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Article

Smart heating and cooling systems for carbon-neutral cities: Policies and practices in Germany and China

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Abstract: Cities play a key role in achieving the climate-neutral supply of heating and cooling. This paper compares the policy frameworks as well as practical implementation of smart heating and cooling in six cities: Munich, Dresden and Bad Nauheim in Germany; and Jinan, Chengdu and Haiyan in China, to explore strategies to enhance policy support, financial mechanisms, and consumer engagement, ultimately aiming to facilitate the transition to climate-neutral heating and cooling systems. The study is divided into three parts: (i) an examination of smart heating and cooling policy frameworks in Germany and China over the past few years; (ii) an analysis of heating and cooling strategies in the six case study cities within the context of smart energy systems; and (iii) an exploration of the practical solutions adopted by these cities as part of their smart energy transition initiatives. The findings reveal differences between the two countries in the strategies and regulations adopted by municipal governments as well as variations within each country. The policy frameworks and priorities set by city governments can greatly influence the development and implementation of smart heating and cooling systems. The study found that all six cities are actively engaged in pioneering innovative heating and cooling projects which utilise diverse energy sources such as geothermal, biomass, solar, waste heat and nuclear energy. Even the smaller cities were seen to be making considerable progress in the adoption of smart solutions.

Keywords: smart heating and cooling; carbon-neutral city; municipal urban energy transition; integrated energy solution; district heating

1. Introduction

Approximately half of the world's end energy consumption is for heating and cooling. This is also true for Germany, as Federal Ministry for Economic Affairs and Energy (BMWK) pointed out, where over 50% of end energy consumption is linked to the heating and cooling of buildings as well as to provide hot water to private households and for industrial processes (2022). As the country has a temperate continental climate with cold winters and moderate summers, significantly more energy is required for heating than for cooling. The primary sources of heat are: natural gas (48.2%), oil (25.6%) and district heating (13.9%). Other typical sources of heat have so far remained far less popular in Germany, i.e., electricity (4.8%), electric heat pumps (2.2%) and night storage heaters (2.6%). All other sources, including liquid gas, wood or pellets and coal, have an overall share of 7.5% (BMWK, 2019). In contrast, residential heating and cooling in China only contributes about 16% to the total end energy consumption (Xiong et al., 2023), due to the dominance of industry as an energy consumer. Despite this, the absolute energy consumption remains significant. In 2021, the heating energy consumed by cities in northern China was equivalent to

212 million tonnes of coal. In fact, about 80% of the heating demand in these cities was met by district heating systems, which mainly rely on coal-fired combined heat and power.

The critical scientific problem to be addressed is the urgent need for cities in Germany, China, and globally to decarbonize their heating and cooling systems to meet national and global greenhouse gas emission reduction targets. Technological advances such as high-efficiency tri-generation, the industrial utilization of waste heat and cold, heat pumps, geothermal systems, solar thermal technology combined with seasonal storage, electric boilers as well as digital technologies such as the Internet of Things (IoT) have reshaped the dynamics between end-users and the traditional energy system, and can be exploited to make energy systems smarter (Hossein Motlagh et al., 2020).

According to Lund et al. (2017), a smart energy system adopts a holistic approach in which smart electricity, heating/cooling and gas grids are integrated with storage technologies to achieve optimal solutions by exploiting their synergies (Lund et al., 2017). Efficiency and decarbonization can thus be achieved under an integrated perspective which utilizes these synergies between heating/cooling and other sectors (Paardekooper et al., 2018). Although there is still no clear definition of what smart heating and cooling entails, we have identified three key features of smart heating and cooling systems:

1) Digitalization: The innovative application of information and communication technologies, particularly the adoption of intelligent control strategies such as IoT-based systems, has proved effective in reducing energy consumption (Yaïci et al., 2023).
2) System Integration: Achieving higher energy efficiency with system integration is crucial. According to the Heat Roadmap Europe studies, a smart energy system with 50% reliance on district heating and sector integration is more efficient than a decentralized or conventional system (Mathiesen et al., 2019).
3) Energy Transition: Driven by decarbonization, the growing share of renewable energies in the energy mix is essential. Digitalization supports this transition by incorporating clean heat sources into district heating and cooling networks, including heat pumps, appliances, renewables, and the utilisation of storage and waste heat from industry (IEA, 2021).

Cities play a key role in achieving the climate-neutral supply of heating and cooling. Here it is imperative to implement smart local strategies and solutions to avoid the inevitable losses when heating and cooling energy is transported over long distances. Various policies and regulations govern municipal actions in this regard. Policy continuity, financial support and the quality of the consumer experience are key factors in the successful deployment of heating and cooling technologies. Policy support is particularly crucial in the case of district heating as this requires a higher degree of coordination and planning at regional or municipal scale. Therefore, the focus of this study is to provide a comparative analysis of smart heating and cooling policies as well as solutions at municipal level.

The primary contributions of this study include a comparative analysis of smart heating and cooling policies and solutions at the municipal level. This analysis addresses the identified scientific problem by exploring strategies to enhance policy support, financial mechanisms, and consumer engagement, ultimately aiming to facilitate the transition to climate-neutral heating and cooling systems.

2. Methods

2.1. Methodological framework

The methodological framework of this study aligns with the legal framework for heating and cooling. Firstly, an overview of recent national policy frameworks for smart heating and cooling systems in Germany and China in proved. Subsequently, smart heating and cooling policies at the municipal level are analyzed, using case studies of three cities in each country. These cities were selected to reflect a range of political levels and municipal sizes. Focusing on the three main features of smart heating and cooling identified in the introductory section, the analysis considers local government documents, including municipal energy strategies, heat supply plans, and other policies related to the transition to smart heating and cooling. Practical solutions for smart heating and cooling adopted in the case study cities are then investigated. The discussion section includes additional aspects such as financing schemes and pricing mechanisms. The conclusion section offers a summary of key findings and some considerations for policymakers. The study is based on a literature review supplemented by expert interviews with policymakers, heating and cooling experts and municipal utilities.

2.2. Case study cities

In selecting the case study cities (see **Table 1**), the aim was to provide a comprehensive overview of how cities of different sizes and political levels in Germany and China are implementing smart heating/cooling strategies and solutions. In particular, the exemplary nature of urban strategies and innovative heating and cooling approaches was a criterion for selection. The case studies in China take into account the country's climate zones, which determine the demand for heating and cooling. During the planned economies, the central government took the Huai River and the Qinling Mountain Range as a geographical divide to determine a winter heating policy line in the 1950s, which bisected the country into two zones: the northern zone, which was to receive heating, and the southern zone, which was not. This division has become a convention in planning practice, despite ongoing

Table 1. Overview of case study cities.

Country	City	Population[1]	Political status	Target year for climate/carbon neutrality
Germany	Munich	1,589,026	State capital of Bavaria	2035
	Dresden	572,240	State capital of Saxony	2035
	Bad Nauheim	33,723	City in Wetterau County in Hesse	2045
China	Jinan	9.41million	Provincial capital of Shandong	2060
	Chengdu	21.26 million	Provincial capital of Sichuan	2060
	Haiyan	468,700	County of Jiaxing City in Zhejiang Province	2060

[1] Population data for Germany from municipal statistics as of 31 December 2023; population data for China from municipal statistics as of 31 December 2022.

discussions about its revision. Based on this background, cities in China were chosen from both zones (see **Figure 1**).

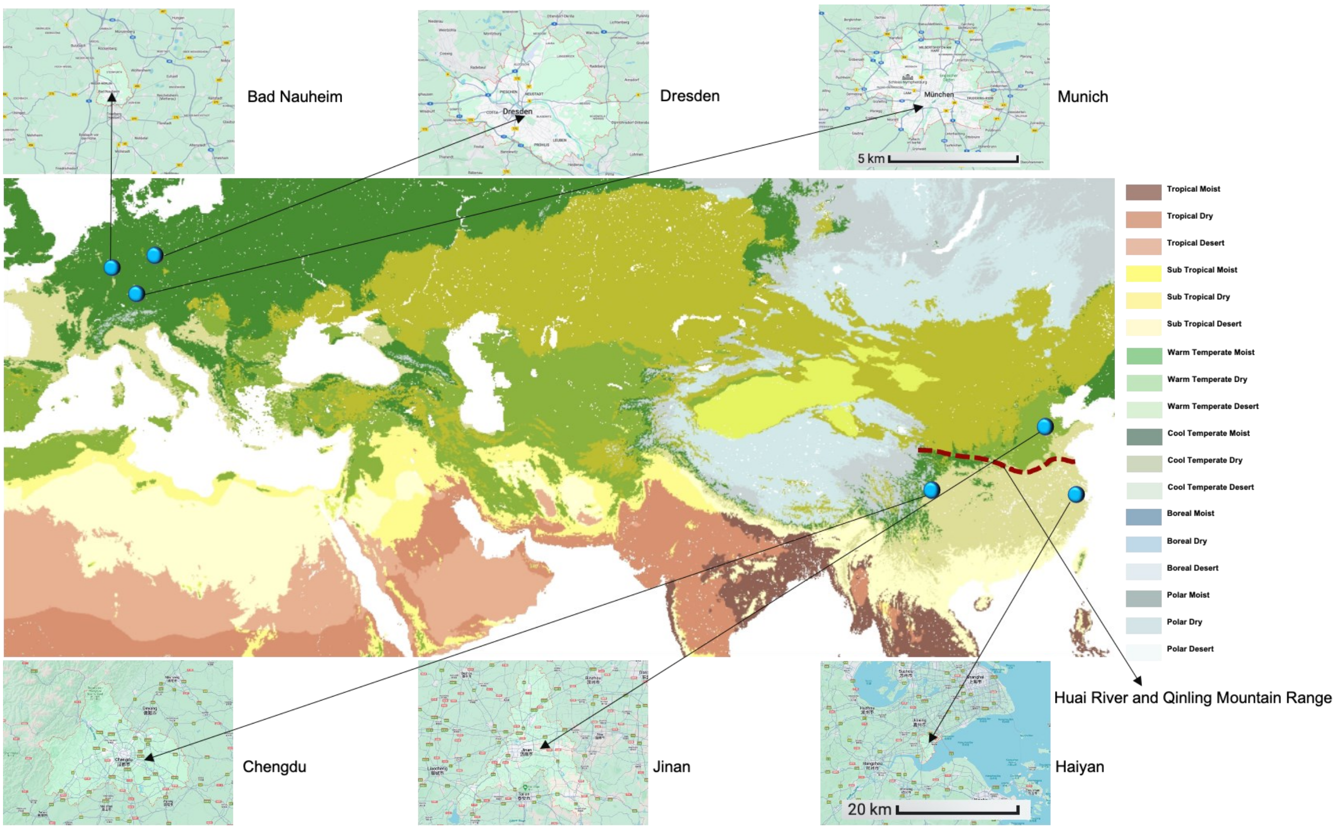

Figure 1. Locations of case study cities in the world's climate regions.

Source: World Climate Regions ©Deniz Karagulle (2020)[1]; Google city maps ©2024 GeoBasis-DE/BKG.

3. Analysis

3.1. Smart heating and cooling policies and regulations at national level

Key heating and cooling policies related to smart energy transitions in Germany and China are summarized here (see **Figure 2**). In Germany, the path to modernizing and digitalizing the energy sector was laid out by the Act on the Digitalization of the Energy Transition from 2016 (revised in early 2023). The Energy Efficiency Strategy 2050 (adopted in 2019) as well as the measures of the National Action Plan on Energy Efficiency (NAPE) 2.0 attach particular importance to raising the energy efficiency of heating and cooling. In NAPE 2.0, for example, high priority is given to sector coupling. The new Heating Cost Ordinance (HKVO) of 2021 stipulates that all new heat meters and heating cost allocators must allow remote monitoring of usage and be connected to a smart meter gateway. The Buildings Energy Act (GEG) of 2020 created a uniform body of legislation regulating the energy performance requirements and the use of renewable energy for heating and cooling buildings by bringing together the Energy Conservation Act (EnEG), the Energy Saving Ordinance (EnEV) and the Act on the Promotion of Renewable Energy in the Heat Sector (EEWärmeG) (BMI, n.d.).

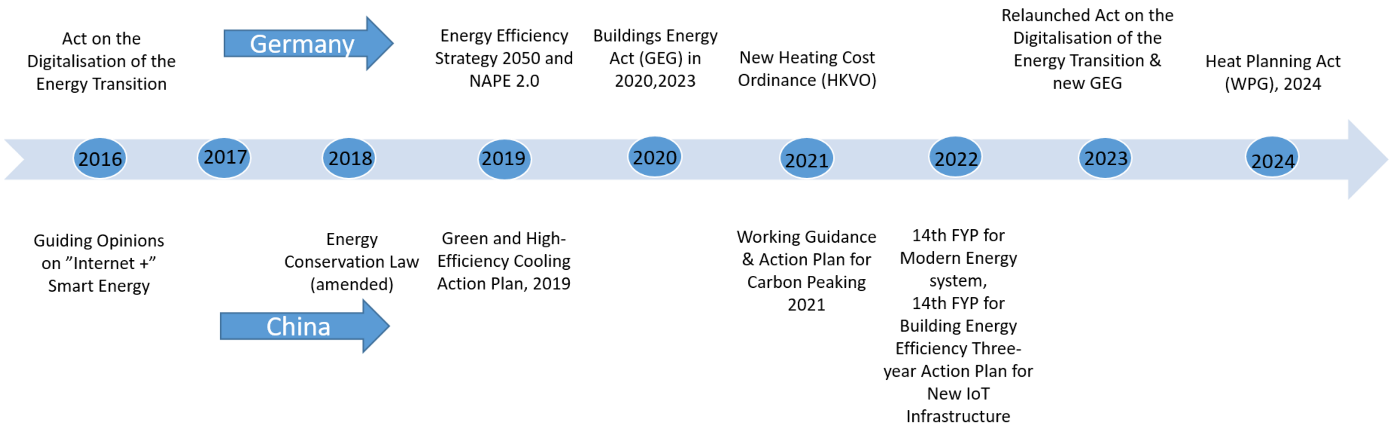

Figure 2. Smart heating and cooling policies at national level in Germany and China.

According to the Law on Renewable Heating (part of the revised Buildings Energy Act of 2023), newly installed heating systems must, from 1 January 2024, use 65% renewable energy sources while the use of fossil fuels in buildings will be ended by 2045 at the latest (Die Bundesregierung, 2023). On 16 August 2023, the Federal Cabinet approved a draft law on Heat Planning and Decarbonization of Heat Networks (Heat Planning Act, WPG), which requires the introduction of municipal heat planning (KWP) in Germany's approximately 11,000 municipalities (BMWSB, 2023). Cities with more than 100,000 inhabitants must introduce municipal heat planning by 30 June 2026, with smaller cities following by 30 June 2028 at the latest. The law is scheduled to come into force on 1 January 2024, the same time as the Building Energy Act (GEG); these interlinked laws aim to achieve a climate-neutral heat supply by 2045.

In China, the key law governing smart heating and cooling is the Energy Conservation Law (amended in 2018), which mandates that buildings with centralized heating must gradually install heat sub-metering and charging based on heat consumed. Additionally, public buildings with air conditioning systems for heating and cooling are required to have a system of temperature control. In 2016, the Guiding Opinions on Promoting the Development of "Internet+" Smart Energy were promulgated with the aim of promoting the development of smart energy infrastructure. The first national cooling policy was in June 2019, namely the Green and High-Efficiency Cooling Action Plan. As the 14th Five-Year Plan (2021–2025) determined China's commitment to reach peak carbon dioxide emissions by 2030 and carbon neutrality by 2060, these climate goals have been incorporated into key governmental tasks at all levels. The concept of smart heating and cooling can be observed in recently released energy policies.

In October 2021 came the announcement of the Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy as well the Action Plan for Carbon Dioxide Peaking Before 2030, which together required cities to renovate heating infrastructure and to operate and manage this in an intelligent way. In March 2022, the 14th Five-Year Plan for a Modern Energy System was introduced, advocating centralized cooling in the south, a combined supply of heating and cooling in the Yangtze River region, as well as clean-energy heating in the north. It also stipulated the market reform of electricity, gas and heat pricing for clean heating. Furthermore, the 14th Five-Year Plan for

Building Energy Efficiency and Green Building Development, unveiled in March 2022, demands the continuous enhancement of user-side building energy efficiency and insulation alongside the intelligent regulation and monitoring of heat networks. One specific goal is to complete the energy-saving renovation of existing residential buildings—with a total area of more than 100 million m^2—by 2025. Lastly, the Three-Year Action Plan for the Construction of New IoT Infrastructure (2021–2023), released in September 2022, includes measures to deploy 5G and other communication facilities, to establish an energy data sharing platform for the flexible interconnection and joint regulation of power grids, gas grids and heat grids. Here the aim is to create a clean, low-carbon, safe and efficient modern energy system.

3.2. Smart heating/cooling strategies and practices at municipal level

Regarding the three German case study cities, digitalization is a key policy instrument in Munich, energy efficiency is being prioritized in Dresden, and cutting-edge technologies are being scaled up in Bad Nauheim. All three are currently in the process of developing their first municipal heating plan. The three Chinese case study cities have expressed a more explicit commitment to creating smart energy systems in their energy plans, including the heating and cooling sector, as seen in Chengdu and Jinan, or directly aim to build smart heat systems, as in Haiyan. In addition to municipal strategies, it is of course vital that local governments take timely and

Table 2. Municipal strategies in the six case study cities related to smart heating and cooling strategies.

City name	Municipal strategies	Time of announcement	Short description of aims
Munich	Integrated Action Program for Climate Protection in Munich (IHKM)	Published in 2010, last updated in 2022	Expansion of efficient district heating networks; harnessing of deep geothermal energy technology for a climate-neutral heat supply
Dresden	Integrated Energy and Climate Protection Concept Dresden 2030 (IEK)	Published in 2013 and currently under revision	Expansion of district heating and raising efficiency; increasing the share of renewables; focus on heat pump technology for decentralized heat supply
Bad Nauheim	Integrated Climate Protection Concept and Climate Management, Municipal Greenhouse Gas Monitoring and Energy Management	Both under development	N/A
Jinan	Jinan 14th Five-Year Plan for Energy Development (2021–2025)	2022	Building an integrated smart energy system with an efficient supply of electricity, heat, cold, gas and water
	Jinan Three-Year Action Plan for High-quality Development of New Energy (2023–2025)	2023	Building an integrated energy network of smart grid (core), heat, gas and other networks; target of 10 million m^2 heating area from new energy sources
Chengdu	Chengdu 14th Five-Year Plan for Energy Development (2021–2025)	2022	Developing information-based and more intelligent energy sector; building the Energy Internet
	Ten Policy Measures for Energy Structure Adjustment in Chengdu (2021–2025)	2022	Promoting smart energy management; establishing a “smart energy cloud platform” and promoting the “gas-to-electricity” transition of heating and cooling facilities in urban complexes, etc.
Haiyan	Haiyan District Heating Plan (2021–2025)	2021	Building smart heat supply systems; incorporating nuclear district heat supply into the plan
	Haiyan Special Plan for Nuclear District Heating Pipeline Facilities (2022–2030)	2022	Constructing a total of180 km heating pipelines by 2025 with projected heat capacity of 150 MW from nuclear energy

targeted actions to implement these strategies and integrate low-carbon technologies effectively. Following an overview table (see **Table 2**), selected heating and cooling projects from the case study cities are showcased, and the solutions adopted are discussed.

3.2.1. Munich

Around 40% of Munich's homes are supplied by a district heating network spanning 900 km. Run by the city's utility company, Stadtwerke München (SWM), district heating is primarily powered by coal, gas and waste incineration (Decarb City Pipes, 2022). As outlined in the Integrated Action Programmer for Climate Protection in Munich (IHKM) (updated in 2022), SWM has ambitious plans to lay more than 100 kilometers of new district heating lines by 2030 in order to supply as many local residents as possible. Additionally, by harnessing deep geothermal energy, the local authorities aim for Munich to become the first major city with district heating generated to 100% from renewable sources.

Apart from the district heating network, the municipal strategy involves developing heat pumps sourced from groundwater or in combination with solar panels, as well as establishing efficient small district heating networks. Digital tools are central to designing and implementing the city's strategy. As part of the city's digital twin project, a map of the local solar power potential was published in the GeoPortal Munich, displaying not only the potential of Munich's rooftops but also indicating the number of solar panels that could be installed on those roofs. (Landeshauptstadt München, n.d.). Furthermore, a geothermal energy map is available in Geoportal Munich.

Regarding municipal heat planning, SWM is collaborating with the city government and various research institutions to create the so-called "Munich Model" for heat transition, utilizing a consistent dataset and various digital tools including the Post GIS database, Python for data processing, Tableau for data publication, Jira software for release management, and Azure cloud (Deutscher Städtetag, 2024)). The central planks of the heat transition are to reduce heat consumption through energy-efficient renovation, expand climate-neutral district heating, and rapidly transition from natural gas and heating oil to district heating, heat pumps and other renewable technologies. The aim is to submit a draft heat plan and heat transition strategy to the city council in 2023, thereby allowing local residents to choose their heating technology with some confidence (Landeshauptstadt München, 2023)

In Munich, the C/sells-project "Intelligent Heat Munich" was launched in 2017. It was funded by the Smart Energy Showcase: Digital Agenda for the Energy Transition (SINTEG) programmer of the German Federal Ministry of Economics and Technology. The SINTEG programmer, which ran 2016 to 2021 included five large-scale showcase regions in which model solutions for future energy supply were developed and tested. The focus was on the digitalization of the energy sector. The Intelligent Heat Munich project explored the potential of networking electricity and heating or cooling, a concept known as "sector coupling" (Weigand et al., 2021). In this project, surplus green electricity was utilized to power electric storage heaters, heat pumps and cooling systems.

The most notable feature of Munich's heat transition is its ambition to become the first major city with district heating fully powered by renewable energies, achieved through the utilization of deep geothermal energy technology. The local utility company SWM operates six geothermal plants in and around the city, with plans to build a seventh from 2024. Since 2016, for example, the Freiham district in western Munich has been heated by a geothermal system that pumps water from a depth of 2500 m, where it is heated naturally to 90 °C. Munich is also encouraging innovative solutions in district cooling aimed at replacing conventional air conditioning systems in large non-residential buildings. Since 2011, SWM has operated a district cooling network extending over 23 km, which, for instance, utilizes cold groundwater from subway culverts to cool the BMW Group's research and innovation center (Stadtwerke München GmbH, n.d.).

3.2.2. Dresden

Dresden boasts one of the largest central district heating networks in Germany. As early as 2012, nearly half of the city's homes were supplied with district heating from combined heat and power (CHP) sources. The district heating system primarily relies on the Nossener Brücke gas-and-steam turbine power plant and the gas turbine in the Cogeneration Plant Nord. Since 1997, Dresden's district heating grid has been operating without coal, although it still relies on natural gas as the main fuel (Teuffer, 2023). The proportion of renewables in the heating and cooling sector remains significantly below the German average, presenting the city with substantial potential for their increased use.

In its "Integrated Energy and Climate Protection Concept Dresden 2030", published in 2013, the city proposed implementing smart metering and smart grids, although smart heating and cooling were not explicitly mentioned. Energy efficiency, however, received top priority in this 2013 Concept, including the optimization and expansion of district heating, a reduction in transmission losses, enhanced efficiency, an increased share of renewables (including biomass as the sole base load renewable energy source in the city) and a recognition of the strategic importance of geothermal energy. In the case of decentralized heat supply, i.e., in the outskirts and suburban areas, the focus was on heat pump technology, with high expectations for its effectiveness.

A thematic city map of geothermal energy was created and made accessible to every citizen to identify potential areas for the utilization of geothermal energy and to estimate heat output. According to the Dresden Requirements for Energy and Climate Protection Concepts for Development Plans, published in August 2022, key measures for achieving climate-neutral buildings by 2050 include stringent energy efficiency standards for the building stock, efficient heating systems and other technical solutions, as well as the one-site use of renewable energy.

Currently, the city is in the process of updating its Integrated Energy and Climate Protection Concept, which involves analyzing the potential for energy savings, exploring opportunities for utilizing waste heat and renewable heat sources, as well as working toward a municipal heating plan to achieve a climate-neutral heat supply. This endeavor is being pursued in close collaboration with SachsenEnergie AG (whose majority owner is the city), the largest municipal utility in eastern Germany. The objective is to finalize the municipal heating plan by the second half of 2024.

Dresden was part of the Wind NODE project, funded by the SINTEG programmer (see above). One of the project's work packages was to develop efficient and flexible cold storage solutions for industrial refrigeration systems. The use of vacuum ice slurry technology helped raise the share of renewable energy in the network and ensure a high level of supply security for the industrial refrigeration sectors (Wind NODE, 2020).

As the city's supplier of power and district heating, Sachsenenergie AG aims to generate climate-neutral electricity and heat by 2035, or, if there are delays in implementation, by 2045 at the latest. As the Dresden partner of the EU-funded project "MAtchUp", Sachsenenergie AG has taken many measures to improve the efficiency and flexibility of the district heating network (Anz and Wittkuhn, 2019). Major actions include increasing the number of thermal storage units, lowering district heating temperatures and connecting future renewable energy sources (RES)-sites to the central district heating system. For instance, Sachsenenergie AG has expanded the large-scale heat storage facility in the Dresden district of Reick so that more surplus green electricity from fluctuating renewable energy sources can be converted into heat and integrated into the grid. The MAtchUP project is now completed. Another that is currently running is the Smart City Dresden model project (2022–2026), funded by the federal government. One of the smart city measures here is to develop sector coupling in Pillnitz, an energy self-sufficient district of Dresden, through the use of geothermal energy and photovoltaics. In addition, Sachsenenergie AG is cooperating with the city's main university, the TU Dresden, to use waste heat for district heating from 2024. To this end, three large-scale heat pumps will be installed to transfer surplus heat from the high-performance computers of the Lehmann Centre on the campus grounds to Sachsenenergie AG's district heating network.

3.2.3. Bad Nauheim

As a member of the association Climate Municipalities of Hesse, Bad Nauheim is committed to achieving carbon neutrality by 2045. In this task, it is guided by the association as well as the Climate Action Plan for Hesse. Since May 2022, the city has been developing its own Integrated Climate Protection Concept and Climate Management, funded by the German Federal Ministry for Economic Affairs and Climate Protection.

The city has taken various steps towards a clean and smart energy transition. In particular, it has initiated a long-term project for Climate-Neutral Municipal Utilities. The municipal utility company Stadtwerke Bad Nauheim is committed to providing a climate-neutral heating supply. The company provides the "Am Goldstein" and "Am Kaiserberg" residential areas with environmentally-friendly district heating using combined heat and power plants. It has also built Germany's largest (as of 2023) geothermal collector fields for the purpose of cold district heating. The city is also in the process of formulating a plan for Municipal Greenhouse Gas Monitoring and Energy Management. In addition, the municipal authorities are developing an integrated neighborhood concept in the Grießbreiviertel district for energy-efficient structural renovation with support from the development bank Kreditanstalt für Wiederaufbau (KfW) and the state government of Hesse. The primary focus of the integrated neighborhood concept is to supply electricity and heat, energy renovation and climate adaptation.

Concerning municipal heat planning, the Hessian Energy Act, which is more ambitious than the draft national law, mandates that municipalities with more than 20,000 inhabitants must introduce ways of heating houses and public buildings in a climate-neutral manner by 2045. With a population of more than 30,000, Bad Nauheim already introduced municipal heat planning in September 2023.

The city's utility company, Stadtwerke Bad Nauheim, operates the largest fifth-generation district heating and cooling (5GDHC) network in Germany. This network boasts a geothermal collector system spanning over 13 km (including supply and return pipes), which supplies more than 400 residential units with climate-neutral heating and cooling (Stadtwerke Bad Nauheim, n.d.). The collector consists of two layers buried at depths 1.5 m and 3.0 m; each layer extends over an area of 11,000 m^2, giving a total collector area of 22,000 m^2. With a network temperature ranging from -2 ℃ to 16 ℃, it efficiently distributes heating and cooling with minimal distribution losses and high energy efficiency. This innovative and promising technology can integrate various renewable technologies as heat sources. Until today, however, only a small number of 5GDHC networks have been constructed in Germany (Wirtz et al., 2022).

3.2.4. Jinan

Jinan is one of the first 12 cities designated by the Chinese government as clean heating pilots. As the capital city of Shandong province, it received an annual public grant of 700 million Chinese Yuan for a period of three years to promote the transition to cleaner heating sources. Historically, coal has been the primary fuel used for heating: at the end of 2018, coal still provided 81.8% of the city's total heating capacity, with the remainder supplied by electricity, natural gas, industrial waste heat and other heat sources (Jinan Engineering Consulting Institute, 2020). By the end of 2020, the area heated by new and renewable energy sources had increased to 4.06 million m^2, with geothermal energy accounting for 2.26 million m^2 and biomass 1.8 million m^2; further, district heat pipelines in the city were extended to a total length of 10,500 km, serving 280 million m^2 of residential heating area (Jinan People's Government, 2022).

The city's Clean Winter Heating Plan of 2019–2022 aimed to centralize heating and to enhance the intelligence of the centralized heat supply system while integrating various energy sources such as coal, natural gas, electricity and renewables. The concept of a smart energy system and smart heating/cooling has become explicit in two newly published municipal documents: the Jinan 14th Five-Year Plan for Energy Development (2021–2025) and the Jinan Three-Year Action Plan for High-Quality Development of New Energy (2023–2025).

The Jinan 14th Five-Year Plan for Energy Development specifies the goal of building an integrated smart energy system with intelligent control of energy collection, transmission, conversion and operation to ensure an efficient supply of electricity, heating, cooling, gas and water. The heat network system will feature a long-distance centralized heat supply and the integration of multiple heat sources, including industrial waste heat, natural gas and renewable energy.

The Jinan Three-Year Action Plan for High-Quality Development of New Energy proposes the construction of a comprehensive smart energy demonstration area in which energy networks (including a smart grid as the core, heat pipelines and natural gas pipelines) are interconnected, various energy forms are synergized and centralized and there is coordination of the distributed energy supply. The plan sets a goal for the heating area powered by new and renewable energy sources to exceed 10 million m^2 by 2025.

The city's utility company, the Jinan Energy Group, has independently developed an integrated energy resource platform (ERP) system for heat and gas, which the company has called "Smart Brain" (Jinan Heating Group, 2021). The ERP platform has digitalized gas and heat pipelines spanning 19,000 km, which serve over two million households. Leveraging the IoT and artificial intelligence (AI) technologies, this smart platform monitors heat sources, heat exchange stations and household heating equipment in real time. It supports malfunction diagnosis and the real-time scheduling of energy sites in the network, providing households with more proactive, efficient and accurate services through powerful data statistics and analysis functions. For example, the previous heat network regulation time of two weeks was cut to just three days after commissioning in the 2021 heating season, greatly enhancing operational efficiency. Users can access real-time updates on the status of their heating equipment and send malfunction alerts through the WeChat app to activate a fast repair service. The ERP platform was expanded by the East Jinan Smart Heating Project, which was integrated at the end of 2023. This Smart Heating Project harnesses waste heat from Zhangqiu Diaozhen Chemical Industrial Park to provide an additional heating capacity of 1102 megawatts, cutting carbon dioxide emissions by 803,000 tons.

3.2.5. Chengdu

Due to its warm climate, Chengdu has a greater demand for cooling than heating. Air conditioning accounts for 40%–50% of the city's peak summertime power load, presenting a significant challenge to the local power grid. For instance, in the summer of 2022, many power plants had to be temporarily shut down to reduce electricity consumption and shift the load to residential areas. Therefore, innovative solutions are required to help address this challenge.

Simultaneously, in its municipal 14th Five-Year Plan for Energy Development (2021–2025), Chengdu introduced the Warm Homes Project, which included the development of the first centralized heating pilot zones. These heating pilots, implemented by the Chengdu Gas Company, will largely rely on natural gas, complemented by various renewable heat sources including solar hot water as well as ground-source and air-source heat pumps. The Five-Year Plan also emphasizes the promotion of an information-based intelligent energy sector, active development of the energy internet and the construction of a green, efficient smart grid.

Furthermore, the Ten Policy Measures for Energy Structure Adjustment in Chengdu (2021–2025) outline initiatives to promote smart energy management, establish a "smart energy cloud platform" and promote the "gas-to-electricity" transition of heating and cooling facilities in urban complexes, large shopping malls, universities, hospitals and office buildings.

Chengdu is implementing innovative solutions to meet its cooling and emerging heating demands. Since May 2023, the city's utility company, the Chengdu Drainage Corporation, has been operating a pilot project for a water source heat pump at the 9th

Sewage Treatment Plant, one of its nine water treatment plants. This marks the first time that the technology of a reclaimed water source heat pump has been used in the center of Chengdu. The system has a total cooling capacity of 398.2 kilowatts and a total heating capacity of 238.9 kilowatts. The plan is to install water heat pumps in all new reclaimed water treatment plants in Chengdu. These pumps will be used to provide heating and cooling for large supermarkets, office buildings and industrial parks, with the aim of reducing carbon emissions.

In the east of the city, a Smart Energy Centre is being constructed with a total investment of about 1 billion Chinese Yuan by the Chengdu Jinmao Smart Energy Technology Company, a subsidy of the state-owned China Jinmao Holdings Group. The project will utilize shallow geothermal resources at a depth of more than 100 m, combined with heat pump technology, to provide high-quality, low-cost heating and cooling service for more than two million m^2 of nearby commercial, office buildings and homes. It is estimated that the project, which should be completed and operating by August 2024, will cut annual carbon dioxide emissions by 19,748 tonnes.

3.2.6. Haiyan

Like Chengdu, the city of Haiyan does not lie in the subsidized heating area of northern China; nonetheless, the local authorities face a growing demand for household heating. The centralized cooling load, which is estimated only for public buildings and large industrial data centers, is projected to hit around 70 megawatts by 2025. In 2020, the centrally supplied heat loads in Haiyan were predominantly related to industrial needs.

Published in May 2021, the Haiyan District Heating Plan (2021–2025) marked a significant milestone: for the first time, the municipal plan took account of residential heating loads. It initiated a large-scale centralized supply system for residential heating in southern China, a pioneering effort in the region. The plan proposed the development of smart heat supply systems, supported by nuclear-powered district heating.

Subsequently, the Haiyan Special Plan for Nuclear District Heating Pipeline Facilities (2022–2030), unveiled in December 2022, outlined ambitious goals to construct a network of heating pipelines totalling 180 km to achieve a nuclear-powered heat supply capacity of 150 megawatts by 2025. In the long term, the objective is to provide district nuclear heating for the whole of Haiyan.

Haiyan is home to the Qinshan nuclear power plant, the largest such facility in China. In 2021, the Qinshan Nuclear Power Company signed a cooperation agreement with the Haiyan government to conduct the Zhejiang Haiyan Nuclear Energy Heating Demonstration Project, the first nuclear heating project in southern China. With a total investment of about 940 million Chinese Yuan, the aim of the project is to utilise heat generated by nuclear fission to provide environmental-friendly heating for public facilities, homes and industrial parks. In December 2021, the first phase of this district heating demonstration project was commissioned, providing nuclear-generated heating to homes with a total area of 464,000 m^2. Additionally, in December 2022, China’s first nuclear industrial heating project began operations in Haiyan. Currently, it guarantees a 24-hour supply of industrial heating totalling about 288,000 gigajoules per year to companies. Upon its completion in 2025, the overall project will provide an annual heat supply of 704,000 gigajoules through a pipeline network spanning 180 km. This will serve to cut annual carbon emissions by 24,600 tonnes.

4. Discussion

4.1. Funding

Financial support schemes can be highly effective in stimulating the deployment of smart heating and cooling technologies. In Germany, various funding support instruments are implemented at national level. These include the Market Incentive Programmer (MAP), primarily targeting renewable heating/cooling technologies and the gradual phasing-out of grants for coal, which in turn create opportunities for innovative energy technologies. Furthermore, there are integrated energy efficiency and renewable heat grant schemes such as the Federal Subsidy for Efficient Buildings (BEG), which is managed by the German development bank KfW (IEA,2022). Another example is the Municipal Directive, which has been in place since 2008 and supports municipalities and municipal stakeholders in achieving sustainable reductions in emissions. For instance, cities can apply for heat planning funding, with their own contribution as low as five percent or even waived entirely for financially weak municipalities (National Climate Protection Initiative, 2021). The Federal Funding for Efficient Heating Networks (BEW) is another initiative that promises around €3 billion for renewable heat generation and the expansion of heat network infrastructure (the money to be disbursed from September 2022 up to the end 2026). Grants cover up to 50% of planning costs and 40% of installation costs. In this way cities can cover their investment costs for innovative heating and cooling networks based on renewable heat.

The Chinese central government also provides substantial subsidies and runs pilot programs, with local governments also making significant financial contributions to these subsidies. One notable example is the Clean Heating Plan in northern China, which has pledged a 1083 billion Chinese Yuan fund for 88 selected pilot cities since 2017. Each pilot receives the central special fund for three years according to the standard of 1 billion Chinese Yuan per year for centrally-administrated municipalities, 700 million Chinese Yuan per year for provincial capitals, and 500 million Chinese Yuan per year for prefectural cities. City governments are expected to co-finance nearly three times that amount. As a pilot capital city, Jinan has received a total of 2.1 billion Chinese Yuan to exploit clean heat sources, improve the efficiency of heat networks and renovate buildings for higher energy efficiency. Subsidies can be allocated from central budgetary investment funds and local financial funds for the renovation of ageing urban heat pipelines, while commercial banks are encouraged to increase credit support for such renovation. However, the main financing burden falls on municipal governments.

4.2. Pricing mechanisms

The different pricing mechanisms in the two countries play a mixed role in the transition to heating and cooling solutions. In Germany, prices are generally governed by the market; governmental intervention is limited to, for instance, national carbon pricing for the heating and transport sectors and the Gas and Heat Price Brake Act

(EWPBG). Every individual home is metered. In China, the pricing mechanism for heating and cooling is still undergoing reform. Since 2007, cities have been required to combine the basic cost of heating, determined by the heating area (accounting for a share of 30% to 60% of the total), with the metered heat price, where applicable (National Development and Reform Commission, 2007). The dual tariff system for district heating (i.e., for residential and non-residential buildings) is fixed by city governments or established under their guidance, and can vary from city to city. In principle, district heating is more efficient and energy saving. However, due to the incomplete implementation of heat pricing reforms, district heating in northern in China is still highly inefficient, heating larger spaces than necessary for longer periods than required, resulting in the excessive consumption of energy (Jin et al., 2021).

In Jinan, for example, the price for residential customers has been 26.7 Chinese Yuan per m^2 floor space since 2008, and for non-residential customers 39.8 Chinese Yuan per m^2 gross floor space since 2010. In buildings installed with meters, the heat price has been determined since 2017 by the basic heat price (30% of the total) combined with the metered heat price (70%). For households, the basic price is 8.01 Chinese Yuan per m^2 with a metered price of 0.20 Chinese Yuan per kilowatt, while for non-households the two prices are 11.94 Chinese Yuan per m^2 and 0.30 Chinese Yuan per kilowatt, respectively. According to the regulations, each user must pay the heating bill as a lump sum before November 15, which is the official beginning of the heating season. In many cities, the heating price is generally low and inflexible. As it does not cover the basic costs of heating, the utility companies suffer major losses every year.

5. Conclusions

The following conclusions are derived from the comprehensive analysis of smart heating and cooling policies across cities of differently sizes in Germany and China, supplemented with studies on best practices:

At national level, legislation and long-term plans play an important role in steering cities in their efforts to transform the heating and cooling sector. In Germany, strong policies aim at continuously raising the energy efficiency requirements for buildings; in particular, municipalities are required to meet minimum standards in the smart heat transition. In China, the setting of targets for carbon peaking and neutrality has been followed by climate objectives for governmental activities at all levels along with various policy supports for the heating and cooling sector.

Policy measures for smart heating and cooling systems are largely targeted at digitalization, energy efficiency and building codes; these measures are generally developed within national policies rather than at the municipal level. In China, great emphasis has been placed on digitalization of the heating infrastructure and its smart control, while in Germany the focus has been on energy efficiency measures such as stricter requirements for building insulation. If energy-efficiency retrofits and metered pricing mechanisms were implemented more consistently in Chinese cities, this would help save a great deal of energy.

While big cities can deploy and experiment with a diverse mix of smart heating and cooling approaches based on local resources, they also face a more complex set of challenges in their smart energy transitions. In particular, it is more difficult for them to achieve energy self-sufficiency as they have to take account of the interactions with heating/cooling systems and infrastructure. For example, long transmission pipelines play a more important role in the heating networks of Chinese cities than in Germany, entailing high upfront investments and long paybacks for heat networks and related infrastructure.

Small cities can also play the roles of pioneers in the smart energy transition and thereby attract public attention. In some cases, they have even more ambitious heat transition plans and targets than major cities. Despite smaller revenues, they are more agile and are able to roll out certain heating and cooling technologies as a dominant solution more quickly. For example, Germany's Bad Nauheim and China's Haiyan have both adopted cutting-edge solutions to provide smart heating services to local residents.

6. Recommendations for municipal strategies

Cross-governmental collaboration is important for cities to promote the transition to smart heating and cooling. Municipal authorities can interact proactively with regional and national governments to gain political and financial support, including dedicated funds to upgrade heating infrastructure. Clearly, greater awareness of these factors will ensure that the energy transition receives additional financial support. Under China's system of urban governance, smaller cities are under the jurisdiction of large cities with higher political groupings, which determine the allocation of many economic resources. Therefore, small municipal authorities must work actively with these higher-level authorities to gain support for successful transition.

Planning for smart heating and cooling can create a strong push for cities to decarbonize and digitalize the heating and cooling sector. Germany's mandatory system of municipal heat planning requires and empowers municipal governments to take quick action. In China, the mainstreaming of smart energy concepts into municipal energy plans in the case study cities has facilitated the transition to smart heating and cooling in a short period, significantly cutting carbon emissions. As target setter and planner, cities can introduce measures and initiatives to complement national policies and even adopt more ambitious requirements at local level to drive the transition to smart heating and cooling.

Smart technologies for the heating and cooling transition are readily available for cities. However, municipal governments must act fast to grasp these opportunities. Cities are important laboratories to test and demonstrate the feasibility of policies as well as the scalability of technologies which, if they succeed in one city, can be quickly adopted by others with similar needs and the requisite technical conditions. The deployment of advanced technologies will not only cut carbon emissions over the short term but also promote the development of new energy industries in the long run.

While smart heat planning is already underway or foreseen in all of our case study cities, cooling planning has hitherto been rather neglected. Yet as heatwaves become increasingly frequent and extreme, cities such as Munich and Chengdu are beginning to adopt innovative solutions to address their cooling demands.

The shifting priorities of municipal government strategy can facilitate, restrict and steer the deployment of certain smart heating and cooling technologies. Local governments must find smart heating and cooling solutions that suit their circumstances and needs within the frameworks of national policies. Policymakers must be careful to pick an intelligent mix of solutions and to ensure the proper public procurement of goods, services and work. For instance, although direct and smart electrification is regarded as the key strategy for decarbonizing heating and cooling systems, this approach should be viewed cautiously in China, where electricity is still mostly generated by coal-fired plants.

Public ownership can be an effective lever to drive the transition to smart heating and cooling. Indeed, municipalities tend to use public companies to facilitate change: they work with national energy utilities or city-owned utilities to deploy cutting-edge heating solutions. This public ownership enables cities to control tariffs and to guard against energy poverty among their residents. In particular, they can lead by initiating innovative heating and cooling systems for municipal buildings.

Rapid action in the heating and cooling sector can only be achieved on the back of sufficient financial support. Dedicated funds from the national or municipal authorities can promote active and effective action. At the same time, such subsidies can prove a severe strain on governmental budgets; for this reason, they must be carefully considered to ensure that local governments are not overburdened. In addition, the awarding of subsidies must always be thoroughly transparent to ensure that funds are utilised effectively and do not unduly distort the marketplace.

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Notes

1 The World Climate Regions plan is based on the maps from "World Climate Regions: A New Approach for Developing a New Map of Standardized Global Climate Regions" available on the open-source platform ArcGIS Story Maps (Accessed on 24/02/2024). This citation also references the research article by Sayre et al. (2020) (see Reference).

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