate perspective, highly efficient electricity-based heating is seen as the most beneficial pathway for clean heating, while natural gas or clean coal-based heating is discarded.

Highly energy efficient heating technologies provide an opportunity to significantly reduce energy demand, and thus also operational heating costs, for rural residents which currently are higher than those of urban residents. In the rural areas of Inner Mongolia, where households typically are not connected to a centralised heating network, the widely used coal boilers can be replaced by electric or solar thermal heating. While the installation of electric resistive heating has low initial investment costs and can be installed easily, the low energy efficiency of the technology may result in high electricity demand and thus also energy costs. Further, unless the power supply is clean, resistive heating may not lead to emission reductions (Wang *et al.*, 2020). Heat pumps instead offer a significantly higher energy efficiency and could deliver substantial energy savings. Since operational costs are generally higher in these areas, more energy efficient technologies could thus ease the economic burden of heating for rural residents.

In rural areas where access to land might be more generous, households are less restricted by sticking to a certain type of heat pump. Because GSHPs are significantly more efficient compared to ASHPs, but require more land area, it might be more challenging to install them in urban environments. That is likely to be less problematic in rural areas. GSHPs may thus be particularly suitable in rural areas.

Solar thermal may be particularly suitable in rural areas with existing district heating networks. The abundant solar resource in wintertime also makes hybrid solar and heat pump systems attractive. (Zhang, 2017) found that these systems could bring social, economic, and environmental benefits by providing emissions-free heat at lower operational costs, more secure heating systems which require less human labour[8], and higher air quality. Some rural communities of Inner Mongolia do have district heating networks. In those cases, solar thermal could also be particularly suitable. The attractiveness of solar district heating is further increased by the lack of existing gas and coal infrastructure in those areas (ADB, 2019). This provides an opportunity for rural areas to leapfrog any use of bridge fuels to deep mitigation directly.

7 Clean heating according to the governmental definition of clean heating, i.e., largely focusing on a shift to natural gas.

8 Coal stoves require coal being fed regularly, as well as ash to be removed.

3

Recent Progress and Identification of Gaps

3 Recent Progress and Identification of Gaps

3.1 Recent and ongoing low-carbon heating initiatives in Inner Mongolia

Based on the findings in section 2, we map previous and ongoing heating initiatives in Inner Mongolia that are based on technologies that have the capability to fully decarbonise, i.e., provide zero emissions heat. We do so to increase the understanding regarding prioritised technologies in recent years and to identify gaps in terms of which technologies have not yet been considered or tested.

The list of projects is non-exhaustive as the authors were limited to web search in English. Further, the list is limited to larger scale/central heating projects and not individual set-ups for single households due to limited data availability. In total, we found ten low-carbon heating projects which have materialized since year 2010, as presented in Table 3.

Table 3. Clean heating projects in Inner Mongolia

Energy carrier/ source	Technology	Project	Start year	Reference(s)
Electricity	Resistive heating	CPIC Siziwangqi Wind Power Heating Demonstration Project (large-scale)	2012	(China Power Investment Corporation, 2014)
		Wind-powered electric boilers in Hohhot (large-scale) (ADB)	2013	(ADB, 2018)
	ASHP	China Longyuan Power Group Co., Ltd. (largescale)	2022	(CEIC, 2022)
	GSHP	None		
Direct use of renewables	Solar thermal district heating	Bayanor City Urad Zhongqi	2010	(Huang, 2019)
		XuChen, Baotou solar district heating (largescale)	2016	(Epp, 2020)
		Baotou City Equipment Manufacturing Industry Park Baotou	pre-2018	(Huang, 2019)
		Baotou Branch Park of Peking University S&T Park Hong	pre-2018	(Huang, 2019)
		Huhot Tuzuo Qi Sanliang Township Central School Lanzhou	pre-2018	(Huang, 2019)
		Hong Qing De Village	pre-2018	(Huang, 2019)
	Geothermal	None		
Hybrid systems	SAHP	None		
Other	Green hydrogen	None		
	Biomass and wastes	Biomass Comprehensive Utilization Project	2017	(CDM Fund, 2017)
	Industrial waste heat	None		

Studying the timeline of the identified low-carbon heating projects, a higher number of projects was initiated between 2010 and 2018 compared to in more recent years where only one project was identified (2022) (Figure 5). In terms of specific technologies, solar thermal district heating has been the most intensively deployed technology within the studied period (six out of ten projects) while the first and only heat pump project was initiated first in 2022.

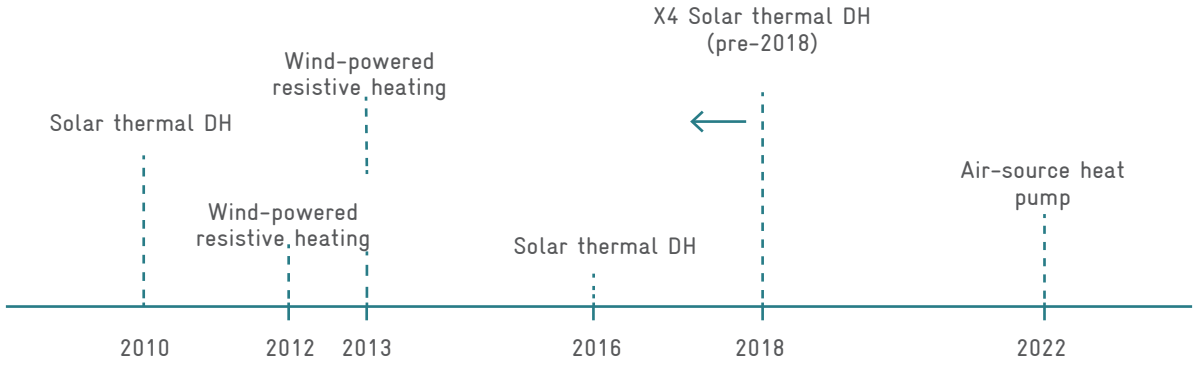


Figure 5. Low-carbon heating projects initiated in Inner Mongolia between the period of 2010-2022.

Several solar thermal district heating projects have been successfully established in Inner Mongolia, but no new projects have been initiated in recent years. Solar thermal district heating was established in Inner Mongolia already in 2010 in Baotou, followed by the construction of the second largest solar district heating system globally in 2016 in Bayannaoer City. In the latter project, excess heat in summer is used for heating hotels, swimming pools and spas, while gas and electric boilers are used as backup heat during the heating season (Epp, 2020). Four additional solar district heating projects were initiated with unspecified start years but before 2018. The solar district heating projects have led to several positive outcomes in addition to emission mitigation, such as lower operating costs and the creation of jobs in the manufacturing industry. Despite such developments, however, there are no additional solar thermal projects in the pipeline from what can be found publicly.

Electric heating can be coupled with wind power and could reduce curtailments, but the clean electricity could be better used with more efficient electricity-based heating technologies. Electric heating projects have most commonly been coupled with the deployment of wind power following efforts to reduce wind power curtailments. Two such projects were initiated in 2012 and 2013 and uses largescale resistive heating. Experience from resistive heating projects demonstrate a certain vulnerability to volatile fossil fuel prices, if the electricity generation is fossil fuel based: The Hohhot wind-power project (2013) was combined with gas boilers, but its capacity was revised downwards following changes in gas policy and prices. Instead, parts of its capacity was replaced by waste heat from CHP plants and waste incineration plants (Sustainia, 2019). Such sensitivities could be reduced through the application of electric heating technologies with higher energy efficiency, i.e., heat pumps. Only one heat pump project was identified which was only initiated last year. Several potential reasons might explain why heat pumps have not been deployed earlier such as high upfront costs and poor functionality in extreme cold climates. In recent years, however, technical development has substantially improved heat pump operation in cold climates.

Despite its high suitability and the benefits hybrid systems could bring Inner Mongolia, testing and demonstrating the technology is lagging. Experiences and knowledge from solar thermal projects in Inner Mongolia could be valuable in testing hybrid systems which have not yet been tested in the province. On a national level, however, several SAHP installations (solar assisted heat pump) have been made since the early 2000s (Lin *et al.*, 2022). Despite the better conditions in terms of solar irradiation in regions such as the northwest where Inner Mongolia is located, most Chinese SAHP projects to date are found in areas with moderate solar resources including eastern coastal and inland areas which have more developed economies. For less economically developed regions such as Inner Mongolia to benefit from the lower operational costs of solar hybrid systems, stronger financial support to decrease high upfront costs are needed.

There is a strong need for increased piloting and demonstration of heat pumps and solar- and electric hybrid systems. Although solar thermal has significant potential in Inner Mongolia and has shown good results, it cannot on its own decarbonise the full heat supply. Heat pumps and hybrid systems using solar thermal and heat pumps could play an important role in doing so, but Inner Mongolia is lagging in piloting and demonstrating those technology which is an essential step for wider deployment. In terms of industrial waste heat and biomass, those are more established technologies and thus not in as much need for demonstration. Further, neither industrial waste heat nor biomass are expected to make major contributions to the total heat supply of Inner Mongolia.

More and better data is needed to evaluate the progress of clean heating in rural areas of Inner Mongolia. Available data on clean heating projects focuses on centralized and urban heating. Better data is required to identify trends and gaps in rural decentralised clean heating.

4

Key Conclusions

4 Key Conclusions

Decoupling the heat and power sectors can promote the integration of renewables

Renewable power curtailments continue to be a problem in Inner Mongolia. Due to a number of issues including limited electricity transmission infrastructure, variations in demand, and an inflexible electricity baseload of coal based CHP, the rapid expansion of renewable-based power capacity in Inner Mongolia resulted in increased curtailments after 2014 (Zheng, Hennessy and Li, 2019). Despite some improvements, substantial levels of renewable-based electricity are still being curtailed.

The decoupling of the heat and power sectors could enable a higher integration of renewables and reduce curtailments. The interlinkage of the power and heat sectors by using CHP as the baseload challenges the integration of renewables as the demand for heat and power often do not match, particularly in cold climates. In periods of high heat demand, excess electricity generation might be required to meet the heat demand and vice versa (further discussed in (Nilsson *et al.*, 2022)). The power generated from CHP plants is then prioritized and, as a result, renewable power generation is curtailed. Instead, the decoupling of the heat and power sectors and the gradual integration of renewable- and electricity-based heating could facilitate a higher integration of renewable electricity and reduce curtailments (Zhang *et al.*, 2016)as is the case for north China. Pumped hydro storage (PHS. Using district heating networks for heat storage could further improve the situation (Zheng, Hennessy and Li, 2019).

Expanding natural gas infrastructure for heating purposes risks delaying the decoupling of the heat and power sectors and locking in fossil fuels. The build out of natural gas infrastructure, as promoted in the Inner Mongolia FYP on climate change, risks locking in fossil fuels despite renewable and electricity based heating technologies being commercially available as an alternative option. Transitioning CHP from coal to natural gas fired could indeed reduce emissions, but risks blocking the long-term transition to net zero emissions by keeping the electricity and heat sectors coupled.

Shifting to electric and renewables-based heating could bring several sustainable development and cost benefits

Direct use of renewables and electricity can generate zero emissions heat at a large scale. The study shows that the deployment of heating technologies able to generate zero emissions heat are preferable to those with limited mitigation potential as they could reduce emissions faster and lead to less carbon lock-in on the long-term. Renewable-based heating is naturally emissions free, while electricity-based heating can be decarbonised by ensuring that the electricity supply is clean. Among Chinese provinces, Inner Mongolia has set the highest renewable energy power generation target which aims to achieve a penetration of more than 50% of renewables by 2030. This indicates that the electrification of heating will lead to higher emissions reductions as renewables are increased. Other potential zero emissions heating fuels including sustainable biomass, industrial waste heat, and green hydrogen either show limited potential or economic unfeasibility. Therefore, renewable-based solar thermal and electricity-based heat are suggested as main contributors to the achievement of the 30/60 targets. To maximise the mitigation potential while the power supply is still being decarbonised, and to reduce operational costs, more efficient electric heating technologies including heat pumps should be prioritised over resistive heating. Further, hybrid systems using solar thermal and heat pumps could further increase energy efficiency and the robustness of the system.

Solar thermal, heat pumps and hybrid systems could significantly bring down operational costs. Due to the free solar heat and reduced electricity demand when using heat pumps or hybrid systems, these systems can deliver heat at substantially lower costs compared to fossil fuel-based or less energy efficient technologies. Hybrid solar thermal and heat pump systems tested in Hebei, for instance, resulted in 45% cost savings compared to just using an ASHP. Further, such a system is less vulnerable to volatile fossil fuel prices, particularly as the electricity supply is decarbonised.

The already widespread district heating infrastructure in Inner Mongolia's urban centres is a great opportunity to gradually diversify the heating supply and integrate more renewables. By using the district heating infrastructure existing in most urban centres of the province, the portfolio of heating technologies can be broadened with more electricity and renewables while CHP is gradually reduced. The deployment of separate heating supply systems for individual households in urban centres which are densely populated could be challenging as space availability could become an issue. Using district heating, solar collectors and large-scale heat pumps can be distributed in clusters where space is available and suitable for the harvesting of renewable resources. Similarly, rural communities with small-scale district heating systems could make use of their availability to vast and cheap land for renewable heat generation.

There is a lack of pilot and demonstration projects on novel heating technologies which could play an important role in achieving the 30/60 targets

There is a need for increased piloting and demonstration of innovative technologies to enable a timely and wide integration of renewables heating. Because low-carbon heating still is a relatively new concept in Inner Mongolia and other extreme cold regions globally, innovative low-carbon heating technologies need to be piloted and demonstrated to optimize the systemic operation and prove their robustness. A number of low-carbon heating projects have been realized in the province in the last decade, but the intensity of their deployment seems to have decreased in recent years. We also did not find any new projects planned to be initiated in the future. The multiple benefits of discussed low-carbon heating technologies, their suitability in Inner Mongolia, and the lack of projects signal a lack of awareness and willingness to transition.

Low-carbon heating projects should prioritize technologies that could contribute to achieving the 30/60 targets while also contributing to sustainable development. The majority of the analysed low-carbon heating projects in Inner Mongolia have been solar thermal projects which have provided important knowledge and experience. However, very few technologies have focused on heat pumps and their operation in hybrid systems together with solar thermal. Instead, the majority of electricity-based heating projects have focused on resistive heating. A clearer prioritization of technologies and their need for piloting and demonstration could guide stakeholders involved in the development of low-carbon heating projects.

Provincial policies could more clearly promote the direct use of renewable heat and heat pumps while including the long-term perspective

The wide shift to direct renewables and heat pumps would require increased and clearer policy support which could be realized by the provincial government. The currently wide selection of heating technologies under the public definition of clean heating in China fails to highlight the variations in mitigation potential and their potential role or ability/inability to deliver zero emissions heat. The provincial government could make a clear distinction between heating technologies that are able to generate heat without generating GHG emissions and those that have a limited mitigation potential. Those technologies could further be promoted through measures such as quantitative targets, information campaigns and financial support.

In addition to pilot and demonstration projects, useful experience and lessons learned can be shared by other provinces as well as international experiences. The provincial government could increase cooperation with other provinces in similar climates to share lessons learned and develop common research projects. For instance, low-carbon pilot cities which have shown successful results in several mitigation areas could be a useful instrument (Nilsson, Smit and Kuramochi, 2021). Similarly, international experiences from countries which are further ahead in their transition to clean heating such as Denmark could share important experiences in terms of technological as well as policy issues.

High upfront costs should not be a barrier for rural households to opt for the more energy efficient technologies. The affordability of clean heat should be included as a priority in clean heating policy and aim to counteract disproportional economic burden on urban versus rural households. Policies and financial support should thus aim to remove high upfront costs of highly energy efficient heating technologies in rural areas.

Official clean heating plans and policies could better include the long-term perspective for a smoother transition and achievement of the 30/60 goals. Official clean heating and energy policy currently lack an inclusion of the long-term perspective. The development of a vision and subsequently a strategy for the transition of the Inner Mongolia heating sector could make the low-carbon heating transition smoother and more economically efficient by avoiding lock-in effects and bringing down heating costs for its citizens. The development of such a vision and strategy could be informed by sophisticated modelling exercises from which quantitative targets for the deployment of clean heating technologies could be derived. Finally, the development of a clean heating vision could benefit from the involvement of relevant stakeholders such as local enterprises and manufacturing industry.

A decarbonised heating sector will have major implications for the power sector

A fully decarbonised heating sector in Mongolia will inevitably increase the electricity demand and thus also the pressure on the deployment of renewable electricity. As suggested in this study as well as by other research, the transition to a decarbonised heating sector in Inner Mongolia will require a major shift to electrified heating (Tang et al., 2021). That will lead to a substantial rise in electricity demand which will require a significant expansion of renewable energy capacity as well as transmission and distribution infrastructure, particularly in rural areas. The development of long-term technology pathways could be a useful tool in long-term energy planning.

5

Future Research Needs

5 Future Research Needs

Experiences with alternative low carbon heating options are increasing around the world. It is important to understand the challenges that are faced in Inner Mongolia, so that future research can focus on extracting valuable lessons from experiences elsewhere in the world.

The aim of this research is to present the opportunities for low carbon heating in Inner Mongolia by comparing government plans to technology options and ongoing projects in Inner Mongolia. This could be used as a basis for developing alternative heating scenarios in a more detailed modelling exercise which could further provide a basis for the development of a clean heating vision for Inner Mongolia. High quality data is a key requirement for robust modelling analysis. Better access to, and the generation of, high quality data is thus also needed.

Co-benefits related to sustainable development including health impacts from air pollution and the affordability of clean heat are key aspects of a transition of the Inner Mongolian heating sector. Future research collaborations could combine co-benefits analysis with GHG emissions modelling and the development of a vision for the Inner Mongolian heating sector.

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Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

GIZ Office East Asia Sunflower Tower 1100
37 Maizidian Street, Chaoyang District
100125 Beijing, PR China

E climatechangechina@giz.de
I www.climatecooperation.cn