From the holdings of the Department of Special Collections , Princeton University Library, Princeton, NJ

These documents are either in the public domain, or can only be used for educational and research purposes (Fair use) as per U.S. Copyright law (text below). By accessing this file, all users agree that their use falls in the public domain or within fair use as defined by the copyrightlaw. We do not charge any permission or usage fees for the publication of images of material inour collections, including those provided by Princeton University Library, via our website, catalog, or directly from staff.For more information regarding copyright, credit, and citation please review the information onthe Copyright, Credit and Citation Guidelines page of our website.
https://library.princeton.edu/special-collections/policies/copyright-credit-and-citation-guidelines. If you have any questions, including how to order higher-quality images from the collection, contact Special Collections Public Services via our Ask Us! Form. https://library.princeton.edu/special-collections/ask-us

Doctoral Dissertations, 2011-2026 Public and International Affairs

2024

Accelerating Decarbonization of China’s Building Sector Through Supply-Side Low-Carbon Technology Deployment and Demand-Side Efficiency Improvements

Liu, Shangwei

Princeton, NJ : Princeton University

http://arks.princeton.edu/ark:/88435/dsp01wd376062w

U.S. Copyright law: The copyright law of the United States (Title 17, §108, United States Code) governs the making of photocopies or other reproductions of copyrighted material. Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be used for any purpose other than private study, scholarship, or research. If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of fair use that user may be liable for copyright infringement. This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve a violation of copyright law. https://www.copyright.gov/title17/title17.pdf

ACCELERATING DECARBONIZATION OF CHINA'S BUILDING SECTOR THROUGH SUPPLY-SIDE LOW-CARBON TECHNOLOGY DEPLOYMENT AND DEMAND-SIDE EFFICIENCY IMPROVEMENTS

Shangwei Liu

A DISSERTATION

PRESENTED TO THE FACULTY

OF PRINCETON UNIVERSITY

IN CANDIDACY FOR THE DEGREE

OF DOCTOR OF PHILOSOPHY

RECOMMENDED FOR ACCEPTANCE BY

PRINCETON SCHOOL OF PUBLIC

AN D INTERNATIONAL AFFAIRS

Adviser: Denise L. Mauzerall

March 2024

© Copyright by Shangwei Liu, 2024. All rights reserved.

Abstract

China, the world's largest energy consumer and carbon emitter, has committed to peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. Building operations account for 20% of China's total carbon emissions in 2022. Decarbonizing China's building sector is a crucial component of the nation's efforts to meet its air quality targets, protect human health, and contribute to global efforts to combat climate change. My dissertation investigates the impacts of various technologies and policies on carbon emissions and costs in Chinese buildings. It consists of three analytical chapters.

Chapter 2 provides a quantitative assessment of potential energy-savings, costs, greenhouse gas emission reductions, and adoption strategies for increasing building envelope efficiency in Chinese rural residential buildings. I find that for existing buildings, implementing easy and moderate retrofits can reduce CO_2 emissions as well as reducing clean heating costs to avoid backsliding to coal. For new construction, deploying the most efficient technologies, i.e., whole-home insulation and heat pumps, reduce CO_2 emissions and costs compared to current clean heating policy but significantly increase household upfront costs.

Chapter 3 provides a quantitative assessment of costs and benefits of increasing urban building envelope energy efficiency in China from 2020 to 2050. I find the benefits resulted from energy system cost savings and carbon emission reduction are likely to offset or outweigh the technical costs associated with implementing nearly zero energy building standards. However, the cost-effectiveness of building energy efficiency improvements is subject to various factors, including building envelope costs, thermal comforts, and carbon prices.

Chapter 4 analyzes the impact of various possible short-term investments in China's district heating sector (2020-2030) on CO_2 emissions and capital and operating costs. I find that replacing dirty coal technologies with existing and new combined heat and power (CHP) plants poses a risk of carbon lock-in from coal-fired district heat production and associated coal-fired electricity generation. However, expanding the use of industrial waste heat and air/ground-source heat pumps in district heating systems can avoid the need for new CHP construction while providing household heating at moderately increased cost.

My dissertation demonstrates various cost-effective opportunities for China to decarbonize its building sector through both demand-side energy efficiency improvement and supply-side low-carbon technology deployment.

Acknowledgement

First and foremost, I want to express my deepest gratitude to my advisor, Professor Denise L. Mauzerall, for her unwavering support and guidance throughout my PhD journey. Denise has guided me through every aspect of academic research – from framing research questions to presenting results, labeling figures, and drafting manuscripts. She consistently encourages us to think about the big picture and to engage in critical thinking. I am continually inspired by her passion and energy in dedicating her life to exploring sustainability science, aiming to facilitate the development of sound environmental policies.

Secondly, I would like to express my sincere gratitude to my other committee members. Professor Valerie Karplus has been my long-time mentor. I worked as her research assistant before coming to Princeton, and she has been extremely supportive at every milestone of my PhD journey, including general exams, prospectus, and final oral defense. Dr. Fabian Wanger consistently provides me with helpful suggestions and offers fresh, eye-opening perspectives on my research. Discussing with him always inspires me. I took my general exam on climate policy with Professor Jesse Jenkins, and I also attended his class on the electricity sector. His class motivated me to explore the relationship between the power grid and building decarbonization and to learn energy system models. Professor Hongxun Liu is one of the most positive and modest people I have ever known. She collects detailed data on building energy efficiency costs, a crucial input for my research. She provides valuable suggestions on research design and manuscripts.

I also want to thank my other co-authors: Professor Yang Guo, who gave valuable suggestions on research design and career planning; Professor Ryna Cui, for providing detailed data for China's power plants; Dr. Liqun Peng and Dr. Jiang Lin, for their assistance in setting up the Gridpath

model and providing power grid data; and Xiangwen Fu, with whom I collaborated on urban building energy simulations.

I also want to express my gratitude to the amazing staff at SPET and SPIA – Charles Crosby, Keely Swan, and Ann Lengyel – for organizing fantastic climate events and talks, providing delicious food, and assisting me with research logistical paperwork.

I would like to express my gratitude to other members in the research group: Junnan Yang, Yixin Guo, Xu Chen, Mi Zhou, Feiqi Liu, Zhongshu Li, Da Pan, Disha Sharma, Mingwei Li, Yiheng Tao, Jing Liang, Yuanyu Xie, Malini Nambiar, Rohit Gupta, Glen Chua, Yujie Wu, Ned Downie, and Jieyi Lu. The whole group has been amazing and supportive. Additionally, my colleagues and friends in the STEP program and SPIA department have also been immensely helpful. This interdisciplinary group has been a great source of learning and support.

I also want to extend a special shoutout to my co-hosts of my climate policy podcast and blog, Minghao Qiu and Pan He. Running a climate podcast and blog has helped me connect with various practitioners and researchers around the world. A big thanks to all the wonderful guests who have joined me on my podcast!

Finally, heartfelt thanks to my parents and family. My cat, *Mimi*, provides me with many enjoyable moments. My parents consistently offer unconditional love and support, standing behind every step of my PhD journey.

Abstract 3

Acknowledgement 5

Chapter 1 Introduction 9

Chapter 2 Improving building envelope efficiency lowers costs and emissions from rural residential heating in China 20

1 Introduction 20

2 Methods 24

2.1 Building energy simulations 24
2.2 Building envelope scenarios and costs 25
2.3 Household costs, burdens, and payback periods calculations 27
2.4 Household air pollutant and CO_2e emission calculations 28

3 Results 29

3.1 Household energy consumption and heating loads 29
3.2 Household capital and operating costs 30
3.3 Household CO_2e emissions 31
3.4 Building envelope improvement strategies for existing rural residential buildings 33
3.5 Building envelope improvement strategies for new rural residential buildings 36
3.6 CO_2e emissions and cost implications of various clean heating policies in 2030 39

4 Discussion 41

Chapter 3 Cost and benefits of improving urban building energy efficiency in China 51

1 Introduction 51

2 Results 53

2.1 Scenario design 53
2.2 Energy savings from building energy efficiency 54
2.3 Costs and benefits from building energy efficiency improvements 56
2.4 Sensitivity analysis 58

3 Discussion 61

4 Methods 63

4.1 Building stock turnover and energy demand modeling 63
4.2 Power system planning model 65
4.3 Costs and benefits of building energy efficiency 66

Chapter 4 Diversifying Heat Sources in China's Urban District Heating Systems Will Reduce Risk of Carbon Lock-in 72

1 Introduction 72

2 Results 74

2.1 Emissions, costs, and availability of various district heating technologies 74
2.2 Chinese district heating systems in 2030 75
2.3 Carbon lock-in risks with new coal CHP investments 78
2.4 Strategies for a low-carbon district heating transition 82

3 Discussion 86

4 Methods 88
4.1 Infrastructure database 88
4.2 Carbon emissions calculation 90
4.3 District heat production potential calculation 90
4.4 Matching industrial plants with cities 92
4.5 District heat cost calculation 93
4.6 Power sector decarbonization scenarios 94
4.7 Scenario design of near-term investment 95
4.8 Carbon lock-in associated with existing and new CHP plants 98

Chapter 5 Conclusion 105

Appendix for Chapter 2 112

Appendix for Chapter 3 155

Appendix for Chapter 4 156

Chapter 1 Introduction

Human-induced climate change poses one of the most significant threats to both the natural environment and societies. Swiftly reducing greenhouse gas (GHG) emissions and achieving net-zero emissions are imperative to prevent the severe consequences of climate change (Masson-Delmotte et al., 2018).

The decarbonization of the building sector is a key component of reaching net-zero emissions. In 2022, building operations accounted for 30% of global energy consumption, in the form of electricity, natural gas, solid fuels, and district energy for various building energy end-uses, including heating, cooling, hot water, lighting, and equipment (United Nations Environment Programme, 2022). Building operations are also responsible for 27% of global energy-related CO_2 emissions. Heating and cooling systems are the foremost energy consumers in building operations. Heating alone accounts for approximately 45% of building emissions, while the demand for cooling is projected to increase by over threefold by 2050 (IEA, 2023a; Staffell et al., 2023). The use of solid fuels for space heating and cooking in residential buildings is also a major contributor to indoor and outdoor air pollution, leading to significant health impacts (Rehfuess et al., 2006).

China is the world's largest energy consumer and carbon emitter (Global Carbon Project, 2022). In 2020, the Chinese government committed to reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060. Decarbonizing China's building sector is a crucial component of the nation's efforts to meet its air quality targets, protect human health, and contribute to global efforts to combat climate change.

Over the past two decades, China's total building floor area nearly doubled, growing from 35

billion m^2 in 2001 to 64 billion m^2 in 2020 (S. Hu et al., 2022). Additionally, the per capita floor area for Chinese urban residents increased from 32.9 m^2 in 2012 to 41.0 m^2 in 2021 (National Bureau of Statistics, 2022). As a results, China now has the largest building stock in the world, which is nearly double the total building stock in the US (34 billion m^2) (Potter, 2020). This rapid expansion of building floor area and the increased comfort demand have resulted in a notable rise in building-related emissions in China. In 2020, building operations accounted for 2.2 gigatons of CO_2 emissions in 2021, representing 21% of China's total CO_2 emissions (S. Hu et al., 2022). Of these building-related CO_2 emissions, approximately half (~1.1 gigatons) come from electricity use, while the other half can be attributed to direct coal and natural gas consumption.

Moreover, the use of solid fuels, primarily coal, for space heating in residential buildings has been a major source of both indoor and outdoor air pollution in China (W. Meng et al., 2019). Until 2016, coal remained the predominant fuel for space heating in northern China (Z. Zhang et al., 2021). In urban areas, coal-based district heating was commonly used. District heating systems distribute heat from central sources, such as coal boilers or coal-fired combined heat and power (CHP) plants, through a network of insulated pipes to supply heat to buildings throughout a city. In rural areas where district heating was not available, rural households used small coal stoves burning unprocessed coal for winter space heating. Because both district coal boilers and small household coal stoves are very inefficient and lack effective end-of-pipe controls, coal use in residential sector had a disproportionately negative impact to air pollution and public health (X. Yun et al., 2021). Previous studies estimated that the use of solid fuels in the residential sector was responsible for over half of air pollution-related premature deaths and contributed to around 10% of China's CO_2 emissions in 2016 (X. Yun et al., 2020).

To combat the serious winter air pollution, the Chinese government initiated a nationwide clean heating campaign in 2017 (NDRC (National Development and Reform Commission of China), 2017). The objective of this campaign was to replace millions of dirty coal boilers and stoves with various alternative clean heating technologies. These technologies include large and efficient CHP plants, natural gas boilers, the utilization of industrial waste heat, and large heat pumps for district heating, as well as improved coal stoves (using processed clean coal), natural gas heaters, electric resistance heaters, and air-source heat pumps for individual heating.

These efforts resulted in a substantial reduction in the use of polluting coal for space heating from 2017 to 2021. By 2021, approximately 80% of district heating was produced by clean heating sources, primarily large coal-fired CHP plants; nearly half of rural households in northern China switched from small coal stoves to household clean heaters, primarily using natural gas heaters and electric resistance heaters (S. Liu et al., 2023; Nie et al., 2023). Previous research has shown that the clean heating campaign has led to significant improvement in air quality and associated health benefits. For example, Zhou et al. (2021) demonstrated that substituting coal stoves with clean heating options could have led to a 13-15% decrease in $PM_{2.5}$ concentrations and averted 54,000-65,000 premature death in 2015.

However, the sustainability of the clean heating campaign faces several challenges (C. Liu & Wei, 2021). First, the clean heating campaign has not achieved significant carbon emission reductions because it primarily promotes efficient fossil fuel technologies, including large CHP plants, improved coal stoves, natural gas heaters, and electric resistance heaters (which still used coal-dominant grid electricity as of 2020). These fossil fuel technologies, while substantially reducing air pollutant emissions when compared to dirty coal boilers and stoves, still result in high carbon

emissions (M. Zhou et al., 2021). For instance, according to Wang et al. (2020), the adoption of electric resistance heating in northern China is projected to lead to increased CO_2 emissions by 2030. In 2020, the Chinese government committed to reaching peak carbon emissions by 2030 and achieving carbon neutrality by 2060. Therefore, it is essential to identify opportunities for "co-benefits" in the clean heating transition that can simultaneously reduce air pollution and carbon emissions, facilitating China to achieve its climate goals.

Second, switching to clean heating technologies may result in an increase in household heating costs, particularly for low-income rural households. For example, Wang et al. (2023) found that replacing coal-fired CHP plants with clean heating alternatives will significantly increase residential heating costs, particularly in economically disadvantaged areas; Liu and Mauzerall (2020) found that the total annualized costs (annualized heating equipment costs plus annual operating costs) for clean heating in rural homes can be 2-5 times higher compared to using coal stoves. National and local governments usually offer fuel subsidies to reduce household heating costs, but this approach has downsides. Fuel subsidies compromise energy saving and carbon emission reduction goals and are not a sustainable solution because they put a heavy burden on government finances (C. Liu & Wei, 2021). As a result, many local governments are considering phasing out these subsidies. Therefore, it is crucial to understand the costs of various heating options to design cost-effective polices for promoting the adoption of cleaner heating technologies.

Third, the current clean heating policies have mainly focused on supply-side solutions (deploying clean heating equipment and facilities) and have paid much less attention to demand-side approaches, particularly the improvement of building energy efficiency. One of the major reasons for the high costs and emissions associated with space heating in China is the inadequate insulation

of buildings (Tsinghua BERC, 2018). Since 1980s, the Chinese government has introduced various policies to make new buildings more energy-efficient (especially through building codes) and retrofit existing buildings (Hong et al., 2014). However, nearly half of the urban residential buildings in China still lack proper insulation. In rural areas, only about 20% of homes in northern China have any insulation (NDRC (National Development and Reform Commission of China), 2017). Additionally, the windows and doors in rural homes are often poorly sealed, making these homes drafty. Moreover, improving building energy efficiency can also reduce the need for cooling in the summer and lower costs for energy infrastructure (e.g., less electricity generation and transmission, gas pipelines). Therefore, it is important to understand the potential benefits, cost-effectiveness, and environmental impact of enhancing energy efficiency in buildings.

My Ph.D. dissertation focuses on finding cost-effective solutions for rapidly and affordably decarbonizing buildings in China. I explore opportunities from both the supply side, i.e., using efficient, clean, and low-carbon heating technologies and the demand side, i.e., reducing heating needs through better building energy efficiency. I evaluate the potential for utilizing various energy efficiency and heating/cooling technologies and analyze their environmental impacts and costs using various analytical tools such as building energy models, energy system models, optimization methods, and life-cycle analysis.

Chapter 2 focuses on decarbonize *rural* residential heating using *demand-side* energy efficiency improvement. In this Chapter, I analyze the energy-saving potential, carbon emission reductions, costs, and adoption strategies for improving building envelope efficiency in existing and new rural residential buildings with various household heaters in northern China.

The clean heating campaign aimed to replace polluting coal stoves in rural households with cleaner

heating options. These replacements led to substantial improvements in air quality and health, but their impact on carbon emissions varied, depending on the chosen heating methods and the carbon footprint of the electricity grid (M. Zhou et al., 2021). Moreover, these replacements also significantly raised rural household heating costs. One of the major reasons for high carbon emissions and high heating costs in rural homes is their very poor thermal performance. However, the current clean heating campaign has only proposed to retrofit less than 1% of existing rural homes, and few studies have investigated the costs and benefits of improving rural building envelope energy efficiency.

Chapter 2 demonstrates that improving building envelope efficiency can significantly reduce heating demand, associated capital and operating costs, and air pollutant and carbon emissions. Our findings have direct policy implications and can help policymakers understand the costs and benefits of improving rural building envelope efficiency, as well as design effective policies to improve energy efficiency in rural homes.

Chapter 3 focuses on decarbonize *urban* buildings using *demand-side* energy efficiency improvement. In this Chapter, I assess the costs and benefits of improving urban building envelope energy efficiency in China from 2020 to 2050.

The existing literature has concentrated on supply-side solutions to decarbonize buildings, such as improving heat pump efficiency and expanding renewable electricity capacity. It has paid much less attention to the potential and cost-effectiveness of demand-side approaches, e.g., improving building insulation and implementing smart thermostats. Reducing building energy use is vital to achieve global climate goals because it not only directly reduces emissions but also facilitates other emission mitigation strategies. Improved building energy demand management reduces overall

energy consumption and peak loads, thus reducing the need for extensive grid infrastructure upgrades and associated costs and emissions. A key strategy to reduce emissions from buildings is electrifying end uses with renewable energy. However, building electrification will require substantial grid infrastructure expansion, posing challenges to grid operations and planning. To alleviate the pressure on the power grid caused by building electrification, improving management of energy demand in buildings is crucial. Additionally, enhancing building energy efficiency lowers water temperatures needed in district heat networks, leading to a more efficient use of electric heat pumps for heating. However, these benefits have not been well investigated to date.

Chapter 3 provides a comprehensive cost-benefit analysis of improving energy demand management in Chinese buildings. I quantitively estimate costs, economic benefits, and emissions reductions from various energy demand management measures by integrating building energy models and power capacity expansion models. We find it would be highly beneficial for China to prioritize and improve its building energy efficiency.

Chapter 4 focuses on decarbonize *urban* district heating systems using *supply-side* low-carbon technology deployment. In this Chapter, I investigated the emission and costs implications of various possible near-term investments (2020-2030) in China's urban district heating systems.

Coal-based urban district heating systems in China pose significant threats to both the health and well-being of China's massive population and to the global fight against climate change. District heating accounts for 5% of China's CO_2 emissions (International Energy Agency, 2017). Since 2017, the Chinese government has invested heavily in improving its urban district heating infrastructure as part of the national clean heating campaign, with a particular focus on deploying large-scale, efficient coal-fired CHP facilities and promote non-fossil district heating. As a result,

the share of urban district heating demand met by large CHP plants increased significantly to 54% in 2021 (Nie et al., 2023). However, the share of non-fossil sources in China's district heating systems remains low (~10% in 2021), falling short of the 27% non-fossil heating goals set by the clean heating campaign for 2021 (Nie et al., 2023).

Previous studies have demonstrated various benefits of using efficient CHP facilities relative to the direct burning of coal, including reducing district heating costs, air pollutant emissions, and water consumption (Ramaswami et al., 2017; W. Zheng et al., 2020). However, new and improved coal-fired CHP facilities require significant investments and have long lifespans. This may result in a "carbon lock-in" where a reliance on coal is established for decades, hindering the transition to low-carbon alternatives such as industrial waste heat and air-source heat pumps (D. Tong et al., 2019).

Chapter 4 demonstrates that replacing dirty coal technologies with existing and new CHP plants, while resulting in cost savings, will likely lead to an increase in total CO_2 emissions in China's district heating systems from 2020 to 2030 due to increased heating demand and only a slight decrease in CO2 emissions per unit heat. Building new coal-fired CHP plants also poses a risk of carbon lock-in for both heat and electricity generation. Expanding the adoption of industrial waste heat and air/ground-source heat pumps powered via the extraordinary increase in renewable energy deployment in district heating systems can avoid the need for new CHP construction while providing household heating at only moderately increased cost.

Overall, my dissertation demonstrates various cost-effective opportunities for China to decarbonize its building sector through both demand-side energy efficiency improvement and supply-side low-carbon technology deployment.

Reference:

Global Carbon Project. (2022). Carbon budget and trends 2022.

Hong, L., Zhou, N., Fridley, D., Feng, W., Khanna, N., & Berkeley, L. (2014). Modeling China's Building Floor-Area Growth and the Implications for Building Materials and Energy Demand. ACEEE Summer Study on Energy Efficiency in Buildings, 146–157. http://aceee.org/files/proceedings/2014/data/papers/10-230.pdf

Hu, S., Jiang, Y., & Yan, D. (2022). China Building Energy Use and Carbon Emission Yearbook 2021. In China Building Energy Use and Carbon Emission Yearbook 2021. Springer Nature Singapore. https://doi.org/10.1007/978-981-16-7578-2

IEA. (2023). Tracking Clean Energy Progress 2023.

International Energy Agency. (2017). District Energy Systems in China. https://www.iea.org/reports/district-energy-systems-in-china

Liu, C., & Wei, C. (2021). The World'S Largest Residential Energy Switching Program Is at Risk. In Environmental Science and Technology (Vol. 55, Issue 22, pp. 15004–15006). American Chemical Society. https://doi.org/10.1021/acs.est.1c06544

Liu, H., & Mauzerall, D. L. (2020). Costs of clean heating in China: Evidence from rural households in the Beijing-Tianjin-Hebei region. Energy Economics. https://doi.org/https://doi.org/10.1016/j.eneco.2020.104844

Liu, S., Liu, H., & Mauzerall, D. L. (2023). Improving Building Envelope Efficiency Lowers Costs and Emissions from Rural Residential Heating in China. Environmental Science & Technology, 57(1), 595–605. https://doi.org/10.1021/acs.est.2c06863

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., & Pidcock, R. (2018). IPCC Special Report on the impacts of global warming of 1.5 C. 1(5).

Meng, W., Zhong, Q., Chen, Y., Shen, H., Yun, X., Smith, K. R., Li, B., Liu, J., Wang, X., Ma, J., Cheng, H., Zeng, E. Y., Guan, D., Russell, A. G., & Tao, S. (2019). Energy and air pollution benefits of household fuel policies in northern China. Proceedings of the National Academy of Sciences of the United States of America, 116(34), 16773–16780. https://doi.org/10.1073/pnas.1904182116

National Bureau of Statistics. (2022). Construction industry maintains steady growth (in Chinese) .

NDRC (National Development and Reform Commission of China). (2017). Clean winter heating planning for northern areas (2017–2021). http://www.gov.cn/xinwen/2017-12/20/content_5248855.htm

Nie, Y., Deng, M., Shan, M., & Yang, X. (2023). Clean and low-carbon heating in the building sector of China: 10-Year development review and policy implications. Energy Policy, 179, 113659. https://doi.org/10.1016/j.enpol.2023.113659

Potter, B. (2020). Every Building in America - an Analysis of the US Building Stock. Construction Physics.

Ramaswami, A., Tong, K., Fang, A., Lal, R. M., Nagpure, A. S., Li, Y., Yu, H., Jiang, D., Russell, A. G., Shi, L., Chertow, M., Wang, Y., & Wang, S. (2017). Urban cross-sector actions for carbon mitigation with local health co-benefits in China. Nature Climate Change, 7(10), 736–742. https://doi.org/10.1038/nclimate3373

Rehfuess, E., Mehta, S., & Prüss-Üstün, A. (2006). Assessing Household Solid Fuel Use: Multiple Implications for the Millennium Development Goals. Environmental Health Perspectives, 114(3), 373–378. https://doi.org/10.1289/ehp.8603

Staffell, I., Pfenninger, S., & Johnson, N. (2023). A global model of hourly space heating and cooling demand at multiple spatial scales. Nature Energy. https://doi.org/10.1038/s41560-023-01341-5

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., & Davis, S. J. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature, 572(7769), 373–377. https://doi.org/10.1038/s41586-019-1364-3

Tsinghua BERC. (2018). China Building Energy Use 2018. China Building Industry Press.

United Nations Environment Programme. (2022). 2022 Global Status Report for Buildings and Construction: Towards a Zero emission, Efficient and Resilient Buildings and Construction Sector.

Wang, J., Zhong, H., Yang, Z., Wang, M., Kammen, D. M., Liu, Z., Ma, Z., Xia, Q., & Kang, C. (2020). Exploring the trade-offs between electric heating policy and carbon mitigation in China. Nature Communications, 11(1), 1–11. https://doi.org/10.1038/s41467-020-19854-y

Wang, Z., Li, H., Zhang, B., Wang, B., Li, H., Tian, X., Lin, J., & Feng, W. (2023). Unequal residential heating burden caused by combined heat and power phase-out under climate goals. Nature Energy. https://doi.org/10.1038/s41560-023-01308-6

Yun, X., Meng, W., Xu, H., Zhang, W., Yu, X., Shen, H., Chen, Y., Shen, G., Ma, J., Li, B., Cheng, H., Hu, J., & Tao, S. (2021). Coal Is Dirty, but Where It Is Burned Especially Matters. Environmental Science & Technology, 55(11), 7316–7326. https://doi.org/10.1021/acs.est.1c01148

Yun, X., Shen, G., Shen, H., Meng, W., Chen, Y., Xu, H., Ren, Y., Zhong, Q., Du, W., Ma, J., Cheng, H., Wang, X., Liu, J., Wang, X., Li, B., Hu, J., Wan, Y., & Tao, S. (2020). Residential solid fuel emissions contribute significantly to air pollution and associated health impacts in China. Science Advances, 6(44), 1–8. https://doi.org/10.1126/sciadv.aba7621

Zhang, Z., Zhou, Y., Zhao, N., Li, H., Tohniyaz, B., Mperejekumana, P., Hong, Q., Wu, R., Li, G., Sultan, M., Zayan, A. M. I., Cao, J., Ahmad, R., & Dong, R. (2021). Clean heating during winter season in Northern China: A review. Renewable and Sustainable Energy Reviews, 149(May), 111339. https://doi.org/10.1016/j.rser.2021.111339

Zheng, W., Zhang, Y., Xia, J., & Jiang, Y. (2020). Cleaner heating in Northern China: potentials and regional balances. Resources, Conservation and Recycling, 160(April), 104897. https://doi.org/10.1016/j.resconrec.2020.104897

Zhou, M., Liu, H., Peng, L., Qin, Y., Chen, D., Zhang, L., & Mauzerall, D. L. (2021). Environmental benefits and household costs of clean heating options in northern China. Nature Sustainability. https://doi.org/10.1038/s41893-021-00837-w

Chapter 2 Improving building envelope efficiency lowers costs and emissions from rural residential heating in China

1 Introduction

Ambient and indoor air pollution in China contributed to more than 1 million deaths in 2014, of which more than half were attributed to the residential sector, mainly because of the massive and inefficient use of solid fuel, particularly coal (P. Yin et al., 2020; X. Yun et al., 2020). Coal remained the predominant heating fuel for rural households without district heating in northern China in 2016. Because small household coal stoves are very inefficient and end-of-pipe controls are infeasible, coal use in rural households contributes disproportionately to air pollution, public health harms, and climate change (X. Yun et al., 2021; M. Zhou et al., 2021).

In 2017, to address the extensive and polluting use of dispersed coal with traditional stoves (DCTS), the Chinese government launched a clean winter heating campaign (i.e., Clean Winter Heating Plan in Northern China), focusing on two key regions, the "2+26" cities and the Fen-Wei Plain(NDRC (National Development and Reform Commission of China), 2017). A major goal of this campaign was to replace coal stoves in rural households with clean heaters (Figure S1). Natural gas heaters (NGHs), resistance heaters (RHs) with/without thermal storage (RH*w*TS and RH*wo*TS), and air-to-air heat pumps (AAHPs) are the four most widely adopted technologies (see Supplementary Note 1 for the description of various heaters) (NDRC (National Development and Reform Commission of China), 2017; M. Zhou et al., 2021). Clean coal with improved stoves (CCIS) are also considered a short-term option to replace DCTS (Liu et al., 2018; Zhou et al., 2021). Decisions of which clean heaters to adopt are often made at county or village levels. By the end of 2021, >25 million rural and suburban households had switched to clean heaters from

solid fuels, resulting in ~60% of rural households in the "2+26" cities and the Fen-Wei Plain region using clean heaters (PKU Institute of Energy, 2021). Most households adopted NGHs and RHs, except in Beijing, where the local government offers generous subsidies for AAHPs (Natural Resources Defense Council, 2018).

Previous research has shown that replacing residential coal stoves with clean heaters leads to substantial air quality and health benefits but can both increase and decrease greenhouse gas (GHG) emissions, depending on the choice of clean heaters and the carbon intensity of grid electricity (W. Meng et al., 2020; Tao et al., 2021; J. Wang et al., 2020). For example, Zhou et al. (2021) found that entirely replacing coal stoves with various clean heaters would have led to a 13-15% reduction in ambient $PM_{2.5}$ concentrations and prevented 54-65 thousand premature deaths in northern China in 2015. Although all clean heaters dramatically reduce emissions of air pollutants, their GHG emissions vary significantly. While NGHs offered the largest GHG emission reduction in 2015, natural gas use locks in future GHG emissions. Emissions from electric heaters depend on both their efficiency and the carbon intensity of the power grid. This resulted in increases in GHG emissions from the deployment of inefficient RHs and decreases in GHG emissions from the deployment of efficient AAHPs.

Replacing coal stoves with clean heaters can increase household heating costs substantially. The total annualized costs for clean heating in rural households increase 2-5 times relative to coal stoves due to both capital costs of purchasing clean heaters and operating costs of consuming natural gas and electricity (H. Liu & Mauzerall, 2020). Therefore, national and local governments provide subsidies to rural households for clean heater purchases and natural gas and electricity consumption. These subsidies vary across cities, depending on governments' budgets. Most cities

promise to offer fuel subsidies for at least three years after switching to a clean heater (Gong et al., 2020). Nevertheless, even with subsidies, household heating costs still increase by 1.5-3 times relative to coal stoves except for some regions offering generous subsidies (H. Liu & Mauzerall, 2020). The high operating costs of clean heaters lead some rural households to reignite their coal stoves (J. Li et al., 2021). For example, ~15% of households returned to burning coal for heat in the "2+26" cities during the 2020 Spring Festival, challenging the sustainability of the clean heating campaign (China Coal Cap Project, 2020).

One of the major reasons for high heating costs in rural homes is their poor thermal performance (C. Liu & Wei, 2021). Rural houses in China are usually designed and constructed by rural residents themselves and local homebuilders based on their experience rather than relying on building codes. Rural homes are often poorly insulated and drafty (B. jie He et al., 2014; L. Zhu et al., 2020a). Walls are commonly built of solid clay bricks without any thermal insulation and windows are made with a single layer of glass (M. Shan et al., 2015). Windows and doors are also poorly sealed, resulting in significant heat loss through uncontrolled air infiltration (M. Shan et al., 2015). Due to the poor thermal performance, Chinese rural homes are often warmed only to an indoor temperature of 10-14 ℃ (Building Energy Research Center of Tsinghua University, 2012; M. Shan et al., 2015).

Improving building envelope energy efficiency reduces heating demand, hence reducing both the size of the required heater (and associated capital costs) and the fuel needed to operate it (and associated operating costs) as well as resulting air pollutants and GHG emissions. However, these benefits have not been well explored to date. Although the government developed demonstration programs to subsidize building energy retrofits, less than 1% of rural homes have benefited from

those programs. The implementation of voluntary rural residential building energy standards has not been effective because of limited administrative capacity and low income levels (Evans et al., 2014).

Few studies investigate rural building envelope energy efficiency. A few case studies calculate the energy-saving potential, costs, and benefits of building energy retrofits in China (J. Liu et al., 2015; Pan & Mei, 2020; W. Wang et al., 2019; Q. Zhang, Hao, et al., 2017; Y. Zheng, 2020a). For example, Cui et al. (2020) found that retrofitting a typical rural house in Shandong to meet the current design standard can lead to a ~70% efficiency improvement, yet they did not estimate the cost of such a retrofit, nor did they evaluate the resulting change in GHG emissions. Shan et al. (2015) reported a building retrofit program including ~500 households in suburban areas of Beijing and found that the retrofit program cut energy bills in half with payback periods of 5-6 years. Although these case studies provide useful guidance on implementing building retrofits, their results may not be generalized because regional variations exist with households in different regions using different heaters and experiencing different climates and fuel prices. Additionally, while most previous studies focus on existing buildings, new construction offers a better opportunity to deploy efficient technologies. Chinese rural residential buildings are often short-lived with a lifetime of 15-30 years indicating that the rural housing stock is likely to be replaced before 2060 (Hong et al., 2014). Thus, improving the energy efficiency of new buildings will be critical in meeting China's 2060 carbon neutrality commitment.

Here we provide a comprehensive examination of the energy-saving potential, equivalent CO_2 (CO_2e) emission reductions, costs, and adoption strategies for improving building envelope efficiency in existing and new rural residential buildings with various heaters in the "2+26" cities

plus the Fen-Wei Plain region of northern China. We find that, for existing buildings, implementing some easy and moderate retrofits can reduce CO_2e emissions as well as reducing clean heating costs to avoid backsliding to coal. For new construction, deploying the most efficient technologies –whole-home insulation and heat pumps – reduce CO_2e emissions and annualized costs over the long term compared to current clean heating policy but significantly increase household upfront costs.

2 Methods

2.1 Building energy simulations

We simulate household heating loads using an integrated building energy simulation model, EnergyPlus, which has been widely used and validated (Fumo, 2014; J. Wang et al., 2020). Building energy simulation in EnergyPlus requires three types of inputs: (1) building prototype and envelopes, (2) thermostat setting, and (3) weather data. We design a baseline building to represent a typical rural house in the "2+26" cities and the Fen-Wei Plain region based on Shan et al. (2020). The baseline building is a detached single-story house, consisting of one living room and two bedrooms with a total heating floor area of ~80 m^2 (Tables S1 and S2). The indoor temperature is assumed to be 14 °C in our main analysis. This indoor temperature represents the prevailing practice in northern China in winter (Evans et al., 2014; M. Shan et al., 2015). The hourly weather data is obtained from the World Meteorological Organization (https://www.energyplus.net/weather), using the nearest meteorological station for each city.

We first simulate household heating loads on an hourly basis in EnergyPlus to maintain indoor temperatures at 14/18 °C in each city. We use household peak heating loads during the heating season to estimate the required sizes of various heaters and associated capital costs (Table S3). We

estimate annual energy consumption by adding up all hourly heating loads during the heating season for each city. The total number of hours (days) in the heating season varies for each city and are obtained from the Chinese building energy efficiency design standards (Ministry of Housing and Urban-Rural Development of China, 2010). We then convert annual heating loads to annual energy (coal, natural gas, and electricity) consumption based on the heating values of fuels and efficiencies of heating devices, as shown in Eq. (1):

$$AEC_{c,f,h,e} = \frac{AHL_{c,e}}{HV_f \times \eta_h} = \sum_{hr=1}^{nh_c} \frac{HHL_{hr,e}}{HV_f \times \eta_h} \quad (1)$$

where $AEC_{c,f,h,e}$ is household annual energy consumption using fuel f and heater h with various building envelope scenarios (denoted as e, see the scenario design below) in city c during the heating season; $AHL_{c,e}$ is the annual heating loads; HV_f denotes heating values of fuels, and η_h denotes efficiencies of various heaters (Table S4). $HHL_{hr,e}$ is the hourly heating load calculated in EnergyPlus; hr denotes hours, and $nh_c$is the total number of hours in the heating season for city c. We validate our model by comparing our baseline simulations of annual heating energy intensity (expressed as annual heating loads per unit floor area, GJ/m^2) with survey data (Figure S2). Our results fit within the range of data from previous literature (Building Energy Research Center of Tsinghua University, 2012; Peng et al., 2019; M. Zhou et al., 2021).

2.2 Building envelope scenarios and costs

We collect building energy efficiency measures that can be widely adopted in rural houses from the peer-reviewed literature, government technical guides, and building material suppliers in 2020v(Shandong Provincial Department of Housing and Urban-Rural Development (Shandong DHURD), 2019; Y. Zhu et al., 2018). We include 84 individual energy efficiency measures in our

analysis (Table S5). We collected costs (including removal/demolition costs, material costs, accessories costs, and installation costs) of these measures in 2020 from the literature, government documents, conversations with building material suppliers, etc. Costs of increasing building envelope efficiency for existing buildings are 5-20% higher than those for new buildings because of additional demolition costs during the retrofit. We run EnergyPlus to calculate the energy-saving potential of each measure. We do not consider the scenarios of a combination of coal stoves and improved building envelopes because improving airtightness may unintentionally deteriorate indoor air quality and increase the risk of dangerous CO and fine particulate accumulation from coal burning.

We then select the most cost-effective (largest energy-saving per yuan) measures for each envelope and order these measures based on their cost-effectiveness. This order suggests a step-by-step envelope efficiency improvement strategy for common Chinese rural homes: first windows (particularly air sealing), then north wall, roof, and finally other walls. On this basis, we design three scenarios for improving building envelope efficiency: easy, moderate, and large improvements, as shown in **Table 1**. Our energy-saving estimates are comparable with the prior literature (Y. Cui et al., 2020; M. Shan et al., 2015; Shandong Provincial Department of Housing and Urban-Rural Development (Shandong DHURD), 2019).

Table 1 (a) Building envelope scenario design and (b) heater scenario design. Details of scenario development are provided in **Methods**.

(a) Building envelope scenarios	**Envelope efficiency measures**	**Incremental costs for existing buildings** (yuan)	**Incremental costs for new buildings** (yuan)	**Energy savings**[2] 14 °C
Baseline building envelope[1]	-	0	0	0
Easy envelope improvement	Energy efficient windows, Air sealing	~2200	~1900	25~35%

Moderate envelope improvement	Energy efficient windows, Air sealing, North wall insulation	~5700	~4600	36~48%
Large envelope improvement	Energy efficient windows, Air sealing, Roof insulation, All wall insulation	~21000	~16000	74~85%

(b) Heater scenarios	**Upfront capital costs in the baseline building** without subsidies, 14 °C (yuan)	**Annual operating costs in the baseline building** without subsidies, 14 °C (yuan)
Dispersed coal with traditional stoves (DCTS)	~300	880~2200
Clean coal with improved stoves (CCIS)	~1400	550~2000
Natural gas heaters (NGHs)	3000~3500	900~3000
Resistance heaters with thermal storage (RH*w*TS)	5400~9200	1000~2600
Resistance heaters without thermal storage (RH*wo*TS)	1100~1900	1500~3600
Air-to-air heat pumps (AAHPs)	8000~14000	560~1550

[1]The baseline building represents prevailing envelope efficiency practices in the "2+26" cities and the Fen-Wei Plain region.
[2]Energy savings are relative changes (%) in simulated operating heating load compared to the baseline building to maintain the indoor temperature at 14 °C during the heating season.

2.3 Household costs, burdens, and payback periods calculations

Our analysis includes three types of household heating-related costs: heater capital costs, building envelope capital costs, and operating costs. Heater capital costs and building envelope capital costs are described in the previous subsections. We calculate annual operating costs ($AOC_{c,f,d}$) using heater h and fuel f with envelope e in city c as Eq. (2):

$$AOC_{c,f,h,e} = AEC_{c,f,h,e} \times P_{f,c} \quad (2)$$

where $AEC_{c,f,h,e}$ denotes the household annual energy consumption calculated using Eq. (1). $P_{f,c}$ denotes the unsubsidized/subsidized price of fuel f in city c (see Tables S6 and S7 and Figure S3). We also estimate operating heating burdens (defined as the percentage of household disposable income in 2020 spent on operating heating costs during the heating season) to examine the affordability of operating heating costs. The use of >10% of household income on energy is usually considered a threshold for energy poverty (Drehobl et al., 2020).

For existing buildings, we calculate payback periods for building envelope retrofits. Payback periods measure how long it takes for cumulative savings to offset the initial investment. We include two types of savings from improving building envelope efficiency: savings from reduced capital costs of clean heaters (one-time savings) and savings from reduced annual operating costs (annual net cash flow). Many rural households plan to move to cities or build new homes in the next 5-15 years, which reduces their inclination to make investments that pay off over the long term.

For new buildings, rural households must purchase clean heaters and decide the efficiency of their building envelopes during the construction process. We calculate total annualized costs (TACs, annualized upfront capital costs plus annual operating costs) and upfront capital costs (UCCs) of space heating. TACs reflect what a household must pay annually for heaters, envelopes, and heating fuels when loans are available, while UCCs are the one-time expenses that a household must pay to purchase heaters and envelopes when loans are not available. See Supplementary Note 1 for more details.

2.4 Household air pollutant and CO_2e emission calculations

We calculate household annual air pollutant and CO_2e emissions under the 20/100-year global warming potentials (GWP_{20}/GWP_{100}, including CO_2, CH_4 and fluorinated refrigerants) from space heating with various heaters and building envelopes. We focus on analyzing CO_2e emissions because previous studies showed that replacing coal stoves with clean heaters always significantly reduces air pollutant emissions but does not necessarily decrease CO_2e emissions (J. Wang et al., 2020; M. Zhou et al., 2021). We also present results for air pollutant emissions in Figures S4–S9. Our emission calculations include both downstream emissions (on-site emissions from fuel

burning and the leakage of refrigerant liquids in AAHP) and upstream emissions from fuel production, processing, transmission, and distribution (for gas, coal, and electricity) and the production of efficient building envelopes (i.e., efficient windows and insulation materials). See Supplementary Note 1 for more details.

3 Results

3.1 Household energy consumption and heating loads

We calculate heating energy consumption and peak loads of a typical rural household with various clean heaters and building envelopes (Figure S10). We estimate that a full replacement with NGH in the studied region would require about 20 billion m^3 of natural gas annually (10% of China's domestic natural gas production or 6% of total consumption in 2020), while full electric heating with RHs or AAHPs will require ~162 or ~63 TWh of electricity annually (2.1% or 0.6% of China's total electricity consumption), respectively.

Peak heating loads are very important both environmentally ("peaker" power plants are usually inefficient and dirty in China) and economically (peak heat demands affect both required heater size and associated costs for the homeowner as well as power plant and transmission capital costs for power generators and grid operators). The peak heating loads for a typical rural household are estimated to be 5.0-8.7 kW with a NGH, 4.2-7.4 kW with a RH, and 1.6-3.2 kW with an AAHP. For comparison, the household maximum allowable electrical load in Chinese rural areas is, on average, only 2.7 kW (National Energy Administration, 2020). Such a significant increase in household electric peak load will require substantial increases in transmission, distribution, and voltage control infrastructure buildout.

Building envelope efficiency improvements in rural homes can significantly reduce both energy consumption and peak loads from clean heating. Our results show that easy, moderate, and large improvements can reduce energy consumption by 25-35%, 36-48%, and 74-85% as well as peak heating loads by 23-30%, 30-38%, and 61-68%, respectively, thus substantially reducing energy infrastructure costs.

3.2 Household capital and operating costs

Improving building envelope efficiency reduces required sizes of clean heaters by lowering heating loads, thus reducing associated capital purchase costs (Figures S11 and S12). Capital costs of NGH are only slightly affected by their heating capacity, so improving building envelope efficiency only leads to marginal capital cost savings when NGH are employed. In contrast, capital costs of electric heaters (RH*w*TS, RH*wo*TS, and AAHPs) strongly depend on their required heating loads. For the most expensive and efficient clean heater, AAHP, the moderate (large) improvements can reduce its needed size and associated capital costs by ~3000 (~6000) yuan on average, equal to ~0.8 (~1.6) months' income of a typical rural household.

We estimate operating heating burdens on rural households with various heaters and building envelopes (Figure S13 and S14). Rural households using CCIS typically spend 5-11% of their income purchasing coal. Switching from CCIS to NGHs, RH*w*TS, and RH*wo*TS will magnify operating heating burdens by a factor of 1.9, 1.9, and 2.5 on average, respectively, making clean heating unaffordable. The operating heating burdens of AAHPs are lower than coal stoves, but few households switched to AAHP because of their high upfront capital costs. With fuel subsidies, household operating clean heating burdens can be reduced to 6-13% of household incomes, generally slightly higher than that of using coal stoves. However, fuel subsidies will encourage

clean heating choices with higher CO_2 emissions.

Improving building envelope efficiency can reduce operating fuel consumption, thus reducing operating heating costs and burdens. We find that for rural households using NGHs, RH*w*TS, and RH*wo*TS, easy and moderate building envelope improvements can reduce their operating heating burdens to ~7-14% and ~6-12%, respectively, which are comparable to using CCIS or using clean heaters with fuel subsidies. Moderate (large) improvements in building envelopes, which reduce ~60% (~80%) of energy consumption, can dramatically reduce operating heating burdens to ~4% (~1%) when combined with AAHPs.

3.3 Household CO_2e emissions

Household annual CO_2e emissions under GWP_{100} from space heating with various heaters and building envelopes in the studied region are shown in **Figure 1**. Household CO_2e emissions from space heating vary significantly, and strongly depend on local climate, heater types, the carbon intensity of electricity, and building envelope energy efficiency. Generally, with the 2020 power mix (~64% of electricity is from fossil fuel), switching from CCIS to NGHs and AAHPs reduce household CO_2e emissions by ~27% and ~42% in the baseline building, respectively, while using inefficient RHs increases CO_2e emissions by ~35%. Refrigerant leakage from heat pumps is also an important source of GHG, making up ~10% of total GHG emissions from AAHP in the baseline building. Commonly used refrigerants have a strong near-term warming effect because they are hydrofluorocarbons (HFCs) and have high radiative forcing and have short atmospheric lifetimes (see the GWP20 results in Figure S15).

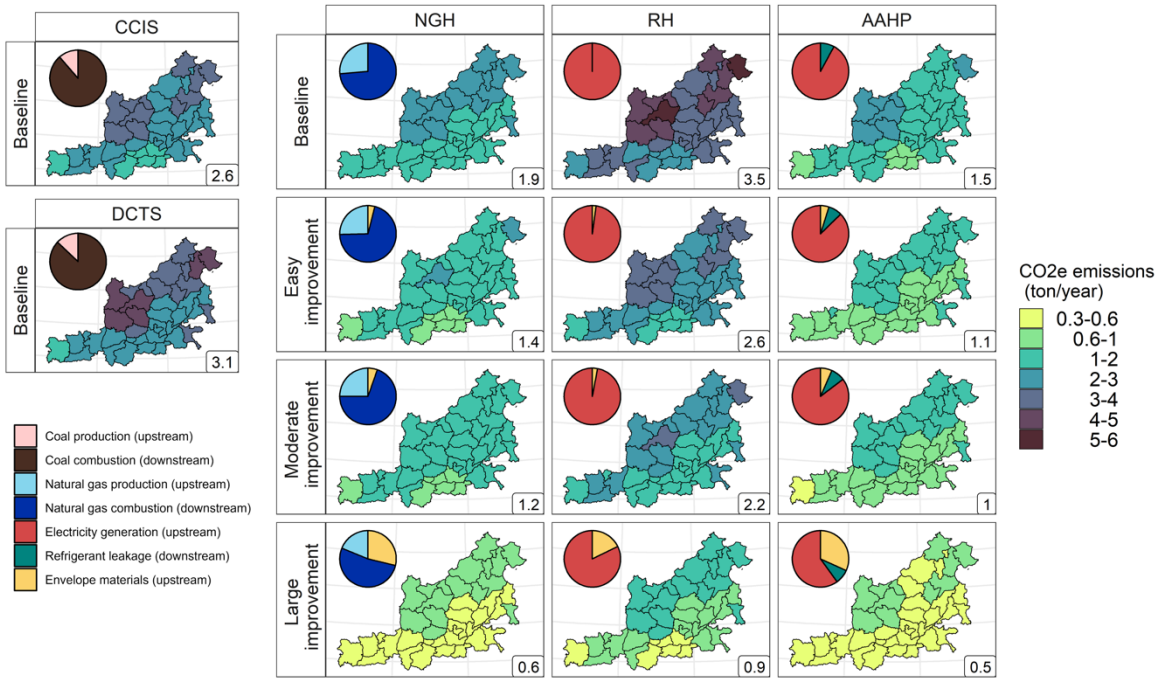


Figure 1 Household heating-related CO_2e emissions under GWP_{100} with various heaters (across top) and building envelopes (down columns) in the "2+26" cities plus the Fen-Wei Plain region of northern China. The figure shows the CO_2e emissions related to household space heating necessary to maintain indoor temperatures at 14 °C during the heating season. The pie charts at the upper left of each subfigure show the share of emissions by source types. The numbers at the bottom right of each subfigure denote the population-weighted average household CO_2e emissions for each heater type in the studied region in 2020. Legend at the left shows sources of GHG emissions while legend at the right shows annual CO_2e emissions from each city. Results for CO2e emissions under GWP20 are shown in Figure S15. Results for indoor temperatures at 18 °C are shown in Figure S16. See **Table 1** for definitions of heater acronyms.

Increasing envelope efficiency for rural homes using RHs delivers the largest emission reductions because RHs are less efficient than NGHs and AAHPs. However, with the decarbonization of the power sector, operating RHs and AAHPs will result in less CO_2e emissions, so CO_2e reduction potentials of building envelope efficiency improvements on rural homes with RHs and AAHPs will decrease as the grid decarbonizes. AAHP combined with large improvements in building envelopes are now the lowest emission heating option (0.6 tons annually per household), cutting ~80% of emissions compared to CCIS with the baseline building. As the grid decarbonizes, AAHP

emissions will decrease further.

The CO_2e emission reduction from energy efficiency improvements usually far exceeds the additional emissions required for production of the materials needed to improve building envelopes. However, as rural building envelopes become more efficient, the proportion of life-cycle emissions from the envelope materials increases. For example, as shown in **Figure 1** efficient window and insulation material production accounts for 17-27% (2-5%) of total CO_2e emissions in large improvement (easy improvement) building envelope scenarios.

3.4 Building envelope improvement strategies for existing rural residential buildings

For existing buildings with clean heaters, the capital costs of clean heaters are considered sunk costs, so the household benefits of increasing building envelope efficiency only relate to operating cost savings. In contrast, for existing buildings with coal stoves, retrofitting building envelopes before installing clean heaters can reduce the sizes required for the clean heaters and the associated capital costs. Thus, the benefits of increasing building envelope efficiency before installing clean heaters are obtained from savings from both reduced capital costs due to the ability to purchase a smaller heater and operating costs.

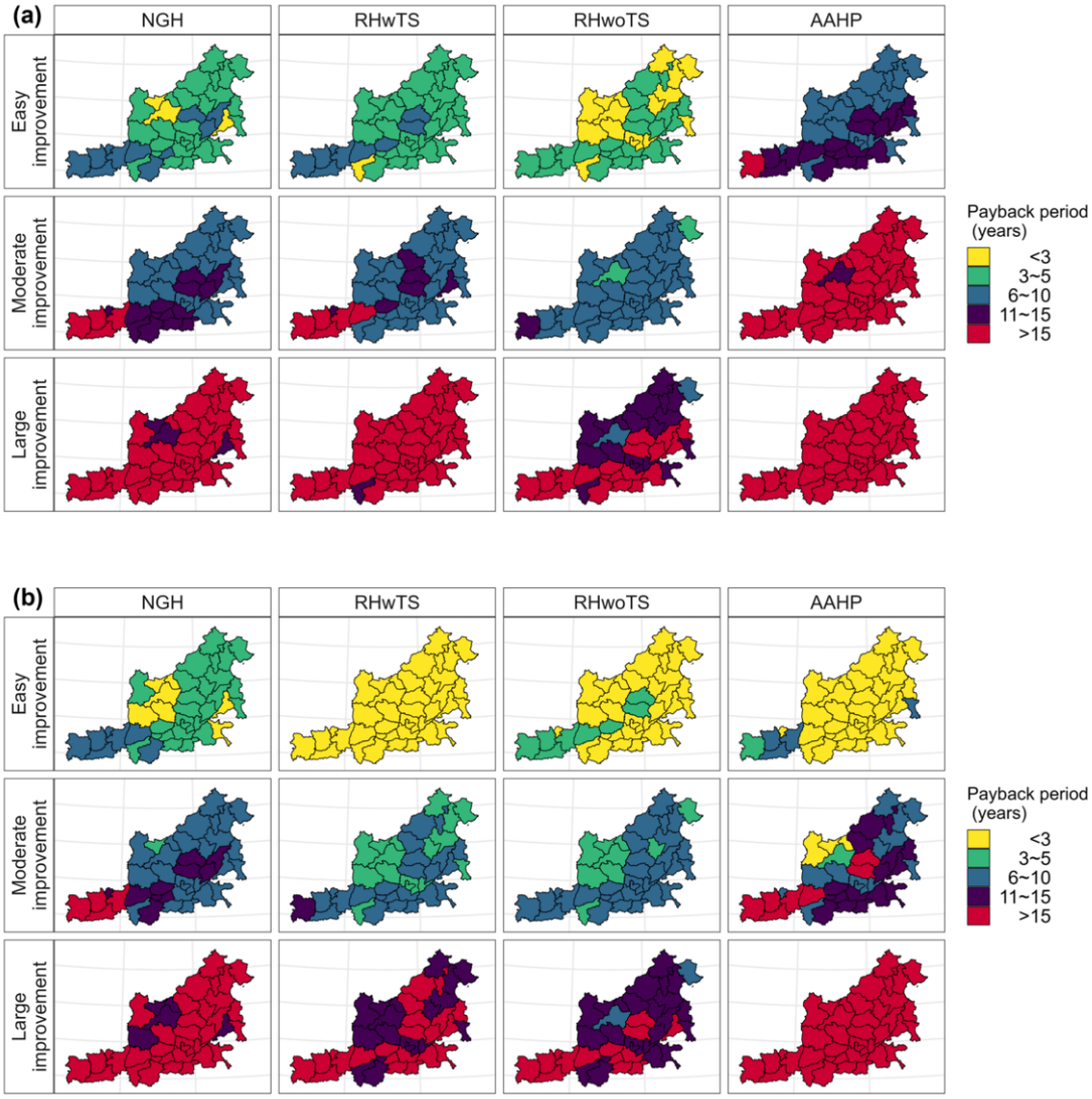


Figure 2 Payback periods for building envelope efficiency improvements to (a) existing buildings already using various clean heaters and (b) existing buildings that will soon install various clean heaters in the "2+26" cities plus the Fen-Wei Plain region of northern China. This figure shows payback periods when rural households maintain the indoor temperature at 14 °C during the heating season. The discount rate used is 5%. In subfigure (a), only savings from reduced annual operating costs are considered because capital costs of clean heaters are sunk costs. In contrast, in subfigure (b), both savings from reduced capital costs of clean heaters and savings from reduced annual operating costs are considered. Results for indoor temperatures at 18 °C are shown in Figure S17. See **Table 1** for definitions of heater acronyms.

Local governments usually decide which clean heaters will be adopted, but rural households can

determine whether and when to retrofit their homes. We therefore examine payback periods for various building envelope retrofits. **Figure 2a** shows payback periods for various building envelope efficiency improvements on existing rural buildings with various clean heaters. We find that easy and moderate envelope improvements to rural houses using NGHs, RH*w*TS, and RH*wo*TS have payback periods of 4.1 and 8.8 years on average, respectively, while large improvements are cost-prohibitive due to high capital costs. Retrofitting rural homes with inefficient RH*wo*TS has relatively short capital cost payback periods because so much electricity is saved. However, retrofitting buildings with more efficient AAHPs has much longer payback periods because less electricity is needed to achieve the desired indoor temperature.

Figure 2b shows payback periods for envelope efficiency improvements on existing buildings that current policy requires install clean heaters soon. When savings from reduced capital costs of clean heaters are considered, payback periods for easy and moderate improvements to rural homes that plan to switch to electric heaters (RH*w*TS, RH*wo*TS, and AAHPs) are shortened to 1.1 and 6.8 years on average, respectively. Thus, the order in which the decision to improve building envelope efficiency and choice of clean heater size matters. This is particularly relevant to AAHPs which have very high capital costs so building envelope efficiency improvement prior to installation facilitates the purchase of a smaller AAHP with lower capital costs and is critical to enable the penetration of AAHPs. In addition, payback periods are significantly affected by city-level fuel prices and climates. For example, implementing retrofits to rural houses with NGHs in Taiyuan, Jinzhong, and Jinan often has a short payback period of <3 years because of relatively high natural gas prices and cold climates. In contrast, building retrofits are generally less economically attractive in cities in southern Shaanxi because warm climates and relatively low fuel prices result in lower cost savings.

3.5 Building envelope improvement strategies for new rural residential buildings

For new buildings, during the construction process, rural households must purchase clean heaters and decide on the efficiency of their building envelopes. New buildings have two additional advantages over existing buildings: first, the construction costs of new efficient envelopes are lower than retrofitting existing buildings; second, new buildings tend to have longer lifetimes than existing buildings, enabling investments that pay off over the long term to be attractive. Here we compare TACs and UCCs of space heating scenarios for various building envelopes and heaters in new buildings without subsidies.

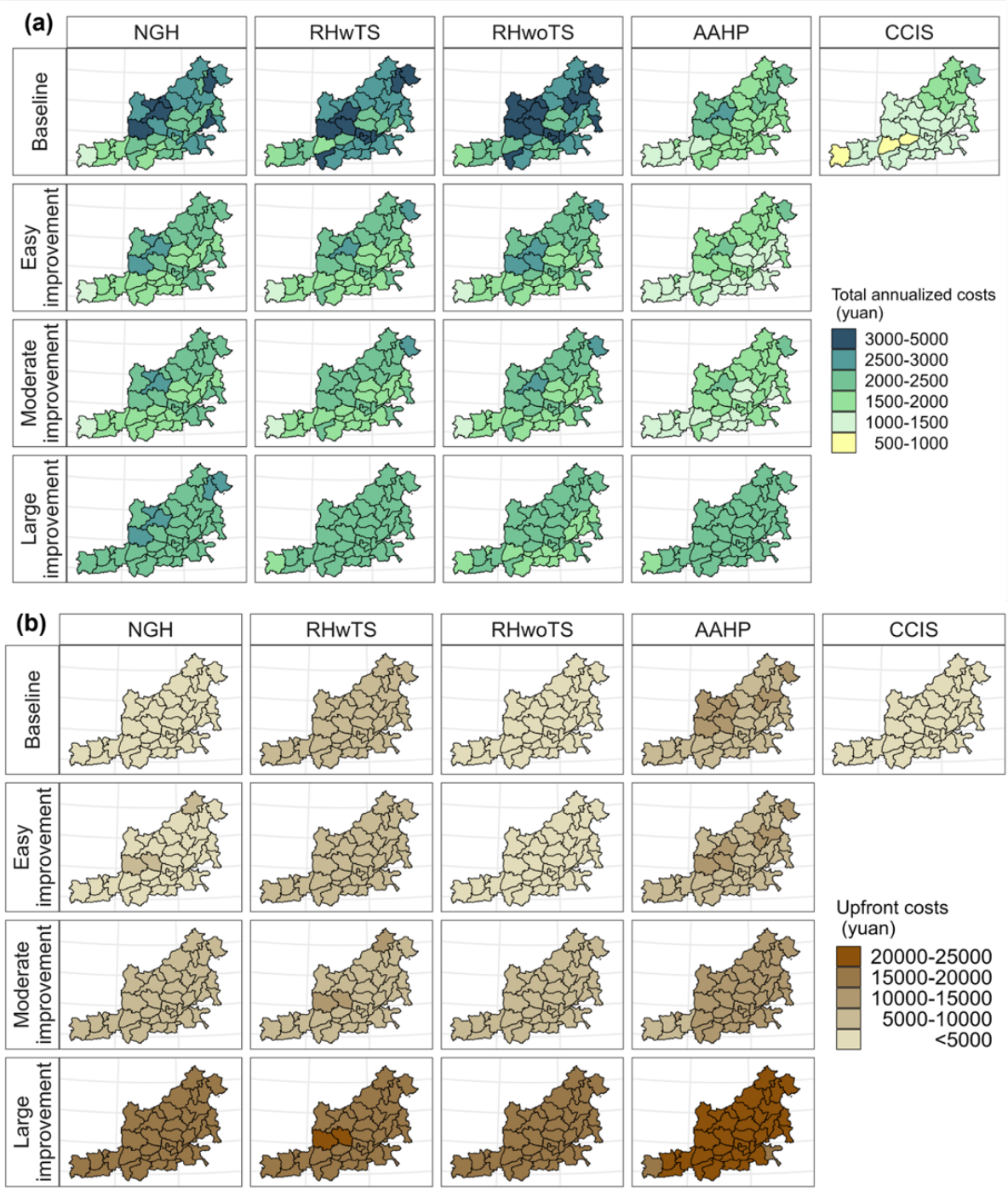


Figure 3 Household (a) total annualized costs (TACs, annualized capital costs plus annual operating costs) and (b) upfront capital costs (UCCs) under various indoor temperature and carbon price scenarios in new buildings in the "2+26" cities plus the Fen-Wei Plain region of northern China. The figure shows costs when rural households maintain indoor temperatures at 14 °C during the heating season. The discount rate is 5%. The expected lifetime of new building envelopes is assumed to be 15 years. Results for indoor temperatures at 18 °C are shown in Figure S18. See **Table 1** for definitions of heater acronyms.

Figure 3a shows TACs for scenarios of various heaters and building envelopes. We find that AAHPs have the lowest TACs among all clean heaters, generally ~15-22% lower than NGHs, RH*w*TS, and RH*wo*TS. This is consistent with previous studies that showed AAHPs tend to be the most economic clean heater over the long term in the studied region (H. Liu & Mauzerall, 2020; Natural Resources Defense Council, 2018; M. Zhou et al., 2021). Regarding building envelopes, our results show that greater building envelope efficiency is always more economic than current practices (i.e., the baseline buildings). In fact, many new rural residential buildings are now installing efficient windows and some levels of insulation (L. Zhu et al., 2020b).

The lowest-cost clean heating combination is usually AAHP plus easy improvements in building envelopes in the studied region (Figure S19). AAHP with easy envelope improvements have TACs of ~1500 yuan (~6-20% of household income during the heating season), which are on average higher than TACs of CCIS by ~20%. However, in some cities where coal prices are high (mostly in the Beijing-Tianjin-Hebei region), TACs of AAHP plus easy building envelope improvements are close to or already cheaper than the costs of CCIS.

TACs of the lowest emission combination – AAHP plus large envelope improvements – are higher than TACs of AAHP plus easy envelope improvements by 30-50%. A carbon price will not make large improvements economically favourable for rural households until the carbon price is very high (e.g., >500 yuan per ton). This is because AAHPs themselves are so efficient that further improvements in building envelopes can only lead to a marginal reduction in heating costs and emissions. However, as rural households demand improved thermal comfort and build more durable houses as their incomes increase AAHP with large envelope improvements become

increasingly cost competitive. In this case with high indoor temperatures (>18°C) and long lifetimes of building envelopes (~25 years), AAHP plus large improvements in building envelopes will become the lowest-cost option in many cities (Figure 20). Moreover, large improvements are also justified by significantly reducing energy infrastructure costs (e.g., less electricity transmission, gas pipelines) and reducing cooling demand in summer.

Although our results highlight the cost and environmental advantages of combinations of AAHP and efficient building envelopes, rural households may not switch to those combinations because of their high UCCs (**Figure 3b**). The combination of AAHP plus *easy* building envelope improvements has an UCC of ~9,000 yuan (~10-28% of the annual household income). The combination of AAHP plus *large* improvements has a high UCC of ~20,000 yuan, roughly equal to half a year's household income, or ~20-30% of the construction costs of a typical northern Chinese rural house. The high upfront costs will limit the adoption of efficient building envelopes and AAHP unless financial assistance is offered.

3.6 CO_2e emissions and cost implications of various clean heating policies in 2030

The current clean heating policy focuses on replacing all coal stoves (including CCIS) with clean heaters, particularly NHGs and RH*w*TS, to establish a "no-coal zone" in the studied region by 2030 (NDRC (National Development and Reform Commission of China), 2017; State Council, 2021). We estimated that the current policy – if fully implemented in the studied region– will reduce rural residential heating-related CO_2e emissions by 29% but increase household TACs by 14% from 2021 levels (P_0 in **Figure 4**). Such increases in heating costs seem to be acceptable for rural households as rural household incomes are projected to double by 2030 from 2021 levels(Institute of Rural Development of Chinese Academy of Social Sciences, 2022).

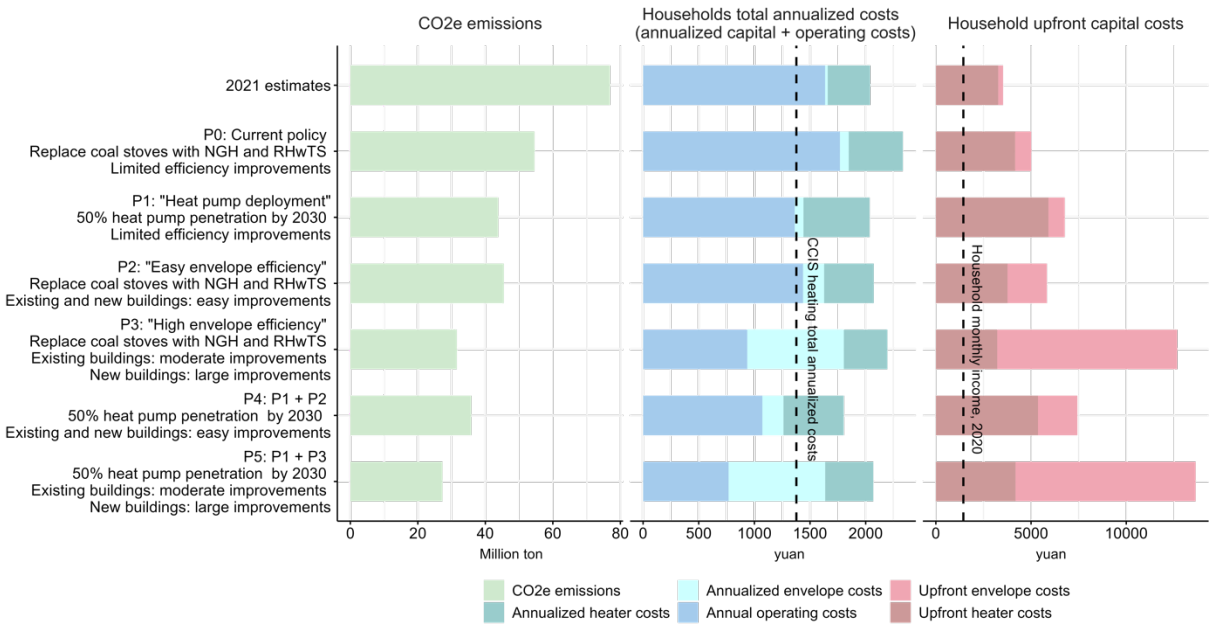


Figure 4 CO_2e emissions, population-weighted household total annualized costs (TACs), and upfront capital costs (UCCs) in 2030 under various policy scenarios in the "2+26" cities and the Fen-Wei Plain region of northern China. The vertical dashed lines denote the TAC of CCIS and household monthly income in 2020 for comparison. P_0 represents the current "no-coal zone" policy, while P_1-P_5 are various possible improved clean heating policy scenarios implemented between 2020 and 2030. See Table S8 for clean heater adoption in 2020. Figure S21 shows results under the assumption of lower grid carbon intensity.

Our analysis indicates that current policies can be strengthened to reduce emissions and household TACs by (1) accelerating heat pump adoption and (2) increasing building envelope efficiency. Therefore, we further explore the emissions and cost implications of various possible strengthened policies between 2020 and 2030. See Supplementary Note 1 for more method details. We find that, in general, policies that increase heat pump uptake and building envelope efficiency decrease both emissions and household TACs but increase UCCs compared to the current policy. Either deploying heat pumps at scale (P_1) or implementing easy improvements in building envelope efficiency for all rural residential buildings (P_2) can cut emissions by ~40% from 2021 levels in 2030 as well as reduce household TACs by ~12% compared to the current policy. Yet either of the

two policies will also increase UCCs by 34% (P_1) and 14% (P_2), respectively, compared to current policy. Implementing those two policies simultaneously (P_4= P_1+ P_2) would further slightly increase household UCCs, but this policy has the lowest household TACs (~1800 yuan) in 2030 across all the scenarios. Requiring large envelope improvements in new construction (P_3) can obtain substantial emission reductions of 60% (or 65% if coupled with heat pump deployment, see P_5= P_1+ P_3) from 2021 levels with a modest decrease in TACs compared to the current policy in 2030. However, the large improvement scenarios have significantly higher UCCs than UCCs in other policy scenarios, indicating that it would be difficult to widely install highly efficient envelopes in rural residential buildings without effective financial assistance.

4 Discussion

In 2021 the Chinese government released its action plan to peak carbon emissions by 2030, planning to "speed up energy-saving upgrades on rural housing" (State Council, 2021). Our results help inform these efforts on how to improve building envelope efficiency in rural homes.

For existing buildings, replacing current fuel subsidies with retrofit subsidies to encourage deployment of easy and low-cost efficiency measures is a win-win-win for rural households, local governments, and the environment. An urgent and important issue of the clean heating campaign is the increase in operating costs of clean heaters relative to coal stoves, making many rural households reignite their coal stoves (C. Liu & Wei, 2021). To address this issue, most local governments now provide fuel subsidies. Fuel subsidies are easy to implement, have relatively low administrative costs, and can be directly perceived by rural households (Gong et al., 2020). However, fuel subsidies compromise emission reduction goals and are not a sustainable solution because they place continuous huge burdens on government finances (China Coal Cap Project,

2020). Therefore, many local governments are now seeking to phase out fuel subsidies. Our results indicate that implementing easy and moderate retrofits can effectively reduce operating heating costs of clean heating thus prevent backsliding to coal. Additionally, replacing fuel subsidies with retrofit subsidies to widely and rapidly deploy energy retrofits also reduces required sizes and associated capital costs of clean heaters, thus facilitating the deployment of clean heaters, particularly expensive AAHPs. Building retrofits also lead to reduced GHG emissions and reduced energy infrastructure costs. Most cities now offer 600-800 yuan fuel subsidies to each rural household per year, equal to ~2000 yuan over the three years of the policy. This money could be better deployed to cover the upfront costs of energy-efficient windows (or north wall insulation) for a typical rural house which would provide benefits beyond the 3-year window of the existing fuel subsidy policy.

In new construction, promoting and deploying AAHP and efficient building envelopes is critical to reducing both costs and emissions over the long term. AAHPs are clearly the best option among all clean heaters in the studied region and provide both cost and environmental benefits when deployed particularly as the grid decarbonizes (M. Zhou et al., 2021). However, the level of energy efficiency recommended for building envelopes is context-specific and determined by local climates and desired indoor temperatures. While AAHP and easy envelope efficiency measures are usually the lowest-cost options for rural households which are satisfied with minimal thermal comfort (~14°C), whole-home insulation (i.e., “large improvement”) is the most economic option for many rural households which can afford and prefer higher indoor temperatures (~18°C). AAHP and well-insulated homes provide multiple co-benefits including improved thermal comfort, reduced carbon emissions, efficient cooling in summer, and reduced energy infrastructure costs(International Energy Agency (IEA), 2013). Therefore, our results indicate that deploying the

most efficient clean heating technologies in new construction–whole-home insulation combined with heat pumps – is vital to avoid carbon lock-in and reduce heating costs over the long term.

Unfortunately, the uptake of energy efficiency in rural homes is usually not a speedy and spontaneous process, even when the benefits accumulating over time outweigh initial investment costs (Tao et al., 2018). Rural residents are usually conservative and busy with farming (Shoemaker et al., 2018). They are either unaware of energy-efficient technologies or skeptical about the technologies despite their energy-saving benefits. When constructing new houses, rural households often hire local homebuilders who lack knowledge and technical skills in building energy efficiency. Qualified contractors are unwilling to serve rural areas because low population density, hard-to-serve customers, and long travel times lead to high costs per rural project (MacDonald et al., 2020). Moreover, energy-efficient technologies such as heat pumps and whole-home insulation have very high upfront costs that rural households with low incomes cannot afford. Financial assistance like loans and on-bill financing is not widely accessible to rural households.

Therefore, policies that are adapted to the rural context are critical to promoting and deploying energy-efficient technologies. First, community-based approaches are central to addressing awareness, access, and geographic barriers. Community-based promotion campaigns have a long history in rural China and have been used to deploy home appliances, electric vehicles, rooftop solar panels, etc. Local authorities can partner with qualified contractors to organize energy efficiency campaigns (e.g., “Weatherization Week”) to promote and demonstrate energy-efficient technologies (MacDonald et al., 2020). Rural communities can also leverage the power of collective purchases for group discounts and benefits. Second, providing subsidies and various

repayment options for purchases and installations is needed to address high upfront costs. Few cities now offer subsidies for building envelope improvements or AAHPs. One exception is Beijing, where the local government has provided up to 20,000 yuan to a rural household which builds a safe and energy-efficient house as well as a subsidy of up to 24,000 yuan for purchase and installation of an AAHP (Beijing Association of Sustainable Development, 2021). This subsidy program greatly improved the energy efficiency of rural homes in Beijing. Other local governments could introduce similar subsidies and loan programs. Innovative financial and business models are also needed to allow rural households to spread upfront costs over multiple years. For example, energy efficiency contractors can partially pay for home improvements to reduce upfront costs for rural households with rural residents repaying contractors through utility bill savings. Third, training local homebuilders in building energy efficiency technologies is especially urgent. Hiring and training local workers reduce workforce shortages and boost local economies. Moreover, local governments may consider enforcing mandatory building codes in rural homes. Building codes have contributed to significant energy efficiency improvements in urban buildings over the past four decades in China. Adapting the urban implementation system to rural buildings requires significant increases in administrative capacity and increases in availability of low-cost energy-efficient building materials and technologies in rural areas (Evans et al., 2014).

Our results are subject to several limitations. First, our analysis is based on a baseline building to represent the average building envelope efficiency in the studied region of northern China because of limited data availability. This approach cannot represent the heterogeneity of the rural residential building stock, such as home sizes, insulation levels, and installed heating systems (Nägeli et al., 2020). Larger energy-savings potential exists in extremely inefficient buildings.

Future work that includes field surveys to investigate the current rural residential building stock would be beneficial. Our baseline building is designed based on survey data from 2007-2015, so our results likely overestimate the energy-saving potential of recently constructed buildings (L. Zhu et al., 2020b). Second, our analysis primarily focuses on costs and benefits, while many other factors can affect the adoption of building envelope efficiency (K. Gillingham & Palmery, 2014). Understanding those non-economic obstacles to energy efficiency adoption is critical for designing effective policy interventions. Third, our estimates are subject to the rebound effect. Improved building energy efficiency may lead to increased household heating energy use (S. Wu et al., 2020). Fourth, we did not consider future cost reduction of heat pumps and efficient building envelopes. Costs of energy-efficient technologies are expected to decrease over time because of learning effects and economies of scale, which facilitates their deployment (Malhotra & Schmidt, 2020). Moreover, the clean heating campaign is now extended to the rest of northern China, where winter is usually colder than our studied regions. AAHPs are less efficient and hence require more electricity to achieve a chosen indoor temperature in cold regions. With higher heating demands, well-insulated homes will be critical to reducing heating emissions and costs across northern China.

Acknowledgement

This chapter is published as **Liu, S.,** Liu, H., & Mauzerall, D. L. (2022). Improving Building Envelope Efficiency Lowers Costs and Emissions from Rural Residential Heating in China. Environmental Science & Technology, 57(1), 595-605. Shangwei Liu thanks the co-authors of this chapter.

Reference:

Beijing Association of Sustainable Development. (2021). Rural Building Energy Saving and Clean Heating Retrofits in Beijing.

Building Energy Research Center of Tsinghua University. (2012). 2012 Annual Report on China Building Energy Efficiency. China Architecture & Building Press.

China Coal Cap Project. (2020). China Dispersed Coal Management Report 2020.

Cui, Y., Sun, N., Cai, H., & Li, S. (2020). Indoor temperature improvement and energy-saving renovations in rural houses of China's cold region—a case study of Shandong Province. Energies, 13(4). https://doi.org/10.3390/en13040870

Drehobl, A., Ross, L., & Ayala, R. (2020). How High Are Household Energy Burdens? September.

Evans, M., Yu, S., Song, B., Deng, Q., Liu, J., & Delgado, A. (2014). Building energy efficiency in rural China. Energy Policy, 64, 243–251. https://doi.org/10.1016/j.enpol.2013.06.040

Fumo, N. (2014). A review on the basics of building energy estimation. Renewable and Sustainable Energy Reviews, 31, 53–60. https://doi.org/10.1016/j.rser.2013.11.040

Gillingham, K., & Palmery, K. (2014). Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence. Review of Environmental Economics and Policy, 8(1), 18–38. https://doi.org/10.1093/reep/ret021

Gong, Y., Cai, B. feng, & Sun, Y. (2020). Perceived fiscal subsidy predicts rural residential acceptance of clean heating: Evidence from an indoor-survey in a pilot city in China. Energy Policy, 144(June), 111687. https://doi.org/10.1016/j.enpol.2020.111687

He, B. jie, Yang, L., Ye, M., Mou, B., & Zhou, Y. (2014). Overview of rural building energy efficiency in China. Energy Policy, 69, 385–396. https://doi.org/10.1016/j.enpol.2014.03.018

Hong, L., Zhou, N., Fridley, D., Feng, W., Khanna, N., & Berkeley, L. (2014). Modeling China's Building Floor-Area Growth and the Implications for Building Materials and Energy Demand. ACEEE Summer Study on Energy Efficiency in Buildings, 146–157. http://aceee.org/files/proceedings/2014/data/papers/10-230.pdf

Institute of Rural Development of Chinese Academy of Social Sciences. (2022). China Rural Development Report 2022.

International Energy Agency (IEA). (2013). Technology Roadmap: Energy efficent building envelopes. https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyEfficientBuildingEnvelopes.pdf

Levesque, A., Osorio, S., Herkel, S., & Pahle, M. (2023). Rethinking the role of efficiency for the decarbonization of buildings is essential. Joule, 7(6), 1087–1092. https://doi.org/10.1016/j.joule.2023.05.011

Li, J., Song, L., & Zhu, Y. (2021). Subsidies, clean heating choices, and policy costs: Evidence from rural households in Northern China. Sustainability (Switzerland), 13(1), 1–18. https://doi.org/10.3390/su13010169

Liu, C., & Wei, C. (2021). The World'S Largest Residential Energy Switching Program Is at Risk. In Environmental Science and Technology (Vol. 55, Issue 22, pp. 15004–15006). American Chemical Society. https://doi.org/10.1021/acs.est.1c06544

Liu, H., & Mauzerall, D. L. (2020). Costs of clean heating in China: Evidence from rural households in the Beijing-Tianjin-Hebei region. Energy Economics. https://doi.org/https://doi.org/10.1016/j.eneco.2020.104844

Liu, J., Liu, B., He, L., & Gao, Y. (2015). Investigation on the Winter Building Energy Consumption in Rural Areas in Jinan, China. Procedia Engineering, 121, 1819–1826. https://doi.org/10.1016/j.proeng.2015.09.162

Liu, Y., Zhang, Y., Li, C., Bai, Y., Zhang, D., Xue, C., & Liu, G. (2018). Air pollutant emissions and mitigation potential through the adoption of semi-coke coals and improved heating stoves: Field evaluation of a pilot intervention program in rural China. Environmental Pollution, 240, 661–669. https://doi.org/10.1016/j.envpol.2018.04.110

MacDonald, S., Winner, B., Smith, L., Juillerat, J., & Belknap, S. (2020). Bridging the rural efficiency gap: expanding access to energy efficiency upgrades in remote and high energy cost communities. Energy Efficiency, 13(3), 503–521. https://doi.org/10.1007/s12053-019-09798-8

Malhotra, A., & Schmidt, T. S. (2020). Accelerating Low-Carbon Innovation. Joule, 4(11), 2259–2267. https://doi.org/10.1016/j.joule.2020.09.004

Meng, W., Shen, H., Yun, X., Chen, Y., Zhong, Q., Zhang, W., Yu, X., Xu, H., Ren, Y., Shen, G., Ma, J., Liu, J., Cheng, H., Wang, X., Zhu, D., & Tao, S. (2020). Differentiated-Rate Clean Heating Strategy with Superior Environmental and Health Benefits in Northern China. Environmental Science and Technology, 54(21), 13458–13466. https://doi.org/10.1021/acs.est.0c04019

Ministry of Housing and Urban-Rural Development of China. (2010). Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ26－2010). In China Architecture and Building Press (in Chinese) (Issue JGJ26－2010).

Nägeli, C., Jakob, M., Catenazzi, G., & Ostermeyer, Y. (2020). Towards agent-based building stock modeling: Bottom-up modeling of long-term stock dynamics affecting the energy and climate impact of building stocks. Energy and Buildings, 211. https://doi.org/10.1016/j.enbuild.2020.109763

National Energy Administration. (2020). A press conference on the energy industry's decisive victory in poverty alleviation. http://www.nea.gov.cn/2020-10/19/c_139451999.htm

Natural Resources Defense Council. (2018). China Dispersed Coal Governance Report 2018.

NDRC (National Development and Reform Commission of China). (2017). Clean winter heating planning for northern areas (2017–2021). http://www.gov.cn/xinwen/2017-12/20/content_5248855.htm

Pan, W., & Mei, H. (2020). A design strategy for energy-efficient rural houses in severe cold regions. International Journal of Environmental Research and Public Health, 17(18), 1–18. https://doi.org/10.3390/ijerph17186481

Peng, L., Zhang, Q., Yao, Z., Mauzerall, D. L., Kang, S., Du, Z., Zheng, Y., Xue, T., & He, K. (2019). Underreported coal in statistics: A survey-based solid fuel consumption and emission inventory for the rural residential sector in China. Applied Energy, 235(November 2018), 1169–1182. https://doi.org/10.1016/j.apenergy.2018.11.043

PKU Institue of Energy. (2021). China Dispersed Coal Management Report 2021.

Shan, M., Wang, P., Li, J., Yue, G., & Yang, X. (2015). Energy and environment in Chinese rural buildings: Situations, challenges, and intervention strategies. Building and Environment, 91, 271–282. https://doi.org/10.1016/j.buildenv.2015.03.016

Shan, M., Yanqing, L., Rongjiang, M., Mengsi, D., Xingli, D., Xudong, Y., Yongjie, Z., & Jiandong, Y. (2020). Comparison of economic and emission performances of different technologies from coal to clean energy in northern rural China (in Chinese). Environment and Sustainable Developemnt, 3, 43–49.

Shandong Provincial Department of Housing and Urban Rural Development (Shandong DHURD). (2019). Technical guidelines for energy saving renovation of existing rural residential buildings in Shandong Province (Trial, in Chinese).

Shoemaker, M., Gilleo, A., & Ferguson, J. (2018). Reaching Rural Communities with Energy Efficiency Programs.

State Council. (2021). China's Action Plan for Carbon Dioxide Peaking Before 2030.

Tao, S., Meng, W., Shen, G., Shen, H., Chen, Y., Yun, X., Li, J., Ma, J., Liu, J., Cheng, H., Hu, J., & Wan, Y. (2021). Synergistic health benefits of household stove upgrading and energy switching in rural China. Environmental Science and Technology, 55(21), 14567–14575. https://doi.org/10.1021/acs.est.1c04242

Tao, S., Ru, M. Y., Du, W., Zhu, X., Zhong, Q. R., Li, B. G., Shen, G. F., Pan, X. L., Meng, W. J., Chen, Y. L., Shen, H. Z., Lin, N., Su, S., Zhuo, S. J., Huang, T. B., Xu, Y., Yun, X., Liu, J. F., Wang, X. L., … Zhu, D. Q. (2018). Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey. Nature Energy, 3(7), 567–573. https://doi.org/10.1038/s41560-018-0158-4

Wang, J., Zhong, H., Yang, Z., Wang, M., Kammen, D. M., Liu, Z., Ma, Z., Xia, Q., & Kang, C. (2020). Exploring the trade-offs between electric heating policy and carbon mitigation in China. Nature Communications, 11(1), 1–11. https://doi.org/10.1038/s41467-020-19854-y

Wang, W., Ge, X., & Xiong, H. (2019). Thermal design optimization and analysis on heating load of rural buildings in northern China. E3S Web of Conferences, 136, 1–5. https://doi.org/10.1051/e3sconf/201913603018

Wu, S., Zheng, X., Khanna, N., & Feng, W. (2020). Fighting coal — Effectiveness of coal-replacement programs for residential heating in China: Empirical findings from a household survey. Energy for Sustainable Development, 55, 170–180. https://doi.org/10.1016/j.esd.2020.02.002

Yin, P., Brauer, M., Cohen, A. J., Wang, H., Li, J., Burnett, R. T., Stanaway, J. D., Causey, K., Larson, S., Godwin, W., Frostad, J., Marks, A., Wang, L., Zhou, M., & Murray, C. J. L. (2020). The effect of air pollution on deaths, disease burden, and life expectancy across China

and its provinces, 1990–2017: an analysis for the Global Burden of Disease Study 2017. The Lancet Planetary Health, 4(9), e386–e398. https://doi.org/10.1016/S2542-5196(20)30161-3

Yun, X., Meng, W., Xu, H., Zhang, W., Yu, X., Shen, H., Chen, Y., Shen, G., Ma, J., Li, B., Cheng, H., Hu, J., & Tao, S. (2021). Coal Is Dirty, but Where It Is Burned Especially Matters. Environmental Science & Technology, 55(11), 7316–7326. https://doi.org/10.1021/acs.est.1c01148

Yun, X., Shen, G., Shen, H., Meng, W., Chen, Y., Xu, H., Ren, Y., Zhong, Q., Du, W., Ma, J., Cheng, H., Wang, X., Liu, J., Wang, X., Li, B., Hu, J., Wan, Y., & Tao, S. (2020). Residential solid fuel emissions contribute significantly to air pollution and associated health impacts in China. Science Advances, 6(44), 1–8. https://doi.org/10.1126/sciadv.aba7621

Zhang, Q., Hao, Y., Sun, D., Nie, Q., & Jin, L. (2017). Research on the Clean Energy Heating Systems in Rural Beijing. Energy Procedia, 143, 137–143. https://doi.org/10.1016/j.egypro.2017.12.661

Zheng, Y. (2020). Study on energy conservation reform and economy of rural existing residential buildings (in Chinese). Architecture Technology, 51(4), 469–471.

Zhou, M., Liu, H., Peng, L., Qin, Y., Chen, D., Zhang, L., & Mauzerall, D. L. (2021). Environmental benefits and household costs of clean heating options in northern China. Nature Sustainability. https://doi.org/10.1038/s41893-021-00837-w

Zhu, L., Liao, H., Hou, B., Cheng, L., & Li, H. (2020a). The status of household heating in northern China: a field survey in towns and villages. Environmental Science and Pollution Research, 27(14), 16145–16158. https://doi.org/10.1007/s11356-020-08077-9

Zhu, L., Liao, H., Hou, B., Cheng, L., & Li, H. (2020b). The status of household heating in northern China: a field survey in towns and villages. Environmental Science and Pollution Research, 27(14), 16145–16158. https://doi.org/10.1007/s11356-020-08077-9

Zhu, Y., Fan, X., Wang, C., & Sang, G. (2018). Analysis of heat transfer and thermal environment in a rural residential building for addressing energy poverty. Applied Sciences (Switzerland), 8(11). https://doi.org/10.3390/app8112077

Chapter 3 Cost and benefits of improving urban building energy efficiency in China

1 Introduction

Decarbonizing the building sector is crucial for achieving global climate goals. In 2022, buildings accounted for 30% of global energy consumption and 26% of global energy-related CO_2 emissions (IEA, 2023a). The primary end-uses in building operations are heating and cooling systems, with heating alone responsible for around 45% of building emissions. Moreover, the demand for cooling is projected to more than triple by 2050 (IEA, 2020a; Staffell et al., 2023).

Curbing emissions from heating and cooling primarily involves two approaches: (1) improving building energy efficiency to reduce demand (e.g., building energy retrofits and passive design), and (2) shifting to low-carbon energy sources for heating and cooling systems (e.g., replacing coal boilers with renewable-powered heat pumps). However, the optimal balance between these two approaches for building decarbonization remains unclear (Rosenow & Hamels, 2023). Specifically, questions arise about the cost-effectiveness of increasing building energy efficiency (Levesque et al., 2023a). Homeowners and small enterprises are concerned that increasing the stringency of energy efficiency standards for new construction and retrofits could overburden them (Fisher & Speed, 2023). Previous studies have also suggested that homeowners may not be able to recover their investment in energy efficiency through reduced building operating costs (Langevin et al., 2023; Y. Liu, Liu, et al., 2018).

However, improving building energy efficiency is important for building decarbonization because

it not only directly saves fuels and reduces emissions but also facilitates other emission mitigation strategies (Levesque et al., 2023b). Improving building energy demand management reduces overall energy consumption and peak loads, thus reducing the need for extensive grid infrastructure upgrades and associated costs and emissions. Specifically, heat electrification – a key strategy in building decarbonization – will lead to a substantial increase in electricity demand during winter which poses great challenges to grid operations and planning (Waite & Modi, 2020). Improving energy efficiency in buildings is crucial to alleviate the pressure on the power grid caused by heating electrification.

Moreover, improving building energy efficiency can facilitate the deployment of clean heating technologies. Improving energy efficiency reduces required sizes of clean heaters by lowering heating loads, thus reducing associated capital costs. Also, enhancing building energy efficiency lowers water temperatures needed in radiator systems and district heat networks, leading to a more efficient use of electric heat pumps for heating (Levesque et al., 2023b).

Therefore, understanding the costs and benefits of building energy efficiency is necessary to design cost-effective building decarbonization policies. Here we provide a comprehensive cost and benefit analysis of improving building energy efficiency in Chinese new urban buildings from 2020 to 2050 by using a building stock turnover model, a building energy model, and a power system planning model. We find that the benefits resulting from energy system cost savings are likely to offset or outweigh the additional technical costs associated with implementing nearly zero-energy building standards. However, the cost-effectiveness of building energy efficiency improvements is contingent on various factors, including building envelope costs, thermal comfort, and carbon prices. Accelerating the cost reduction of efficient building envelopes is key

to promoting energy efficiency in the building sector.

2 Results

2.1 Scenario design

We begin with scenario development of various building energy efficiency scenarios, as described in **Table 2**. China's urban building stock is expected to grow significantly in the coming decades due to urbanization and the rising demand for comfort. Chinese buildings have a relatively short average lifespan of about 35-50 years, much shorter than those in developed countries. As a result, the majority of buildings in 2050 have not been constructed as of 2020 (W. Zhou et al., 2019). This emphasizes the particular importance of improving energy efficiency in new buildings in China. Moreover, as more people move to urban areas, future energy demand for rural buildings is expected to constitute only a small portion of the total building energy demand (N. Zhou et al., 2018). Therefore, we here focus on policies to enhance energy efficiency in new urban buildings in China.

In China, the Ministry of Housing, and Rural and Urban Development (MOHURD) is responsible for publishing building energy standards and ensuring their implementation. In 1986, the MOHURD introduced the first mandatory building energy standard for residential buildings in northern China where the demand for space heating is high (Evans et al., 2010). These mandatory standards expanded to cover most of China in the 2010s, excluding temperate regions. The standards have become more stringent over time. In 2005, the MOHURD also introduced mandatory building energy standards for non-residential buildings, and these standards were updated in 2015. We design a "Baseline" scenario to represent all existing policies implemented before 2018.

Since 2018, the Chinese government has implemented a series of new policies to enhance residential building energy efficiency in new constructions. These policies include increased stringency in residential building energy standards and the introduction of mandatory standards in temperate regions. We design a "Current Policy" scenario to represent these updated policies during 2018-2022.

In the future, the most effective potential enhancement to the current policy is to impose a mandatory nearly zero energy buildings (NEB) standards to improve building energy efficiency. The MOHURD has published a non-mandatory technical standard for nearly zero energy buildings in 2019. To explore the impact of possible future enhanced building energy efficiency policy, we design two scenarios: "Nearly Zero Standard, 2035 (moderately ambitious future)" and "Nearly Zero Standard, 2025 (highly ambitious future)", which assumes all new residential and non-residential buildings constructed after 2025 and 2035 must comply with the new nearly zero energy standard, respectively. The "Nearly Zero Standard, 2025" scenario represents a very ambitious action to improve energy efficiency in Chinese new constructions.

Table 2. Building energy efficiency scenario design and descriptions

Scenarios	Descriptions
Bassline Policy (past)	Existing building energy efficiency policies implemented before 2018
Current Policy (current)	Updated building energy efficiency policies during 2018-2022
Nearly Zero Standard, 2035 (moderately ambitious future)	All new residential and non-residential buildings constructed after 2035 must comply with the new Nearly Zero Energy Standard
Nearly Zero Standard, 2025 (highly ambitious future)	All new residential and non-residential buildings constructed after 2025 must comply with the new Nearly Zero Energy Standard

2.2 Energy savings from building energy efficiency

Figure 5 shows the changes in building stock across various building energy efficiency policy

scenarios. We find that current policies, which introduce a series of new energy standards during 2018-2022, will make 78% residential buildings complying with the 2018-2022 standards. Implementing mandatory net zero standards in energy efficiency in 2035 and 2025 will leads to 43% and 73% residential buildings meeting nearly zero energy standards by 2050, respectively.

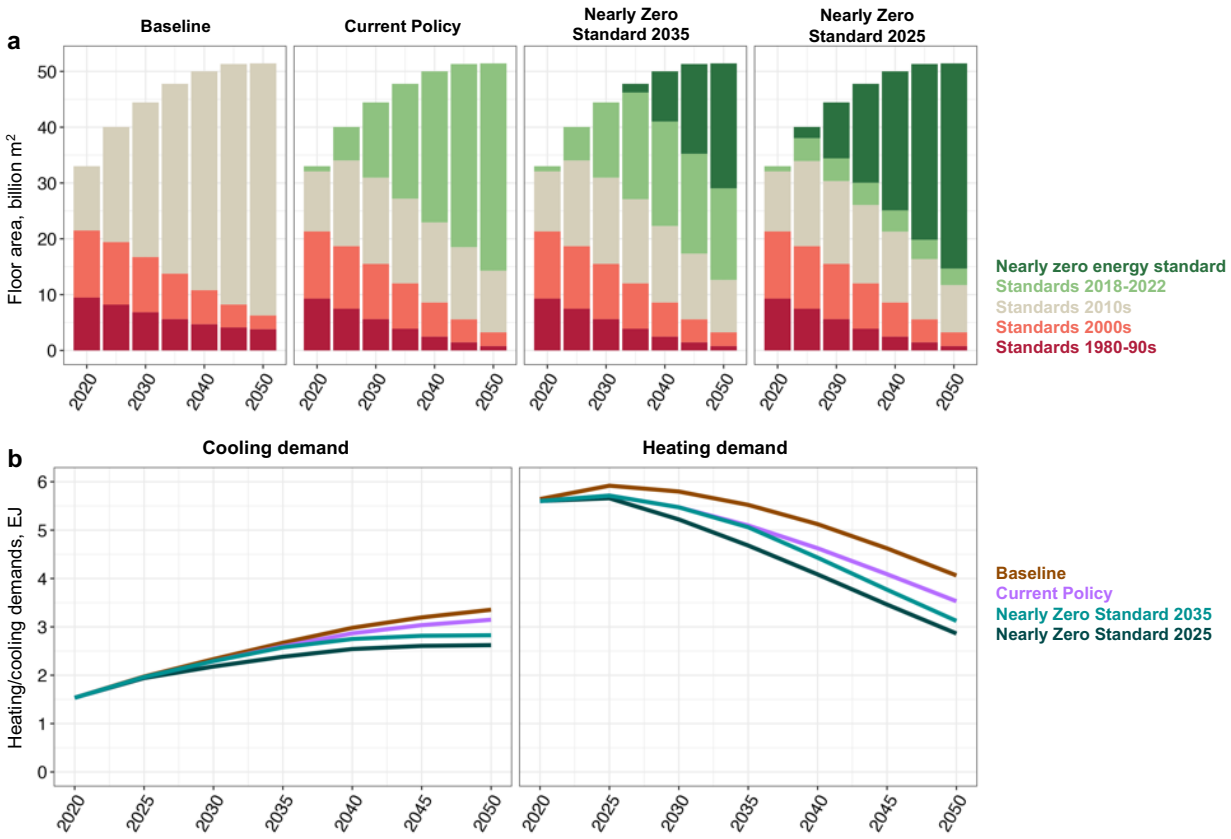


Figure 5. Building energy efficiency in various scenarios. (a) China's residential building floor area by adopted building codes from 2020 to 2050 under various scenarios. (b) China's heating and cooling energy demand from 2020 to 2050 under various scenarios.

Changes in building stock energy efficiency significantly impact on cooling and heating demand. Under the baseline scenario, cooling demand will double from 1.8 EJ in 2020 to 3.9 EJ in 2050, driven by increased urban floor areas and thermal comfort. The current policies will marginally

decrease cooling demand from the baseline scenario by 2% in 2035 and 5% in 2050. In contrast, adopting nearly zero energy standards in 2035 and 2025 will significantly reduce cooling demand by 14% and 20% in 2050, respectively.

We estimate that heating demand from buildings will peak in 2025 at ~6 EJ and decease to 4.3 EJ in 2050 in the baseline scenario. This decrease is primarily due to the assumed heat electrification using efficient heat pumps in our main analysis (assuming that the district heat demand met by heat pumps will linearly increase from 7% in 2020 to 70% in 2050, see Table S9), with a minor contribution from a warming climate. Current policies will significantly lower heating demand by 7% in 2035 and by 12% in 2050, compared to the baseline scenario. Adopting nearly zero energy standards in 2035 and 2025 can reduce heating demand by 22% and 36% in 2050, respectively. In the "Net Zero Standard 2025" scenario, heating energy use is expected to reach a level similar to cooling energy use in 2050.

Improving building energy efficiency reduces heating energy use not only by directly reducing heating service demand, but also by improving efficiency of electric heat pumps. Heat pumps efficiency depends on the temperature difference between heat sources (e.g., industrial waste heat, ground, ambient air) and heat sinks (i.e., water temperate in radiator systems and district heat networks). Enhancing building energy efficiency lowers water temperatures, thus increasing heat pumps efficiency. Therefore, energy efficiency improvement has a larger impact in the reduction of energy use for heating than cooling.

2.3 Costs and benefits from building energy efficiency improvements

Enhancing building energy efficiency poses challenges as the costs are concentrated on specific stakeholders, primarily real estate developers and homebuyers, while the benefits are diffuse and

accrue over the long term. We here examine six types of benefits resulting from building energy efficiency improvement, including (a) direct fuel savings, (b) savings from small heating/cooling equipment costs, (c) reduced grid capacity costs, (d) reduced grid operating costs, (e) reduced grid transmission costs, (f) reduced grid distribution costs (see Methods for detailed calculations). We estimate social benefits resulting from reduced CO_2 emissions as part of a sensitivity analysis in the next subsection.

Figure 6 shows the incremental annualized costs and benefits of various building energy efficiency policies in comparison with the baseline scenario. In general, we find that the incremental costs of improving energy efficiency are generally comparable to the benefits analyzed in this study. Both annualized costs and benefits rise from 2020 to 2050 due to a growing share of energy-efficient buildings in the overall stock. We find that the costs of implementing current policies will be offset by energy system benefits, resulting in a net benefit in 2050. Additionally, while costs initially may exceed the benefits of adopting nearly zero energy standards due to the high costs of meeting these standards, the benefits will surpass the costs, as deployment increases leading to a decrease in building envelope costs (assuming learning rate =10% in the main analysis).

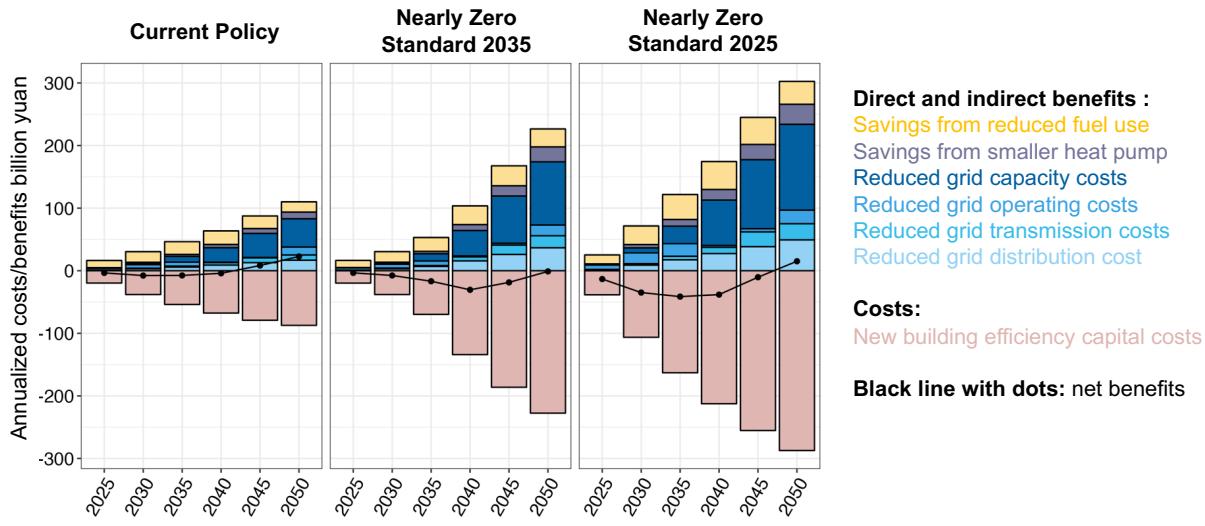


Figure 6. Costs and benefits of increasing building envelope in new urban buildings in China from 2025 to 2050, compared to the baseline scenario. See Table S9 for additional assumptions.

We also observe a significant shift in the patterns of benefits before and after 2035. Before 2035, the main benefits are *operational*, including reduced heating fuel costs and grid operating costs. However, after 2035, the largest benefits are *capital-related*, particularly in reduced grid capacity costs. This shift is primarily due to (a) the increasing electrification of heat and (b) the need for extensive deployment of renewables and storage for deep emission reduction in the power sector after 2035. Consequently, after 2035, the major benefits of improving building energy efficiency come from a reduced need for investments in renewables and storage infrastructure.

2.4 Sensitivity analysis

We conducted a sensitivity analysis to examine the influence of various factors on the cost-effectiveness of improving new building energy efficiency (see **Figure 7** and **Table S9**). We find that the cost-effectiveness of enhancing new building energy efficiency is affected by the costs

associated with efficient building envelopes, thermal comfort, and assumed carbon prices. Other factors considered in our analysis have relatively marginal impacts.

The most significant uncertainties regarding the cost-effectiveness of implementing nearly zero energy standards arise from the future costs associated with highly efficient building envelopes. As of 2020, only approximately 10 million m^2 (less than 0.1% of the total) of building floor area in China meets nearly zero energy standards (S. Zhang et al., 2021). Achieving these standards would entail an incremental cost of 100-600 yuan/m^2 compared to the 2010s standards. However, with increased deployment, the costs of nearly zero energy buildings are expected to decrease significantly (Malhotra & Schmidt, 2020). Our results suggest that the incremental costs of nearly zero energy buildings need to be less than 100 yuan/m^2 to be cost-effective if only accounting for the benefits from energy system cost savings. The high building envelope cost scenario models a scenario where costs fail to decrease significantly (learning rate = 5%, ~120 yuan/m^2 in 2050), resulting in mandatory nearly zero energy standards leading to significant net costs. In contrast, the low building envelope cost scenario models a breakthrough in nearly zero energy building costs (learning rate = 20%, ~30 yuan/m^2 in 2050), making the introduction of mandatory nearly zero energy standards highly cost-effective. These sensitivity tests underscore the importance of developing demonstration projects to lower the costs of nearly zero energy standards before mandating them.

Carbon prices also impact the cost-effectiveness of energy efficiency, especially in the near term. As heating electrification increases and the power grid decarbonizes, the influence of building energy efficiency on carbon emissions (and air pollutant emissions as well) will decrease. We find that, considering the social benefits of carbon emission reduction, with a high carbon price equal

to the estimated social cost of carbon (~¥1300/$185 per ton CO_2) (Rennert et al., 2022), introducing mandatory nearly zero building energy standard is likely to be cost-effective.

Increased thermal comfort will necessitate more building energy use, thereby enhancing the cost-effectiveness of increasing building energy efficiency. We estimate that adjusting the heating/cooling thermostat set point by 1 °C will result in a ~20% increase in heating/cooling energy use. This would significantly increase the net benefits of introducing mandatory nearly zero energy standards. We do not assume any changes in the thermostat set point in the main analysis. However, future thermal comfort is likely to increase with aging populations and rising comfort needs (Han et al., 2022).

Future costs of renewables, CCS (carbon capture and storage), and energy storage technologies also impact the cost-effectiveness of building energy efficiency improvements, particularly after 2035 when electricity demand for heating and cooling is high. Lower renewables costs moderately reduce the net benefits of building energy efficiency improvement, while higher renewables costs increase these benefits. This is because supply-side technologies (e.g., renewables) and demand-side technologies (e.g., building energy efficiency) are complementary in reducing carbon emissions and are in competition with each other. The costs of CCS only have an impact when CCS is deployed at scale after 2040. We find that the costs of energy storage have little impact. However, our capacity expansion modeling approach may not fully represent the characteristics and dynamics of energy storage, potentially underestimating its impact (Levin et al., 2023).

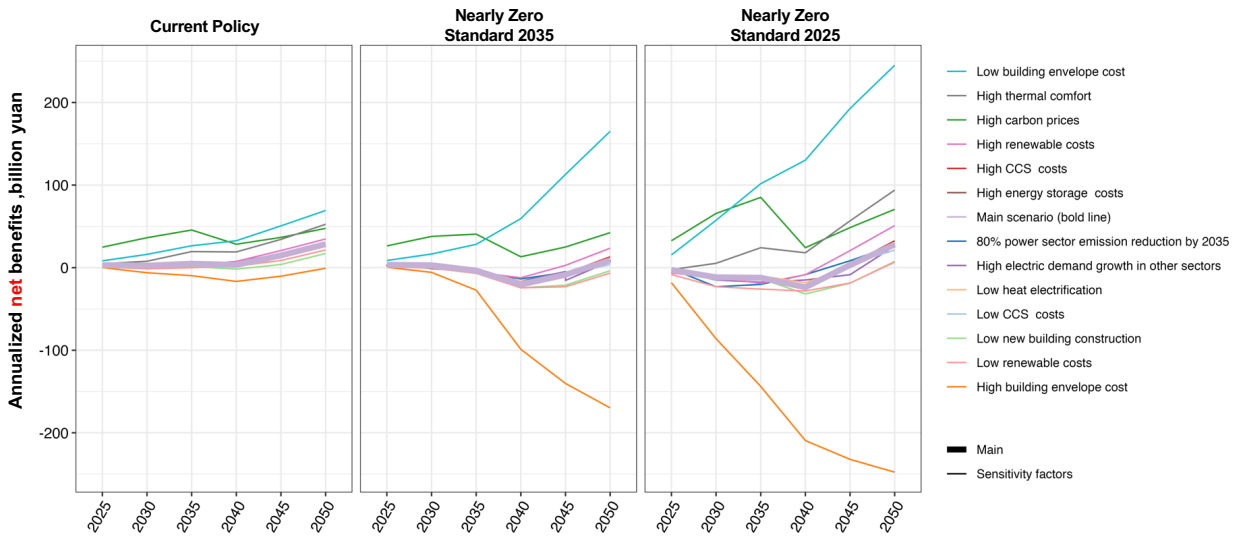


Figure 7. Net benefits of increasing building envelope in new urban buildings in China from 2025 to 2050 under various sensitivity test scenarios. See Table S9 for additional assumptions.

3 Discussion

We provide a comprehensive assessment of the cost-effectiveness of increasing urban building envelope energy efficiency in China. Our findings indicate that the benefits resulted from energy system cost savings and carbon emission reduction are likely to offset or surpass the technical costs associated with implementing new energy standards. These results have direct policy implications, providing guidance on the timing and approach for introducing new energy standards for new urban buildings in China.

A few previous studies have examined the cost-effectiveness of increasing building envelope energy efficiency at the energy system level in the US and Europe. For example, Langevin et al. (2023) found that the high incremental deployment costs of the best currently market-available envelope efficiency improvements are more than double their benefits from energy system cost savings. This is consistent with our results that cost reduction in building envelopes are needed to

make building envelopes cost-effective.

Strengthening building energy codes is ineffective without robust enforcement. Implementing new mandatory building codes requires thorough planning, coordination, and communication (Evans et al., 2010). This involves boosting the production capacity of energy-efficient building materials, providing professional education and training, and updating the building code monitoring system. Over the past twenty years, the Chinese government has established a building energy efficiency inspection system that has effectively increased the compliance rate with mandatory civil building energy efficiency codes from less than 10% in 2000 to nearly 100% in recent years at the design and construction stages (Feng et al., 2015). However, the operating energy performance is usually lower than the designed energy performance due to inferior construction and occupant behavior (e.g., window opening) (X. Wang et al., 2019). Future studies need to better understand effective ways to ensure operational energy savings in building envelope efficiency measures.

Improving building envelope energy efficiency offers various benefits not considered in our assessment, such as improved air quality, enhanced energy independence, reduced vulnerability to extreme weather, and job creation. A previous study estimates that increasing building energy efficiency in the US could lead to an 18 to 25% reduction in particulate matter emissions, preventing thousands of premature deaths by 2050 (K. T. Gillingham et al., 2021). In China, the health benefits could be even more significant, as improved energy efficiency reduces air pollutant emissions from more polluting coal-fired power plants and heat generation facilities (X. Yun et al., 2021). Building energy efficiency can also enhance the resilience of buildings and better address extreme heat and cold waves in a changing climate (Franconi et al., 2023; K. T. Gillingham et al., 2021; Hanif et al., 2023). These additional benefits justify the need to strengthen building

energy codes to better ensure public health, safety, and well-being.

4 Methods

4.1 Building stock turnover and energy demand modeling

We develop a bottom-up build energy model to estimate future heating and cooling demands in Chinese buildings at the prefecture city level from 2020 to 2050 based on Hong et al. (2014). The building heating and cooling energy demands (BEU) in year *t* in city *c* are estimated using building floor areas (FA), heating/cooling penetration rates (P), and heating and cooling intensities (I), as given by Equation (1):

$$BEU_{t,c} = \sum_n \sum_e FA_{t,c,n,e} \times P_{t,c,n,e} \times I_{t,c,n,e} \quad (1)$$

where n represents building type (residential and nonresidential), and e represents various building energy efficiency levels.

We estimate the residential and nonresidential building floor area (FA) for each city from 2020 to 2050 using a building stock turnover model. This model tracks how buildings in a city are built, renovated, or demolished over time. The floor areas of new buildings ($N_{t,c}$) in year t in city c is calculated as Equations (2)-(3):

$$N_{t,c,n} = S_{t,c,n} - S_{t-1,c,n} - D_{t,c,n} \quad (2)$$

$$S_{t,c,n} = P_{t,c} \times a_{t,c,n} \quad (3)$$

where $S_{t,c,n}$ denotes the total floor area in year t and $D_{t,c,n}$ represents the demolished building floor

area. Total building floor area is estimated based on projected population ($P_{t,c}$) and per capita floor area ($a_{t,c,n}$).

We estimate the demolished building floor area based on building age distributions and average building lifetime using a probability function with a cumulative normal distribution, as given in Equation (4):

$$D_{t,c,n} = \frac{1}{2}[1 + \mathrm{erf}\left(\frac{z_{t,c,n}-\mu_n}{\sigma_n\sqrt{2}}\right))] \quad (4)$$

where $z_{t,c,n}$ denotes the age of building stock in year *t* in city *c* for building type *n*. μ_n is the average building lifetime for building type *n* and σ_n is assumed to be one-third of the average building lifetime (Hong et al. 2014). We estimate the age distribution of Chinese buildings in 2020 based on Chinese 2020 census statistics and a historical material flow database (Chen et al. 2022).

We estimate building heating and cooling intensities (in units of kwh/m^2) based on a previous study by Xiong et al. (2023). This study calculated heating and cooling intensities in Chinese buildings with various energy efficiency levels in five representative cities (Harbin, Beijing, Chongqing, Guangzhou, and Kunming) under various future climate scenarios between 2020 and 2060. These five cities were selected to represent different climate zones in China. We estimate heating and cooling intensities in other cities using Equation (5):

$$I_{t,c,e} = I_{t,R,e} \times \frac{HDD/CDD_{t,c}}{HDD/CDD_{t,R}} \quad (5)$$

where $I_{t,R,n,e}$ denotes the heating and cooling intensities in year *t* for the representative city *R* with a specific building energy efficiency level *e*. $HDD/CDD_{t,c}$ and $HDD/CDD_{t,R}$ represent the

heating and cooling degree days (HDDs and CDDs) in city *c* and the representative city *R*, respectively.

We upscale annual heating and cooling energy demand to hourly resolution based on a previous study (Staffel et al., 2023). Variations in heating and cooling demand from day to day are primarily driven by outdoor weather, while variations in hourly demand are largely driven by occupant behavior patterns. Therefore, we first split annual heating and cooling demand into daily demand based on outdoor temperatures, and then further break down daily demand into hourly demand using typical diurnal heating and cooling profiles.

4.2 Power system planning model

We employ an open-source power system planning model, GridPath (available at https://www.gridpath.io/), to analyze the impact on power grid generation and transmission capacity investment resulting from various building electrification and decarbonization pathways. We use the GridPath model to determine the economically optimal investments in generation capacities and transmission line capacities necessary to meet future electricity demand. The optimal investment portfolio minimizes the national total costs of producing and delivering electricity in China while satisfying a set of operational and environmental constraints.

We forecast future annual results for the period between 2020 and 2050 in 5-year intervals. To maintain computational tractability, we select representative days to characterize the electric loads and generation profiles for each model year, which is a common approach for long-term system planning model. We select two representative days for each month and select 6 hours (0th, 4th, 8th, 12th, 16th, and 20th hours) to characterize each day. We use a province as a load zone.

Key inputs for GridPath model include (1) annualized investment capital costs of new power plants, storage facilities, and transmission lines, (2) annual operating and maintenance costs of both existing and new power plants, storage facilities, and transmission lines, (3) fuel costs of coal and gas, (4) emission factors of fossil fuel power plants. We obtain these cost and emission data from BNEF database and previous literature (Chen et al., 2021).

We softly couple the building energy model and the GridPath model by incorporating provincial-level hourly building heating and cooling demand profiles into the load profile inputs for the GridPath model. To estimate future electric load profiles in other sectors, we begin by projecting the annual electricity demand for each sector in every province from 2020 to 2050, using data from IEA reports (IEA, 2021) and the DPEC (Dynamic Projection model for Emissions in China) database (Tong et al., 2020). We then allocate the annual electricity demand into hourly profiles by representative monthly, daily, and hourly profiles for each sector.

4.3 Costs and benefits of building energy efficiency

We collected incremental costs (including removal/demolition costs, material costs, accessories costs, and installation costs, in units of yuan/m^2) of building energy efficiency improvement compared with the baseline scenario from the literature, government documents, conversations with building material suppliers. We annualize all capital costs as loans are generally available for real estate developers, homebuyers, and energy production companies.

We analyze benefits of improving building energy efficiency across six categories, including (a) reduced heating fuel costs, (b) reduced fuel CO_2 emissions, (c) reduced heating and cooling equipment costs, (d) reduced grid capacity costs, (e) reduced grid operating costs, (f) reduced grid transmission costs. We also estimate social benefits resulting from reduced CO_2 emissions as part

of a sensitivity analysis. These benefits are calculated as equation (6):

$$B_{t,i,s} = C_{t,i,s} - C_{t,i,baseline} \quad (6)$$

where $B_{t,i,s}$ represent the benefits of building energy efficiency in scenario s in year t within category i. $C_{t,i,s}$ and $C_{t,i,baseline}$ denote the total annualized costs (annualized capital costs plus operating costs) within category i in year t in the building energy efficiency scenario s and the baseline scenario, respectively. We obtain equipment unit costs, fuel costs and emission factors of various heating and cooling technologies from previous studies (M. Zhou et al., 2021). We use the 97.5% design temperature (i.e., the outdoor temperature that will exceed during 97.5% of the time in winter) and 1.5% design temperature to size cooling and heating equipment, respectively. Grid capacity, operating and transmission costs and grid CO_2 emissions are direct output of the GridPath model. We calculate grid distribution costs based on provincial-level government-regulated distribution unit costs (in units of yuan/kwh).

Acknowledgements

Shangwei Liu thanks the following co-authors of this chapter: Liqun Peng, Xiangwen Fu, Jiang Lin, and Denise L. Mauzerall.

Reference:

Chen, C., Qi, J., Li, N., Ji, T., Wang, H., Huang, Y., ... & Chen, W. Q. (2022). China economy-wide material flow account database from 1990 to 2020. Scientific Data, 9(1), 502.

Chen, X., Liu, Y., Wang, Q., Lv, J., Wen, J., Chen, X., ... & McElroy, M. B. (2021). Pathway toward carbon-neutral electrical systems in China by mid-century with negative CO2 abatement costs informed by high-resolution modeling. Joule, 5(10), 2715-2741.

Evans, M., M. A. Halverson, and Shui A. Delgado. (2010). Enforcing Building Energy Codes in China: Progress and Comparative Lessons.

Feng, Wei, Nan Zhou, Stephane De La Rue Du Can, Michael Bendewald, and Ellen Franconi. (2015). Building Energy Codes in China: Recommendations for Development and Enforcement.

Fisher, Lucy, and Madeleine Speed. (2023). UK Government Says Energy Certificates Need "Fundamental Reform" in Latest Green Shift'. Retrieved 23 November 2023 (https://www.ft.com/content/f1857432-85ae-4289-9ee6-087a205c9bbf#comments-anchor).

Franconi, Ellen, Luke Troup, Mark Weimar, Yunyang Ye, Chitra Nambiar, Jeremy Lerond, Eliza Hotchkiss, Jordan Cox, Sean Ericson, Eric Wilson, Philip White, Conor Dennehy, Jordan Burns, Jeff Maguire, Robin Burton, Tianzhen Hong, Linqian Sheng, Kaiyu Sun, Michael Reiner, Christopher Perry, and Jeremy Williams. (2023). Enhancing Resilience in Buildings Through Energy Efficiency Pacific Northwest National Laboratory.

Gillingham, Kenneth T., Pei Huang, Colby Buehler, Jordan Peccia, and Drew R. Gentner. (2021). The Climate and Health Benefits from Intensive Building Energy Efficiency Improvements. Science Advances 7(34). doi: 10.1126/sciadv.abg0947.

Han, Xiao, Chu Wei, and Gui-Ying Cao. (2022). Aging, Generational Shifts, and Energy Consumption in Urban China. Proceedings of the National Academy of Sciences 119(37). doi: 10.1073/pnas.2210853119.

Hanif, Sarmad, Monish Mukherjee, Shiva Poudel, Min Gyung Yu, Rohit A. Jinsiwale, Trevor D. Hardy, and Hayden M. Reeve. (2023). Analyzing At-Scale Distribution Grid Response to Extreme Temperatures. Applied Energy 337:120886. doi: 10.1016/j.apenergy.2023.120886.

Hong, L., Zhou, N., Fridley, D., Feng, W., & Khanna, N. (2014, August). Modeling China's building floor-area growth and the implications for building materials and energy demand. In ACEEE summer study on energy efficiency in buildings (pp. 146-157).

IEA. (2020). Is Cooling the Future of Heating?

IEA. (2021). An energy sector roadmap to carbon neutrality in China.

IEA. (2023). Tracking Clean Energy Progress 2023.

Langevin, Jared, Aven Satre-Meloy, Andrew J. Satchwell, Ryan Hledik, Julia Olszewski, Kate Peters, and Handi Chandra-Putra. (2023). Demand-Side Solutions in the US Building Sector Could Achieve Deep Emissions Reductions and Avoid over $100 Billion in Power Sector Costs. One Earth 6(8):1005–31. doi: 10.1016/j.oneear.2023.07.008.

Levesque, Antoine, Sebastian Osorio, Sebastian Herkel, and Michael Pahle. (2023). Rethinking the Role of Efficiency for the Decarbonization of Buildings Is Essential. Joule 7(6):1087–92. doi: 10.1016/j.joule.2023.05.011.

Levin, Todd, John Bistline, Ramteen Sioshansi, Wesley J. Cole, Jonghwan Kwon, Scott P. Burger, George W. Crabtree, Jesse D. Jenkins, Rebecca O'Neil, Magnus Korpås, Sonja Wogrin, Benjamin F. Hobbs, Robert Rosner, Venkat Srinivasan, and Audun Botterud. (2023). Energy Storage Solutions to Decarbonize Electricity through Enhanced Capacity Expansion Modelling. Nature Energy 8(11):1199–1208. doi: 10.1038/s41560-023-01340-6.

Liu, Yuming, Tingting Liu, Sudong Ye, and Yisheng Liu. (2018). Cost-Benefit Analysis for Energy Efficiency Retrofit of Existing Buildings: A Case Study in China. Journal of Cleaner Production 177:493–506. doi: 10.1016/j.jclepro.2017.12.225.

Malhotra, A., & Schmidt, T. S. (2020). Accelerating low-carbon innovation. Joule, 4(11), 2259-2267.

Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon, Jordan Wingenroth, Roger Cooke, Bryan Parthum, David Smith, Kevin Cromar, Delavane Diaz, Frances C. Moore, Ulrich K. Müller, Richard J. Plevin, Adrian E. Raftery, Hana Ševčíková, Hannah Sheets, James H. Stock, Tammy Tan, Mark Watson, Tony E. Wong, and David Anthoff. (2022). Comprehensive Evidence Implies a Higher Social Cost of CO2. Nature 610(7933):687–92. doi: 10.1038/s41586-022-05224-9.

Rosenow, Jan, and Sam Hamels. (2023). Where to Meet on Heat? A Conceptual Framework for Optimising Demand Reduction and Decarbonised Heat Supply. Energy Research & Social Science 104:103223. doi: 10.1016/j.erss.2023.103223.

Staffell, Iain, Stefan Pfenninger, and Nathan Johnson. (2023). A Global Model of Hourly Space Heating and Cooling Demand at Multiple Spatial Scales. Nature Energy. doi: 10.1038/s41560-023-01341-5.

Tong, D., Cheng, J., Liu, Y., Yu, S., Yan, L., Hong, C., ... & Zhang, Q. (2020). Dynamic projection of anthropogenic emissions in China: methodology and 2015–2050 emission pathways under a range of socio-economic, climate policy, and pollution control scenarios. Atmospheric Chemistry and Physics, 20(9), 5729-5757.

Waite, Michael, and Vijay Modi. (2020). Electricity Load Implications of Space Heating Decarbonization Pathways. Joule 4(2):376–94. doi: 10.1016/j.joule.2019.11.011.

Wang, Xia, Wei Feng, Weiguang Cai, Hong Ren, Chao Ding, and Nan Zhou. (2019). Do Residential Building Energy Efficiency Standards Reduce Energy Consumption in China? – A Data-Driven Method to Validate the Actual Performance of Building Energy Efficiency Standards. Energy Policy 131:82–98. doi: 10.1016/j.enpol.2019.04.022.

Xiong, J., Guo, S., Wu, Y., Yan, D., Xiao, C., & Lu, X. (2023). Predicting the response of heating and cooling demands of residential buildings with various thermal performances in China to climate change. Energy, 269, 126789.

Yun, Xiao, Wenjun Meng, Haoran Xu, Wenxiao Zhang, Xinyuan Yu, Huizhong Shen, Yilin Chen, Guofeng Shen, Jianmin Ma, Bengang Li, Hefa Cheng, Jianying Hu, and Shu Tao. (2021).

Coal Is Dirty, but Where It Is Burned Especially Matters. Environmental Science & Technology 55(11):7316–26. doi: 10.1021/acs.est.1c01148.

Zhang, S., Fu, Y., Yang, X., & Xu, W. (2021). Assessment of mid-to-long term energy saving impacts of nearly zero energy building incentive policies in cold region of China. Energy and Buildings, 241, 110938.

Zhou, Mi, Hongxun Liu, Liqun Peng, Yue Qin, Dan Chen, Lin Zhang, and Denise L. Mauzerall. (2021). Environmental Benefits and Household Costs of Clean Heating Options in Northern China. Nature Sustainability. doi: 10.1038/s41893-021-00837-w.

Zhou, Nan, Nina Khanna, Wei Feng, Jing Ke, and Mark Levine. (2018). Scenarios of Energy Efficiency and CO2 Emissions Reduction Potential in the Buildings Sector in China to Year 2050. Nature Energy 1. doi: 10.1038/s41560-018-0253-6.

Zhou, Wei, Alice Moncaster, David M. Reiner, and Peter Guthrie. (2019). Estimating Lifetimes and Stock Turnover Dynamics of Urban Residential Buildings in China. Sustainability 11(13):3720. doi: 10.3390/su11133720.

Chapter 4 Diversifying Heat Sources in China's Urban District Heating Systems Will Reduce Risk of Carbon Lock-in

1 Introduction

Mitigating carbon emissions from heating buildings is a critical part of the energy transition (Waite & Modi, 2020). District heating systems, widely used in China, Russia, and Europe, distribute heat from a central location through insulated pipes to buildings throughout a city. District heating is promising for decarbonizing heating as it can integrate diverse low-carbon heat sources (Werner, 2017). However, the full potential of district heating's decarbonization remains largely untapped. In 2020, fossil fuels accounted for 90% of global district heat production, contributing to nearly 4% of global CO_2 emissions (IEA, 2023b). Meeting global climate goals requires a substantial increase in the use of non-fossil energy sources, including industrial waste heat and large heat pumps powered by decarbonized electricity, in district networks (IEA, 2023b).

Northern China hosts the world's largest district heating systems, consuming more energy than the entire UK and contributing ~1.5% of global CO_2 emissions (IEA, 2019a). Until 2016, China's district heating predominantly relied on inefficient dirty coal boilers and small-scale combined heat and power (CHP) plants. In addition to carbon emissions, these facilities contributed to severe air pollution, adversely affecting public health (M. Zhou et al., 2021). In response to the severe air pollution, the Chinese government launched a nationwide clean heating campaign in 2017 (NDRC (National Development and Reform Commission of China), 2017). A primary objective of the campaign was to replace dirty coal boilers and small-scale CHP plants with various clean district heating technologies, including large and efficient CHP plants (equipped with air pollutant emission control systems), natural gas boilers, and various non-fossil heating technologies. As a

result, urban district heating demand met by large CHP plants increased to 54% in 2021, greatly contributing to the notable improvements in air quality observed in China in recent years (W. Meng et al., 2020; Nie et al., 2023). However, the share of non-fossil sources in China's district heating systems remains low (~10% in 2021) (Nie et al., 2023), falling short of the 27% non-fossil heating goals set by the clean heating campaign for 2021 (China Energy News, 2020).

For China to peak carbon emissions by 2030, reducing emissions from district heating will be crucial particularly in industrial cities where carbon emissions continue to rise (Y. Shan et al., 2022). Spurred by the announcement of the 2060 carbon neutrality goal, the Chinese government has actively promoted non-fossil technologies in district heating in recent years (Table S10). Meeting the carbon neutrality goal will require an extraordinary near-term effort to expand low-carbon heat sources in China's district heating networks so that non-CHP sources contribute about two-thirds of total district heating by 2030 (Z. Wang et al., 2023). Additionally, understanding the implications of various strategies for replacing dirty coal technologies while meeting the increasing heating demand in China's cities is necessary to guide further implementation of China's clean and low-carbon heating policy.

Here we analyze the impact of various possible short-term investments in China's district heating sector (2020-2030) on CO_2 emissions and capital and operating costs. We find that replacing dirty coal technologies with existing and new CHP plants, while resulting in cost savings, will likely lead to an increase in total CO_2 emissions in China's district heating systems from 2020 to 2030. Building new coal-fired CHP plants also poses a risk of carbon lock-in for both heat and electricity generation as these plants will likely operate for decades. Improving CHP resources from existing power plants and expanding the adoption of industrial waste heat and air/ground-source heat

pumps can avoid the need for new CHP plant construction while providing household heating at on average 12% increased cost.

2 Results

2.1 Emissions, costs, and availability of various district heating technologies

We assess CO_2 emissions, costs, and availability of various district heating technologies, including five fossil fuel technologies and ten non-fossil technologies (see **Figure 8** and **Table S11**). Currently widely used coal-based technologies, i.e., coal boilers and CHP-extraction, have low costs but high CO_2 emissions. Improved coal-fired CHP technology utilizes large absorption heat pumps to recover waste heat from the power plants' cooling system, resulting in substantial reductions in both costs and emissions compared to current coal-based technologies (See Supplementary Note 2 for details). We find that the improved CHP technology has CO_2 emission factors only slightly higher than those of natural gas boilers and most grid-based options that use the 2020 power mix.

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

operating costs similar to current coal-based technologies; however, their capital costs are high.

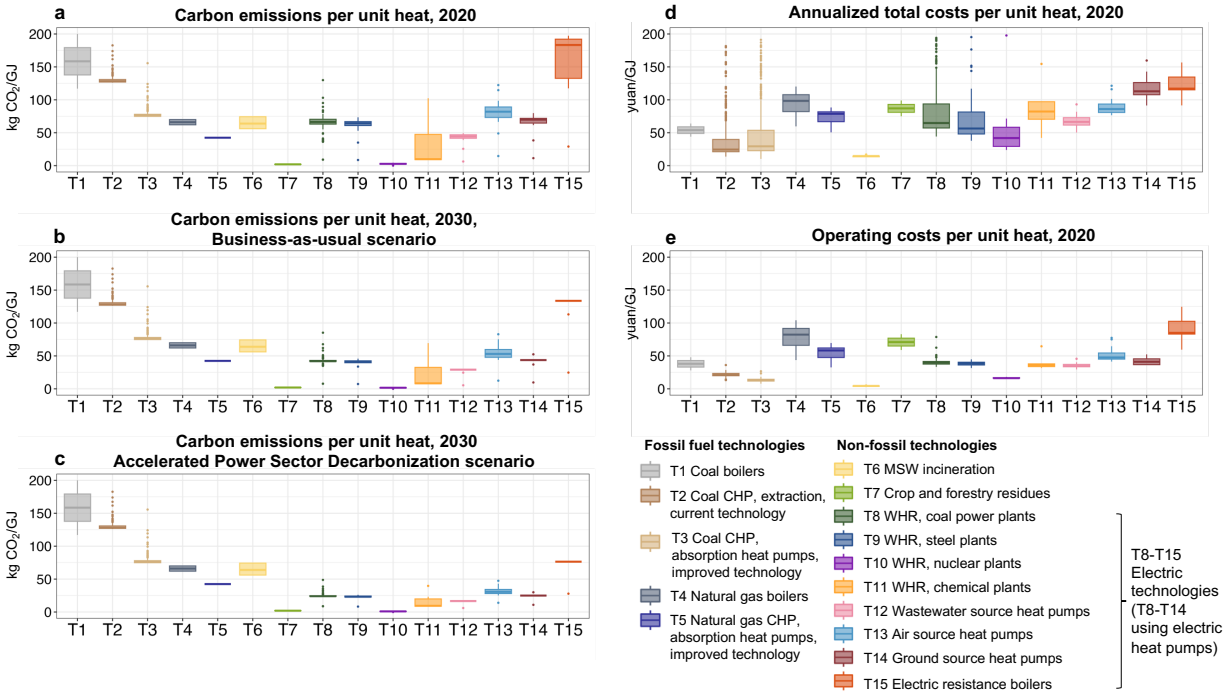


Figure 8. Carbon emissions and costs for 15 district heating technologies. a-c, carbon emissions per unit heat (a) in 2020, (b) in 2030 under the Business-as-usual (BAU) electricity generation scenario (c) in 2030 under the Accelerated Power Sector Decarbonization scenario. d, annualized total costs (annualized capital costs plus operating costs) per unit heat in 2020. e, operating cost per unit heat in 2020. Box plots depict data distribution with central lines as medians, whiskers for data range, and dots as outliers. Abbreviations: CHP, combined heat and power; MSW, municipal solid waste; WHR, waste heat recovery with electric heat pumps. See Methods for calculation details.

2.2 Chinese district heating systems in 2030

To represent various levels of penetration of non-fossil heating technologies combined with existing and new CHP deployment in 2030, we develop three district heating investment scenarios, including high-coal, mid-coal, and low-coal (**Table 3** and **Figure 9**). All three scenarios aim to replace dirty coal boilers and small coal CHP plants with other options that satisfy the ~30% increased district heating demand expected in 2030 relative to 2020 (S. Guo et al., 2022; Z. Wang

et al., 2023).

In the high-coal scenario, many new coal CHP plants are constructed. The mid-coal scenario combines new coal construction with adoption of cost-effective recovery of industrial waste heat from steel plants and nuclear power plants. In contrast, the low-coal scenario represents highly ambitious near-term action to diversify to low carbon heat sources in China's district heating systems. This scenario prohibits new coal CHP plant construction and reduces the capacity factors of existing coal-fired power plants to align with the 2°C climate goal. The low-coal scenario therefore necessitates the extensive integration of industrial waste heat and the implementation of air/ground source heat pumps.

Table 3. Scenario design for China's district heating systems in 2030.

	High-coal scenario	Mid-coal scenario	Low-coal
Coal boilers/small CHP	Phased out	Phased out	Phased out
Natural gas boilers	Same share as in 2020	Same share as in 2020	Same share as in 2020
Existing coal CHP resources	Used if cheaper than air/ground-source heat pumps	Used if cheaper than air/ground-source heat pumps	Used if cheaper than air/ground-source heat pumps
Coal power capacity factors	Continue to operate at 2019 capacity factors	Continue to operate at 2019 capacity factors	Reduced to meet the 2°C climate goal (avg ~18%)
Power sector decarbonization scenario	Business-as-usual scenario	Business-as-usual scenario	Accelerated Power Sector Decarbonization scenario
Local low carbon heating sources (MSW, biomass, wastewater)	20% of total potential	50% of total potential	80% of total potential
Industrial waste heat (Steel, chemical, nuclear)	Not considered	Used if cheaper than air/ground-source heat pumps	Used if cheaper than air/ground-source heat pumps
Air/ground-source heat pumps	Not considered	Not considered	Used to meet remaining heating demand
New coal power plant construction	Allowed	Allowed	Not allowed
Resulting coal CHP share in 2030	~80%	~67%	~42%

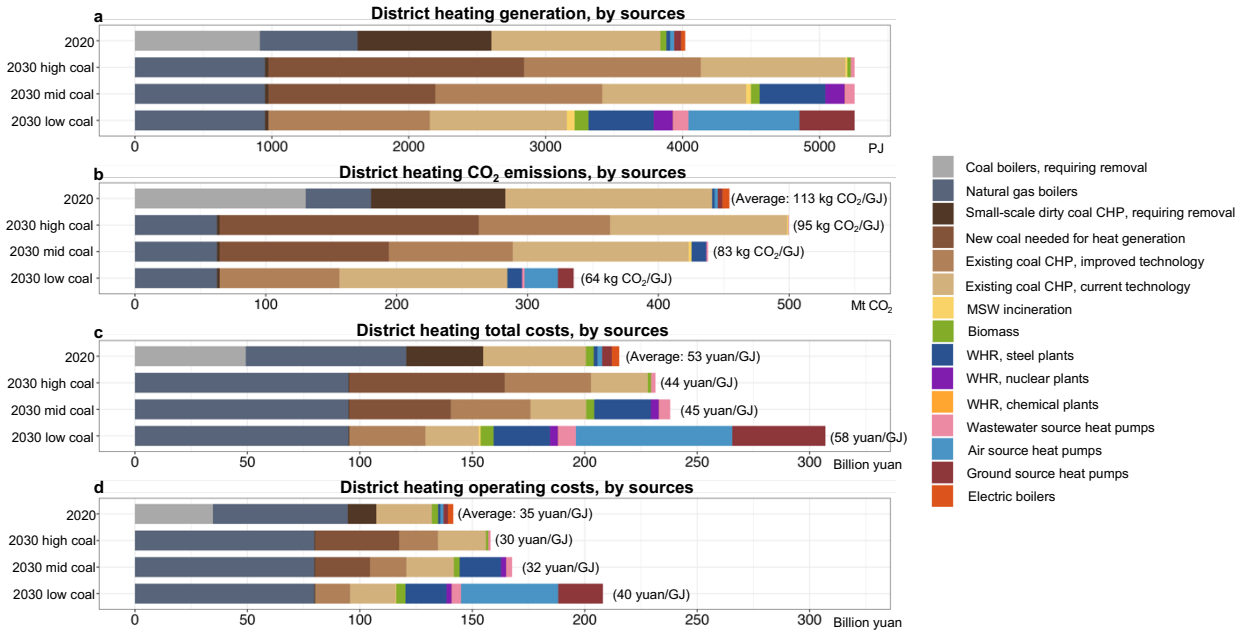


Figure 9. District heating generation, costs, and emissions, by sources, in 2020 and three scenarios projected for 2030. a, district heating generation. b, district heating CO_2 emissions. Average CO_2 emissions per unit heat are shown in parentheses. c, district heating total costs (annualized capital costs plus operating costs). Average heating costs per unit heat are shown in parentheses. d, district heating operating costs. Average operating costs per unit heat are shown in parentheses. Abbreviations: CHP, combined heat and power; MSW, municipal solid waste; WHR, waste heat recovery with electric heat pumps.

Total carbon emissions from district heating will increase slightly in the high-coal scenario but will decrease by 4% and 26% in the mid-coal and low-coal scenarios in 2030, respectively, compared to 2020 levels (**Figure 9**). Notably, the low-coal scenario reduces carbon emissions per unit heat by 43% between 2020 and 2030. This reduction results from the widespread deployment of low-carbon electric technologies and accelerated decarbonization of the power grid.

Total heating costs per unit heat will decrease from 2020 to 2030 in the high-coal and mid-coal scenarios because of the replacement of inefficient coal boilers with CHP plants, while heating costs will rise in the low coal scenario, mainly due to the significant capital and operating costs of

large electric heat pumps. For the low-coal scenario, we estimate that a total capital investment of ~1.1 trillion yuan (~$164 billion) between 2020 to 2030 is required to enable the implementation of low-carbon district heating technologies. To provide context, in 2022 alone, China invested nearly 4 trillion yuan (~$546 billion) on clean energy including solar, wind, electric vehicles, and batteries (BloombergNEF, 2023). In addition, we find that in the low-coal scenario operating costs per unit heat will increase by 12% in 2030 in the compared to 2020 levels (**Figure 9d**). In China's district heating market, operating costs are paid by households while upfront capital costs are largely the responsibility of heating companies and the local governments (National Energy Administration, 2017). Thus, the increase in household heating costs in the low-coal scenario are likely to be manageable, considering that household incomes are projected to rise by around 40% from 2020 to 2030 in China (Z. Wang et al., 2023).

The abatement costs of CO_2 emissions in 2030 between the high-coal to mid-coal scenarios will be ~80 yuan per ton CO_2, and from the high-coal to low-coal scenarios will be ~450 yuan per ton CO_2. These abatement costs are much lower than the social cost of carbon (i.e., the economic damages that would result from one additional ton of CO_2 emissions) currently estimated at ~1200 yuan per ton CO_2 (Rennert et al., 2022). Carbon prices in China's carbon emissions trading markets are ~60 yuan per ton CO_2 and are projected to increase to 150-300 yuan per ton CO_2 by 2030 (Refinitiv, 2021). The current and projected 2030 carbon prices are thus still insufficient to allow low-carbon technologies to effectively displace coal-based CHP technologies.

2.3 Carbon lock-in risks with new coal CHP investments

Building new and improved CHP plants, while leading to cost savings compared to a low-coal scenario, will result in an increase in carbon emissions from 2020 to 2030 in most northern Chinese

cities, making the achievement of China's 2030 carbon emissions peak target challenging. Moreover, new and improved CHP plants require substantial investments and are built to last for decades. Consequently, these facilities may lock in a reliance on coal and continue to generate emissions for decades, hindering the transition to alternative, low-carbon heating technologies and the achievement of China's 2060 carbon neutrality target.

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

We estimate that, if coal CHP capacity expands and operates in accordance with our high-coal scenario, existing and new CHP power plants will cumulatively lock in ~19,000 TWh coal-fired electricity and produce nearly 30 Gt emissions from 2020 to 2060, assuming historical operational parameters (i.e., CHP plant lifetime = 30 years, heat-to-power ratio = 1.5) (**Figure 10**). For comparison, GCAM-China, a widely used integrated assessment model, determines the maximum allowable Chinese coal-fired electricity generation from 2020 onward compatible with the 1.5° and well below 2°C targets are ~37,000 and ~63,000 TWh, respectively. Therefore, in the high-coal scenario, the locked-in coal-fired electricity generation from CHP plants during the heating season alone could represent ~50% of the 1.5°C budget and ~30% of the 2°C budget.

Adopting improved CHP technologies with higher district heat production efficiency and a higher heat-to-power ratio offers a reduction of ~4 Gt CO_2 emissions. Early retirement of CHP plants, for example, shortening the operational lifespan to 20 years, achieves another 4 Gt CO_2 emission reduction. However, early retirement may encounter significant challenges. The low operating costs of CHP plants pose difficulties in replacing them with non-fossil technologies. Early retirement leads to stranded assets and driving up levelized costs of heat, possibly leaving coal-asset owners unable to recover their initial investments.

The most effective way to reduce carbon lock-in is to avoid building new CHP plants. Committed CO_2 emissions drop to 19-23 Gt in the mid-coal scenario and only 10 Gt in the low-coal scenario. The reduction of locked-in coal-fired electricity generation also facilitates more integration of variable renewable energy, supporting the decarbonization of electric district heating technologies.

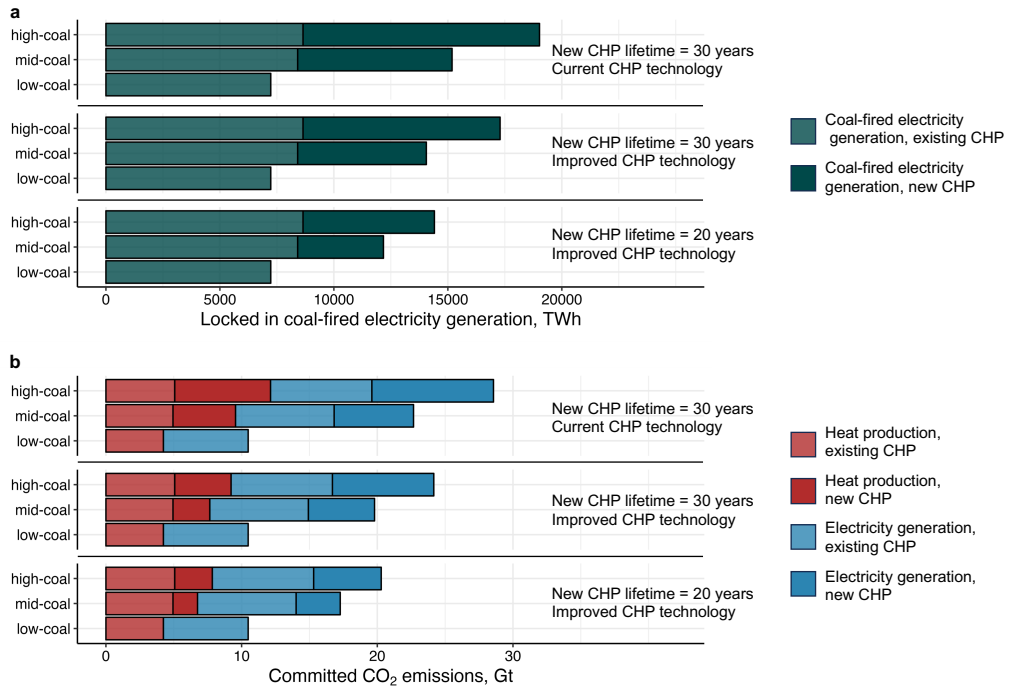


Figure 10. Locked-in coal-fired electricity generation and committed CO_2 emissions from existing and new CHP plants during the heating season in high/mid/low-coal scenarios from 2020 to 2060. a, locked-in coal-fired electricity generation. b, committed CO_2 emissions.

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

We compare these new coal CHP pipeline plants with the necessary new coal CHP capacity in 2030 in our high-, mid-, and low-coal scenarios (**Figure 11**). We estimate that 140-250 GW, 90-160 GW, and 0 additional GW of new coal CHP capacity is required to meet heating demand in the high-, mid-, and low-coal scenarios, respectively. The range of estimates reflects variations in assumptions regarding the capacity factors and heat-to-power ratios of new CHP plants (see Methods). Notably, new coal CHP capacity in the pipeline in provinces including Shanxi, Henan, Inner Mongolia, and Ningxia already surpasses the projected necessary residential district heating needs for 2030. Our results suggest that some of these new CHP plants can be replaced by improving the use of CHP resources from existing coal-fired power plants. Recovering waste heat from industrial facilities and adopting air/ground-source heat pumps can avoid the needs for new coal CHP construction while meeting district heating demand with significant lower emissions.

For newly commissioned CHP plants, adopting the improved CHP technology and planning for early retirement (or carbon capture retrofit) will be important to minimize future emissions.

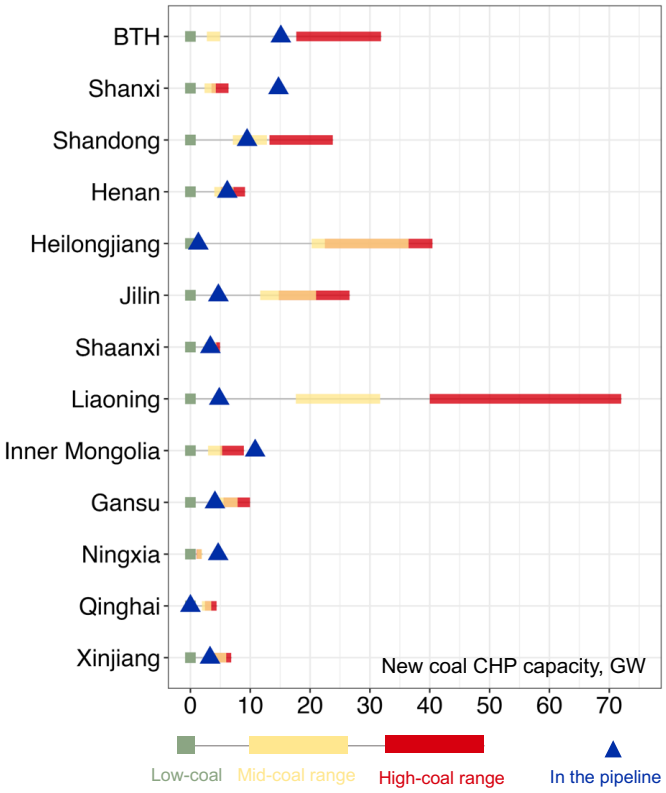


Figure 11. Required new coal CHP capacity in the low/mid/high coal scenarios by 2030 (bars) and new coal CHP capacity in the pipeline (triangles) as of Jun 2023 in northern China. The range of required new coal estimates reflects variations in assumptions regarding seasonal heating capacity factors and heat-to-power ratios of new CHP plants (low value: capacity factor = 0.6, heat-to-power ratio = 1.8; high value: capacity factor = 0.4, heat-to-power ratio = 1.5). No new coal CHP occurs under the low coal scenario. BTH: Beijing-Tianjin-Hebei region.

2.4 Strategies for a low-carbon district heating transition

Diversifying heat sources in China's urban district heating systems is crucial for reducing carbon lock-in. In light of this, we outline a city-level strategy to avoid new coal construction and meet the rising demand for district heating between 2020 and 2030 based on our findings from the low-coal scenario. Our strategy also aligns with the recent government proposal to promote the use of

non-fossil technologies in district heating. The strategy varies across cities primarily based on the availability of existing coal CHP resources and industrial waste heat. Therefore, we categorize the ~300 cities into three main groups according to their greatest heating resource availability: "Abundant CHP", "Abundant Industrial Waste Heat" and "Limited Heating Resources" (**Figure 12a**).

More than half of the cities fall under the "Abundant CHP" group. For these cities, improving the use of existing CHP resources to replace dirty coal technologies enables a gradual shift to lower-carbon technologies. We find that existing CHP plants and existing pipelines can only meet ~27% of the urban district heat demand in 2030 due to retirements of existing power plants and a reduction in capacity factors between 2020 and 2030 to facilitate power sector decarbonization (see Methods). However, with improvement measures, existing CHP resources can meet ~41% of the urban district heating demand in 2030. These improvement measures include converting existing electricity-only power plants into CHP plants (~50 power plants), installing large absorption heat pumps to enhance district heat production efficiency (~110 power plants), and constructing new heat transport pipelines (~110 new city-plant pipelines) (**Figure 12b**). These new pipelines are longer, typically ranging from 15-70 km, compared to most existing plant-city pipelines (<20 km). Total CO_2 emissions will not increase in most "Abundant CHP" cities from 2020 to 2030, despite an average 30% increase in district heating demand. Additionally, operating costs per unit heat in these cities will decrease by ~20% due to improved CHP technology boosting heat production efficiency.

The "Abundant Industrial Waste Heat" group of cities presents a promising opportunity for a swift transition to low-carbon heating technologies by 2030. These cities are predominantly located in

industry-heavy provinces, including Shandong, Shanxi, Hebei, and Liaoning. Maximizing the economic use of industrial waste heat requires retrofitting ~50 steel plants, two nuclear power plants, a few chemical plants, and constructing ~60 associated new plant-city pipelines by 2030 (**Figure 12b**). We estimate that integrating industrial waste heat into district heating will results in similar operating costs per heat unit to 2020 levels, which directly affect household heating expenses. However, a 22% increase in total heating costs (which is primarily subsidized by the government) for the "Abundant Industrial Waste Heat" group from 2020 to 2030 (**Figure 13**). Moreover, this integration will lead to a substantial ~50% reduction in CO_2 emissions relative to 2020 levels. This will greatly help these industrial cities meet the 2030 CO_2 emissions peak target.

The "Limited Heating Resources" group, with limited access to CHP resources and industrial waste heat, faces challenges in adopting low-carbon technologies by 2030. If new coal CHP construction is prohibited, extensive deployment of air/ground-source heat pumps is necessary by 2030 to meet heating demand. This deployment will significantly cut CO_2 emissions by ~65% compared to 2020 levels (**Figure 13**). However, it will also raise total and operating costs per unit heat by ~67% and ~24%, respectively. This cost increase is a significant challenge because these cities are largely located in economically disadvantaged regions with high existing household heating burdens (due to cold climates and low incomes), particularly in Heilongjiang, Jilin and Liaoning provinces (Z. Wang et al., 2023).

Another possibility, which we find to be both more costly with higher greenhouse gas emissions, is to expand the use of natural gas boilers and natural gas CHP plants as a bridge fuel to displace coal. In this case, district heating CO_2 emissions can be reduced by ~40% from 2020 to 2030, while total costs and operating costs per unit heat will both increase by nearly 50% in these

"Limited Heating Resources" cities. Therefore, compared with deploying air/ground-source heat pumps, using natural gas leads to smaller emissions reductions with higher operating costs. Natural gas CHP plants will also lock in CO_2 emissions from both district heat production and electricity production, similar to coal CHP that we have discussed. Moreover, our emission calculations do not include natural gas leakages. Previous studies show that natural gas may even have a similar carbon intensity to coal with a high leakage rate (Gordon et al., 2023). These results indicate that the adoption of air/ground-source heat pumps to replace coal technologies, instead of natural gas, on a large scale should be strongly preferred.

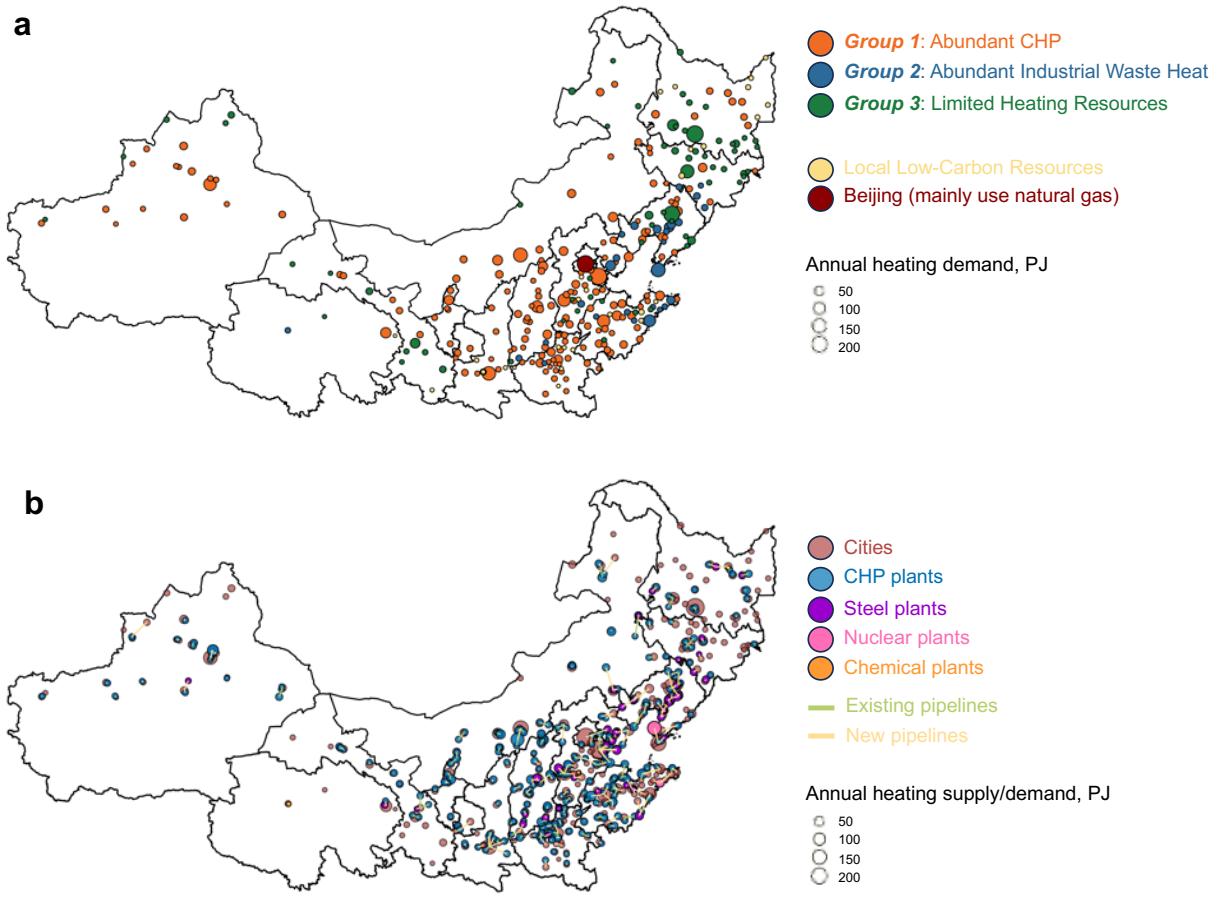


Figure 12. Geographic map of city groups and required infrastructure investments in the low-coal scenario. a, Geographic map of city groups in northern China. Cities are categorized into three groups according to their greatest heating resource availability: "Abundant CHP" (174 cities, representing 62% of total district heating demands in northern China), "Abundant Industrial Waste Heat" (28 cities, 12% of total) and "Limited Heating Resources" (67 cities, 20% of total). Additionally, 28 smaller cities (1% of total) can rely on local low-carbon heating sources (MSW, wastewater, biomass) due to their relatively modest heating demand. Beijing relies on natural gas for heating demand. b, cities, industrial facilities (CHP power plants, steel plants, nuclear plants, and chemical plants), existing and new city-plant heat transport pipelines in 2030 in the low-coal scenario.

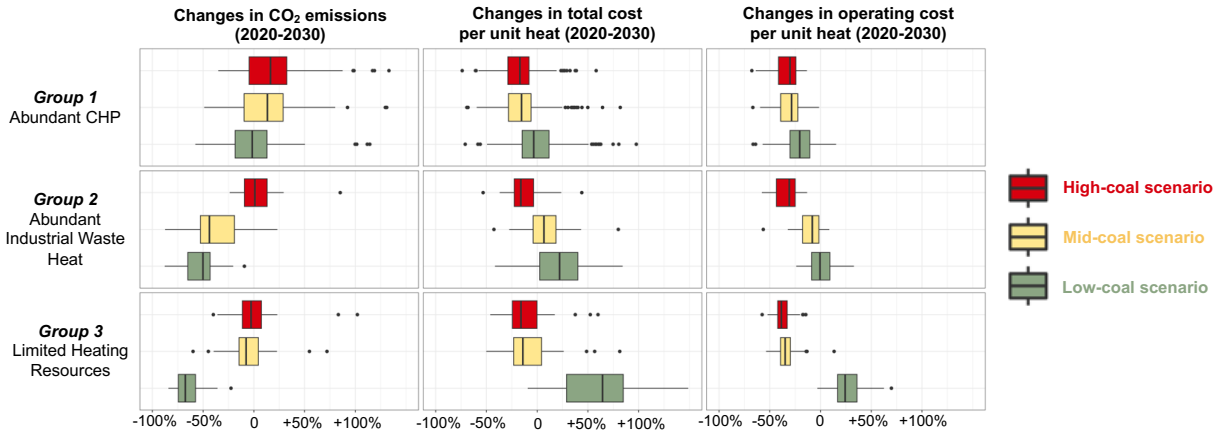


Figure 13. Changes in CO_2 emissions, total costs, and operating costs per unit heat from 2020 to 2030 in three groups of cities under the high/mid/low-coal scenarios. Box plots depict data distribution with central lines as medians, whiskers for data range, and dots as outliers.

3 Discussion

Our findings highlight the substantial impact of near-term investments in district heating systems on China's decarbonization trajectory. Scaling up improved coal CHP capacity to replace dirty coal technologies may unintentionally hinder China's domestic and global climate goals. In contrast, directing investments towards low-carbon heating technologies can yield "co-benefits" that simultaneously address air pollution and reduce carbon emissions.

We also highlight a crucial but often overlooked challenge in reducing coal power generation: the

reliance on coal-fired CHP facilities for district heating. While previous studies have explored ways to decrease coal power generation by ramping up renewables and storage (G. He et al., 2020; Y. Wang et al., 2023), few have addressed the decarbonization of CHP systems in the context of simultaneously meeting both heat and power demands. This is particularly important because relying on coal-fired CHP for district heating hinders decommissioning associated electricity generation.

Instead of using CHP, an alternative is to deploy low-carbon heat technologies, particularly better utilizing industrial waste heat and electrifying district heating using heat pumps while decarbonizing the power grid. In our low-coal scenario, electric technologies, including waste heat recovery with electric heat pumps and air/ground-source heat pumps, meets 37% of total district heating demand by 2030. This substantial electrification necessitates a significant expansion of clean power infrastructure, requiring an additional ~200 TWh of electricity generation during the heating season. To provide context, China is on the track to build an additional 700 GW of utility-scale wind and solar capacity by 2030 (Global Energy Monitor, 2023d, 2023b) and we estimate that these new sources will generation ~500 TWh of electricity during the heating season. Future research that examines strategies to meet electricity demand resulting from residential heating electrification is needed. Using fossil fuel for backup heating as well as improving demand-side energy efficiency can help mitigate grid challenges (Waite & Modi, 2020).

While this study primarily addresses the supply-side transition to low-carbon options, improving demand-side energy efficiency is also very important. Substantial potentials for energy efficiency improvements exist across northern China. Currently, ~20% of district heat production is lost due to overheating and network losses, and about 40% of urban residential buildings lack adequate

insulation (IEA, 2019a). Improving energy efficiency can lower energy consumption and peak loads, reducing the need for extensive infrastructure upgrades and associated costs and emissions (Buonocore et al., 2022). Moreover, improving energy efficiency enables more efficient use of electric heat pumps for district heating by lowering required water temperatures in heating networks (Levesque et al., 2023b). We estimate that, by increasing building energy efficiency by 30%, the coefficient of performance (COP, defined as the ratio of useful heat provided to electricity consumed) of large electric heat pumps could be increased by ~40%, facilitating the adoption of electric heat pumps (Levesque et al., 2021).

Our analysis only includes technical and engineering costs and does not account for the "soft costs" associated with political and social challenges (Gross & Hanna, 2019). Soft costs are often higher for emerging low-carbon technologies, as they lack an established market presence (IEA, 2019a). Future studies could investigate the social and political factors involved in low-carbon heating transitions. Government policies are necessary to enable the adoption of low-carbon alternatives to displace coal-based CHP technologies. This could involve implementing mandates such as renewable heating portfolio standards or mandatory building codes, as well as offering subsidies to low-carbon technologies and establishing government procurement policies.

4 Methods

4.1 Infrastructure database

We compile an infrastructure database of China's coal-fired power plants, steel plants, chemical plants, nuclear power plants and urban district heating systems, utilizing data sources including Global Coal Plant Tracker (Jun 2023) (Global Energy Monitor, 2023a), Global Steel Plant Tracker (March 2022) (Global Energy Monitor, 2023c), recent peer-reviewed literature (Y. Guo et al.,

2022), industry reports, and Chinese Urban Infrastructure Statistical Yearbooks (The Ministry of Housing and Urban-Rural Development, 2020) (see Figure S22). We do not consider the utilization of waste heat from cement plants because most of China's cement plants cease production during the heating season. This regulatory measure is implemented to mitigate air pollution in winter and tackle overcapacity issue in the cement sector. Our infrastructure database includes detailed information including capacities, status, technologies, locations, vintage years for ~1000 coal-fired power plants, ~170 steel plants, ~150 chemical plants, and 2 nuclear power plants ("Hongyanhe" in Liaoning and "Haiyang" in Shandong) in northern China.

This database also includes locations, district heating capacity, and district heating demand for ~300 cities (urban district heating systems) in 15 provinces in northern China, using data from 2020 Chinese Urban Infrastructure Statistical Yearbooks. China's district heating systems are predominantly located in the northern regions of the country, where the climate is colder and heating demand is higher. We determine the specific location of each city by first identifying the "urban grid cells" with a population density of >1000 persons/km^2 using a Chinese population gridded map (Y. Chen et al., 2020). We use the center points of these "urban grid cells" as the geographic coordinates (latitude and longitude) for each city. We estimate urban district heating demand for each city in 2030 based on projected future population (Y. Chen et al., 2020) and per capita district heating demand (S. Guo et al., 2022).

We also collect data on the amount of municipal solid waste (MSW) and wastewater treatment at the city level in 2020 from Chinese Urban Infrastructure Statistical Yearbooks (The Ministry of Housing and Urban-Rural Development, 2020). We use the biomass resource map developed by a previous study (R. Wang et al., 2023) to calculate the potential for district heating generation from

burning agricultural and forestry residues.

4.2 Carbon emissions calculation

We calculate carbon emissions using the specific emission factors for each district heating technology. The CHP extraction and CHP absorption heat pump systems operate using coal-produced hot steam, and their carbon intensity is determined by the steam's emission factors and heat production efficiency (see Figures S23-24 and Table S12 for details). CO_2 emission factors of combustion heating technologies, including coal boilers, natural gas boilers, MSW incineration, and biomass boilers are obtained from previous studies (R. Wang et al., 2022; M. Zhou et al., 2021). See Supplementary Note 3 and Tables S13-14 for details. For grid-based electric technologies, we estimate the carbon intensity of grid-based electricity in 2020 and 2030 using data from the IEA's stated policy and sustainable development scenarios, as well as China's provincial renewable portfolio goals (Table S15) (IEA, 2019b). See Supplementary Note 3 for details.

4.3 District heat production potential calculation

We estimate the plant-level district heat production potential (*DHPP*) for coal-fired power plants, steel plants, chemical plants, nuclear power plants. For coal-fired power plants, the CHP extraction technology and CHP absorption heat pump technology require extracting hot steam from the turbine, and the amount of steam that can be extracted is limited by the amount of electricity generated. For these two technologies, we calculate the district heat production potential by utilizing unit capacity (*C*), capacity factors (*CF*), local heating days (*HD*), and maximum heat-to-power ratios (*HtPR*) as outlined in equation (1) (Table S16). Unit-level maximum heat-to-power ratios are calculated based on unit capacity and cooling methods (Table S17) (W. Zheng et al.,

2020). The extraction-condensing method has a *HtPR* of 1.3-1.6, while the absorption heat pump method has a higher *HtPR* of ~1.8 due to waste heat recovery. We also use equation (1) to calculate district heat production potential for nuclear power plants. The maximum heat-to-power of nuclear power plants is 1.6 (J. Chen et al., 2021).

$$DHPP = C \times CF \times \frac{HD}{365} \times HtPR \qquad (4.1)$$

Electric compression heat pumps can also recover waste heat from coal-fired power plants, steel plants, and chemical plants. For coal-fired power plants, we estimate the amount of recoverable waste heat (*RWH*) in the condenser based on power generation and power cycle efficiency (η) using equation (2). The percentage of total energy input contained in the condenser is represented as α (Table S18). For steel and chemical plants, we estimate the amount of *RWH* based on plant-level production capacity, utilization factors, and waste heat generation per industrial product (Table S19). We then estimate district heat production potential using the coefficient of performance (*COP*) of the large electric heat pump technology (Y. Li et al., 2016), as outlined in equation (3).

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

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

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

4.4 Matching industrial plants with cities

Heat produced in industrial plants (including coal-fired power plants, steel plants, chemical plants, nuclear power plants) needs to be transported to cities through long-distance pipelines. We first pair existing coal-fired CHP plants with cities that are already connected by existing heat transport pipelines. We also propose possible construction of new heat transport pipelines from industrial plants to cities. These proposals are based on an optimization algorithm for the fixed charge transportation problem (FCTP) (Roberti et al., 2015), as described in equations (4)-(6).

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

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

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

The objective of this FCTP is to minimize the annual total costs, including a fixed cost (pipeline costs, $pc \cdot d_{ij} y_{ij}$) and two types of operating costs (fuel costs $fc \cdot x_{ij}$ and heat transport costs $tc \cdot d_{ij} x_{ij}$). Each industrial plant has a district heat production potential a_i and each city requires a certain quantity b_j of district heat from the industrial plants. x_{ij} and y_{ij} are decision variables in the optimization problem. x_{ij} represents the quantity of district heat sent from industrial plant *i* to city *j*. y_{ij} is a 0-1 variable that equals 1 if there is a heat transport pipeline from industrial plant *i* to city *j*. y_{ij} is set to 1 for existing linkages. d_{ij} is the distance between industrial plant *i* and city *j*, and l denotes the annual heat loss factor, in the unit of GJ/km. pc, fc and tc represent annualized pipeline unit costs (in the unit of yuan/km), operating unit costs (yuan/GJ), and heat transport unit costs (yuan/(km·GJ)), respectively (Table S20).

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

We exclude the consideration of interprovincial heat transport pipelines due to the significant political challenges involved, such as challenges in acquiring land and obtaining permits and approvals. We exclude the proposed pipelines that exceed 150 km in length due to high construction cost and heat loss during transport (L. Fu et al., 2021).

4.5 District heat cost calculation

We evaluate operating costs and annualized total costs per heat unit (annualized upfront capital costs plus operating costs per unit heat) of various district heating technologies. In China's district heating market, operating costs directly impact household heating costs, while upfront capital costs are more relevant to the financial burden of developers and local governments (National Energy Administration, 2017).

The annualized total costs per heat unit (ATC) of a district heating technology in year *t* can be calculated as equation (7):

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

where *I* denotes the initial investment costs and *AF* denotes the annuity factor. The discount rate is set at 7% in our analysis. OC_t denotes the operating costs (including fuel costs, operating and

maintenance costs, etc.) in year t. H_t represents the amount of heat delivered to the city (excluding heat loss if involving long-distance heat transport) in year t. Our estimates of emissions, availability, costs of various district heating technologies are generally consistent with previous literature (Ramaswami et al., 2017; Z. Wang et al., 2023; W. Zheng et al., 2020).

4.6 Power sector decarbonization scenarios

In a business-as-usual scenario, most existing large coal power plants in China, particularly CHP plants, are expected to continue operating at their current capacity factors during the heating season until the end of their lifespan (~30 years). However, to meet well below 2°C climate goals, a rapid reduction in coal use in power generation is necessary (Myllyvirta et al., 2022). Therefore, we design two power sector decarbonization scenarios to represent possible power sector decarbonization between 2020 and 2030: (1) a Business-as-usual (BAU) scenario, which assumes that coal power plants operate at their 2019 capacity factors until the end of their historical lifespan of 30 years. We assume that the share of non-fossil sources in China's total power generation will increase from ~35% in 2020 to ~45% in 2030, according to China's provincial renewable portfolio policies, and (2) an Accelerated Power Sector Decarbonization scenario, which represents an ambitious climate policy that the same power plants continue to operate but their capacity factors are reduced by ~18% from 2020 to 2030 to align with the well-below 2°C-consistent decarbonization pathway. This also aligns with current policies that require coal-fired power plants to become more flexible to integrate renewable energy sources. We assume that the share of non-fossil sources in China's total power generation will increase to ~67% in 2030 based on IEA's estimates.

We determine the maximum allowable Chinese coal-fired electricity generation from 2020 onward

compatible with the 1.5°C (modeled as a ~50% chance to reach the 1.5°C climate goal) and well below 2°C targets (modeled as a ~66% chance to reach the 2°C climate goal), using an integrated assessment model, GCAM-China (China-focused version of the Global Change Analysis Model). The simulated well below 2°C-consistent mitigation pathways show that China will achieve carbon neutrality by 2070 and that China's unabated conventional coal power generation will peak in 2020 and be phased out by 2055. While China's pledge to peak CO_2 emissions by 2030 and reach carbon neutrality by 2060 can be seen as compatible with the 2°C climate goal in the long run, its current coal power policies indicate that coal power generation will not peak until 2030 (National Energy Administration, 2023). This suggests insufficient climate efforts for China's coal power phasedown in the near term. Therefore, our 2°C-consistent coal power phasedown scenarios represent a more ambitious near-term climate effort. The details of these power sector decarbonization scenarios are described in a previous study (R. Cui et al., 2020).

4.7 Scenario design of near-term investment

We develop three district heating scenarios (high-coal, mid-coal, and low-coal) to represent various possible near-term investment in China's district heating systems between 2020 to 2030. We assume that existing dirty coal boilers and smaller coal CHP plants (constructed before 2016) must be replaced by 2030 to tackle air pollution, aligning with national and regional policies.

We assume the proportion of natural gas will remain similar from 2020 to 2030 as existing natural gas infrastructure is expected to continue being utilized in 2030 as China's natural gas consumption is likely to see a moderate increase in the near term. Utilizing natural gas boilers for backup heating can help address grid challenges arising from increased electrification in district heating (Waite & Modi, 2020).

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

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

For the remaining heating demand, new CHP plants are assumed to be constructed in the high- and mid-coal scenarios, and air/ground-source heat pumps are deployed in the low-coal scenario. In the latter case, the lowest-cost options from air- or ground-source heat pumps are chosen for each city. Because of the ongoing debate in China regarding the potential benefits of expanding the use of natural gas heating, we also design a supplementary low-coal-natural-gas-heating scenario. In this scenario, everything remains the same as the low-coal scenario, except for the use of efficient natural gas CHP plants, instead of air/ground-source heat pumps, to meet the remaining demand. Our findings show that opting for natural gas heating leads to less emission reduction and higher

heating costs when compared to air/ground-source heat pumps.

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

We find that the transition to low-carbon district heating will affect carbon emissions and costs differently across regions, mainly due to the availability of existing coal CHP resources and industrial waste heat. To illustrate this, we categorized ~300 cities with existing district heating systems based on their greatest heating resource availability. Cities where existing district heating resources (including existing coal CHP, industrial waste heat, MSW, wastewater, and biomass) cannot meet >50% of the 2030 heating demand are in the "Limited Heating Resources" group (67 cities, representing 20% of total district heating demands in northern China). The remaining cities are categorized by their main heating resource: "Abundant CHP" (174 cities, 62% of total demand), and "Abundant Industrial Waste Heat" (28 cities, 12% of total demand). Additionally, 28 smaller cities (1% of total demand) can rely on local low-carbon heating sources (MSW, wastewater, biomass) due to their relatively modest heating demand. Beijing mainly uses natural gas for heating.

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

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

where $H_{newCHP,p}$ represents the heating demand that must be met by new coal CHP in 2030 in the high/mid/low-coal scenarios. In the low-coal scenario, $H_{newCHP,p}$ is zero. HD_p is the number of heating days in each province. CF_{new} denotes the capacity factor for new CHP plants, which we assume to be 0.4-0.6 in our analysis (Z. Wang et al., 2023). $HtPR_{new}$ is the heat-to-power ratio for new CHP plants, which we assume to be between 1.5 (currently widely used extraction technology) and 1.8 (the state-of-the-art improved CHP technology) in our analysis (S. Yin et al., 2020).

4.8 Carbon lock-in associated with existing and new CHP plants

We estimate the locked-in coal-fired electricity (*LCE*) and committed district heat emissions (*E*) from existing and new CHP power plants from 2020 to 2060 in the high-, mid- and low-coal scenarios using equations (9) – (16). This calculation focuses solely on emissions associated with district heat generation thus excluding CHP plant emissions occurring during the non-heating season.

$$LCE = LCE_{existing,electricity} + LCE_{new,electricity} \quad (9)$$

$$E = E_{existing,heat} + E_{existing,electricity} + E_{new,heat} + E_{new,electricity} \quad (10)$$

$$E_{existing,heat} = \sum_i^N \sum_t^{T_i} x_{ij} \times CFR_i \times EF_{heat,i} \quad (11)$$

$$LCE_{existing,electricity} = \sum_i^N \sum_t^{T_i} x_{ij} \times CFR_i \times HtPR_i \quad (12)$$

$$E_{existing,electricity} = LCE_{existing,electricity} \times EF_{electricity,i} \quad (13)$$

$$E_{new,heat} = L_{new} \times H_{newCHP} \times EF_{heat,new} \quad (14)$$

$$LCE_{new,electricity} = L_{new} \times H_{newCHP} \times HtPR_{new} \quad (15)$$

$$E_{new,electricity} = LCE_{new,electricity} \times EF_{electricity,new} \quad (16)$$

where $LCE_{existing,electricity}$ and $LCE_{new,electricity}$ represent locked-in coal-fired electricity from existing and new CHP plants, while $E_{existing,heat}$, $E_{existing,electricity}$, $E_{new,heat}$ and $E_{new,electricity}$ represent committed emissions associated with district heat and electricity generation in existing and new CHP plants, respectively.

Locked-in coal-fired electricity and committed emissions from existing CHP plants are estimate at the plant level. CFR_i denotes the capacity reduction rate. In high/mid-coal scenario, CFR_i is set to 1, as we assume that all coal power plants will operate at their 2019 capacity factors until the end of their lifespan (~30 years). In the low-coal scenario, capacity factor reduction rates are calculated at the provincial level based on our well-below 2°C-consistent power sector decarbonization pathway (R. Cui et al., 2020). $HtPR_i$ is heat-to-power ratio of plant i, based on the district heat generation technology used in plant i. $EF_{heat,i}$ and $EF_{electricity,i}$ are emission factors of district heat generation and electricity generation of plant i, respectively.

Locked-in coal-fired electricity and committed emissions from new CHP plants are estimate based on the required district heating generation from new CHP plants. H_{newCHP} represents the heating demand that must be met by new coal CHP in 2030 in the high/mid/low-coal scenarios. In the low-

coal scenario, H_{newCHP} is zero. Previous studies found that future district heating demand is likely to increase from 2030 to 2060 in most Chinese cities due to urbanization and increased thermal comfort needs (Z. Wang et al., 2023). Therefore, the most important factors affecting committed emissions from new CHP plants are the lifetime (L_{new}) and CHP technology choices (current vs. improved). Improved CHP technologies have both lower district heat generation emission factors ($EF_{heat,new}$) and heat-to-power ratios ($HtPR_{new}$) compared to those of the current technology. $EF_{electricity,new}$ denotes emission factors of electricity generation from new CHP plants, obtained from a previous study (J. Li et al., 2020). We also estimate the impact of CHP plant lifetime, CHP technology choices and other factors on the levelized costs of heat for the new CHP plant.

Acknowledgements

Shangwei Liu thanks the following co-authors of this chapter: Yang Guo, Fabian Wagner, Hongxun Liu, Ryna Yiyun Cui, and Denise L. Mauzerall.

Reference:

BloombergNEF. (2023). Energy Transition Investment Trends 2023.

Buonocore, J. J., Salimifard, P., Magavi, Z., & Allen, J. G. (2022). Inefficient Building Electrification Will Require Massive Buildout of Renewable Energy and Seasonal Energy Storage. Scientific Reports, 12(1), 11931. https://doi.org/10.1038/s41598-022-15628-2

Chen, J., Zheng, W., Kong, Y., Yang, X., Liu, Z., & Xia, J. (2021). Case study on combined heat and water system for nuclear district heating in Jiaodong Peninsula. Energy, 218, 119546. https://doi.org/10.1016/j.energy.2020.119546

Chen, Y., Guo, F., Wang, J., Cai, W., Wang, C., & Wang, K. (2020). Provincial and gridded population projection for China under shared socioeconomic pathways from 2010 to 2100. Scientific Data, 7(1), 83. https://doi.org/10.1038/s41597-020-0421-y

China Energy News. (2020, November 9). Renewable Energy Heating Market Feels Chilled.

Cui, R., Hultman, N., Jiang, K., McJeon, H., Yu, S., Cui, D., Edwards, M., Sen, A., Song, K., & Bowman, C. (2020). A High Ambition Coal Phaseout in China: Feasible Strategies through a Comprehensive Plant-by-Plant Assessment. 37.

Fu, L., Li, Y., Wu, Y., Wang, X., & Jiang, Y. (2021). Low carbon district heating in China in 2025-a district heating mode with low grade waste heat as heat source. Energy, 230, 120765. https://doi.org/https://doi.org/10.1016/j.energy.2021.120765

Global Energy Monitor. (2023a). Global Coal Plant Tracker, Jun 2023 release. In Jan 2023 release.

Global Energy Monitor. (2023b). Global Solar Power Tracker, May 2023 release.

Global Energy Monitor. (2023c). Global Steel Plant Tracker, March 2022 (v2) release.

Global Energy Monitor. (2023d). Global Wind Power Tracker, May 2023 release.

Gordon, D., Reuland, F., Jacob, D. J., Worden, J. R., Shindell, D., & Dyson, M. (2023). Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates. Environmental Research Letters, 18(8), 084008. https://doi.org/10.1088/1748-9326/ace3db

Gross, R., & Hanna, R. (2019). Path dependency in provision of domestic heating. Nature Energy, 4(5), 358–364. https://doi.org/10.1038/s41560-019-0383-5

Guo, S., Jiang, Y., & Hu, S. (2022). The Pathways toward Carbon Peak and Carbon Neutrality in China's Building Sector. Chinese Journal of Urban and Environmental Studies, 10(02). https://doi.org/10.1142/S2345748122500117

Guo, Y., Mauzerall, D. L., Lyu, Y., Hu, W., Tian, J., & Chen, L. (2022). Benefits of infrastructure symbiosis between coal power and wastewater treatment. Nature Sustainability, 5(12), 1070–1079. https://doi.org/10.1038/s41893-022-00963-z

He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., & Phadke, A. (2020). Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. Nature Communications, 11(1), 1–9. https://doi.org/10.1038/s41467-020-16184-x

IEA. (2019a). District Energy Systems in China.

IEA. (2019b). World Energy Outlook 2019. https://doi.org/10.6027/9789289329996-1-en

IEA. (2023). Tracking Clean Energy Progress 2023. https://www.iea.org/reports/tracking-clean-energy-progress-2023

Levesque, A., Osorio, S., Herkel, S., & Pahle, M. (2023). Rethinking the role of efficiency for the decarbonization of buildings is essential. Joule, 7(6), 1087–1092. https://doi.org/10.1016/j.joule.2023.05.011

Levesque, A., Pietzcker, R. C., Baumstark, L., & Luderer, G. (2021). Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5°C scenario. Environmental Research Letters, 16(5), 054071. https://doi.org/10.1088/1748-9326/abdf07

Li, J., Wang, Y., Xu, D., & Xie, K. (2020). High-resolution analysis of life-cycle carbon emissions from China's coal-fired power industry: A provincial perspective. International Journal of Greenhouse Gas Control, 100, 103110. https://doi.org/10.1016/j.ijggc.2020.103110

Li, Y., Chang, S., Fu, L., & Zhang, S. (2016). A technology review on recovering waste heat from the condensers of large turbine units in China. Renewable and Sustainable Energy Reviews, 58, 287–296. https://doi.org/10.1016/j.rser.2015.12.059

Meng, W., Shen, H., Yun, X., Chen, Y., Zhong, Q., Zhang, W., Yu, X., Xu, H., Ren, Y., Shen, G., Ma, J., Liu, J., Cheng, H., Wang, X., Zhu, D., & Tao, S. (2020). Differentiated-Rate Clean Heating Strategy with Superior Environmental and Health Benefits in Northern China. Environmental Science and Technology, 54(21), 13458–13466. https://doi.org/10.1021/acs.est.0c04019

Myllyvirta, L., Zhang, X., & Dong, L. (2022). China's Climate Transition: Outlook 2022.

National Energy Administration. (2017). Drafting Guidelines for Opinions on Promoting Renewable Energy Heating.

National Energy Administration. (2023). Blue Book on New Power System Development. http://www.nea.gov.cn/2023-01/06/c_1310688702.htm

NDRC (National Development and Reform Commission of China). (2017). Clean winter heating planning for northern areas (2017–2021). http://www.gov.cn/xinwen/2017-12/20/content_5248855.htm

Nie, Y., Deng, M., Shan, M., & Yang, X. (2023). Clean and low-carbon heating in the building sector of China: 10-Year development review and policy implications. Energy Policy, 179, 113659. https://doi.org/10.1016/j.enpol.2023.113659

Ramaswami, A., Tong, K., Fang, A., Lal, R. M., Nagpure, A. S., Li, Y., Yu, H., Jiang, D., Russell, A. G., Shi, L., Chertow, M., Wang, Y., & Wang, S. (2017). Urban cross-sector actions for carbon mitigation with local health co-benefits in China. Nature Climate Change, 7(10), 736–742. https://doi.org/10.1038/nclimate3373

Refinitiv. (2021). China's national carbon market exceeds expectations. https://www.refinitiv.com/perspectives/future-of-investing-trading/chinas-national-carbon-market-exceeds-expectations/

Rennert, K., Errickson, F., Prest, B. C., Rennels, L., Newell, R. G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F. C., Müller, U. K., Plevin, R. J., Raftery, A. E., Ševčíková, H., Sheets, H., … Anthoff, D. (2022).

Comprehensive evidence implies a higher social cost of CO2. Nature, 610(7933), 687–692. https://doi.org/10.1038/s41586-022-05224-9

Roberti, R., Bartolini, E., & Mingozzi, A. (2015). The fixed charge transportation problem: An exact algorithm based on a new integer programming formulation. Management Science, 61(6), 1275–1291. https://doi.org/10.1287/mnsc.2014.1947

Shan, Y., Guan, Y., Hang, Y., Zheng, H., Li, Y., Guan, D., Li, J., Zhou, Y., Li, L., & Hubacek, K. (2022). City-level emission peak and drivers in China. Science Bulletin, 67(18), 1910–1920. https://doi.org/10.1016/j.scib.2022.08.024

The Ministry of Housing and Urban-Rural Development. (2020). Chinese Urban Infrastructure Statistical Yearbook 2020.

Waite, M., & Modi, V. (2020). Electricity Load Implications of Space Heating Decarbonization Pathways. Joule, 4(2), 376–394. https://doi.org/10.1016/j.joule.2019.11.011

Wang, R., Cai, W., Yu, L., Li, W., Zhu, L., Cao, B., Li, J., Shen, J., Zhang, S., Nie, Y., & Wang, C. (2023). A high spatial resolution dataset of China's biomass resource potential. Scientific Data, 10(1), 384. https://doi.org/10.1038/s41597-023-02227-7

Wang, R., Li, H., Cai, W., Cui, X., Zhang, S., Li, J., Weng, Y., Song, X., Cao, B., Zhu, L., Yu, L., Li, W., Huang, L., Qi, B., Ma, W., Bian, J., Zhang, J., Nie, Y., Fu, J., … Wang, C. (2022). Alternative Pathway to Phase Down Coal Power and Achieve Negative Emission in China. Environmental Science & Technology, 56(22), 16082–16093. https://doi.org/10.1021/acs.est.2c06004

Wang, Y., Wang, R., Tanaka, K., Ciais, P., Penuelas, J., Balkanski, Y., Sardans, J., Hauglustaine, D., Liu, W., Xing, X., Li, J., Xu, S., Xiong, Y., Yang, R., Cao, J., Chen, J., Wang, L., Tang, X., & Zhang, R. (2023). Accelerating the energy transition towards photovoltaic and wind in China. Nature, 619(7971), 761–767. https://doi.org/10.1038/s41586-023-06180-8

Wang, Z., Li, H., Zhang, B., Wang, B., Li, H., Tian, X., Lin, J., & Feng, W. (2023). Unequal residential heating burden caused by combined heat and power phase-out under climate goals. Nature Energy. https://doi.org/10.1038/s41560-023-01308-6

Werner, S. (2017). International review of district heating and cooling. Energy, 137, 617–631. https://doi.org/10.1016/j.energy.2017.04.045

Yin, S., Xia, J., & Jiang, Y. (2020). Characteristics analysis of the heat-to-power ratio from the supply and demand sides of cities in northern China. Energies, 13(1). https://doi.org/10.3390/en13010242

Zheng, W., Zhang, Y., Xia, J., & Jiang, Y. (2020). Cleaner heating in Northern China: potentials and regional balances. Resources, Conservation and Recycling, 160(April), 104897. https://doi.org/10.1016/j.resconrec.2020.104897

Zhou, M., Liu, H., Peng, L., Qin, Y., Chen, D., Zhang, L., & Mauzerall, D. L. (2021). Environmental benefits and household costs of clean heating options in northern China. Nature Sustainability. https://doi.org/10.1038/s41893-021-00837-w

Chapter 5 Conclusion

As the world's largest energy consumer and carbon emitter, China has pledged to peak CO_2 emissions before 2030 and achieve carbon neutrality by 2060. Previous studies suggest that China's commitment largely align with the Paris agreement's climate targets, but additional actions for immediate and substantial emission reductions are needed (Duan et al., 2021; Myllyvirta et al., 2022). Though specific decarbonization pathways are yet to be outlined, the Chinese government emphasizes a focus on "prioritizing energy conservation" and "seeking maximum benefits with minimal costs" in future climate actions.

My PhD thesis contribute on how China can cost-effectively and efficiently reduce energy consumption and carbon emissions in the building sector. My thesis assesses the carbon emissions and cost impacts of various household and district heating technologies, as well as building energy efficiency technologies. **My thesis concludes that several cost-effective opportunities exist to decarbonize China's building sector; however, to fully utilize these emission reduction opportunities, immediate policy interventions are necessary.**

Chapter 2 concludes that improving energy efficiency in inefficient rural Chinese homes can simultaneously reduce costs and emissions. The most suitable heating solution for most rural households is a heat pump combined with simple and moderate building envelope measures (such as air sealing, double-pane windows, and north wall insulation). Improving building envelope energy efficiency prior to installation facilitates the purchase of a smaller heat pump with lower capital costs and is critical to enable the penetration of heat pumps. Substituting current fuel subsidies (for natural gas and electricity) with retrofit and heat pump purchase subsidies can

effectively reduce costs and emissions at the same time.

Chapter 3 concludes that the benefits arising from energy system cost savings and carbon emission reductions are likely to offset or outweigh the additional technical costs associated with implementing nearly zero-energy building standards. However, the cost-effectiveness of building energy efficiency improvements is contingent on various factors, including building envelope costs, thermal comfort, and carbon prices. Accelerating the cost reduction of efficient building envelopes is key to promoting energy efficiency in the building sector.

Chapter 4 concludes that replacing dirty coal technologies with new CHP plants could lead to substantial carbon lock-in and hinder China's domestic and global climate goals. Using CHP for residential heating will lock in associated coal-fired electricity, thus hindering the decarbonization of the power sector. Shifting investments to expand the adoption of industrial waste heat and air/ground-source heat pumps can avoid the need for new CHP construction at moderately increased household heating costs.

These three chapters also evaluate the emissions and cost impact of various technologies and policies. I summarize my key findings in **Table 4** and **Table 5**.

Table 4. Summary table: emissions and costs impact and recommended strategies of various heating technologies and building energy efficiency technologies

Technology	Impact on carbon emissions	Impact on costs	Recommendation/comment
Household Heaters			
Dispersed Coal with Traditional Stoves (DCTS)	High carbon emissions	Low costs (higher than CCIS due to inefficiency)	Remove because DCTS are a significant source of indoor and outdoor air pollution and carbon emissions
Clean Coal with	High carbon emissions	Low costs	Best used as a short-term option to

Improved Stoves (CCIS)			replace DCTS in remote areas
Natural Gas Heaters (NGHs)	Higher emissions compared to ASHPs (2020 power mix), lower emissions than coal stoves and resistance heaters	30-100% higher than CCIS	May result in carbon lock-in if heavily investing in natural gas infrastructure
Resistance Heaters with Thermal Storage (RHwTS)	High carbon emissions unless powered by renewable electricity	High capital costs and moderate operating costs	Best only used with renewable electricity
Resistance Heaters without Thermal Storage (RHwoTS)	High carbon emissions unless powered by renewable electricity	Low capital costs and very high operating costs	Best only used as occasional heaters
Air Source Heat Pumps (ASHPs)	Low carbon emissions; avoid refrigerant leakages	Very high capital costs and low operating costs	Generally the best option for individual heating; can also be used for household cooling; consider improving building envelope efficiency first
District Heating Technology			
Coal Boilers	Very high carbon emissions	Low costs (higher than improved CHP due to inefficiency)	Remove because coal boilers are a significant source of indoor and outdoor air pollution and carbon emissions
Coal CHP	High carbon emissions	Low costs (higher than improved CHP due to inefficiency)	Best retrofit to adopt improved CHP generation technology
Improved Coal CHP	High carbon emissions; Similar to natural gas boilers	Low costs	New CHP plants pose a carbon lock-in risk
Natural Gas Boilers	High carbon emissions	High costs	Best used only as peak heaters during the coldest hours; May result in carbon lock-in if heavily investing in natural gas infrastructure
Industrial Waste Heat	Low emissions with decarbonized power grids	Slightly higher than coal technologies	Cost-effective solutions in industrial cities; Low-hanging fruit; Potentially meet 20-30% of total heating demand by 2030
Large Air/Ground-Source Heat Pumps	Low emissions with decarbonized power grids	High costs compared to coal technology; generally cheaper than natural gas technologies	Ramp up deployment to avoid new fossil fuel investments
Biomass, MSW, Wastewater	Low carbon emissions	Lower than natural gas and higher than coal technologies	Limited potential; Only meets a small fraction of heating needs
Building Envelope Measures			
Easy Envelope	~30% emission	Low costs;	Most cost-effective and easy way to

Improvement, Rural Homes	reduction	Payback time less than 10 years	reduce emissions; Low-hanging fruit
Large Envelope Improvement/Deep Retrofits, Rural Homes	~70% emission reduction	High capital costs	Use highly efficient envelopes if the need for thermal comfort is high (18~22°C)
Nearly Zero Energy Building Envelopes, Urban Buildings	~30% emission reduction when meeting nearly zero energy standards	High capital costs; Cost likely to decrease in the future	Consider for new construction, especially when costs decrease with more demonstrations

Table 5. Summary table: emissions and costs impact and recommendation of various clean heating and building decarbonization policies

Policy	**Impact on carbon emissions**	**Impact on costs**	**Recommendation/comment**
Fuel Subsidies	May increase emissions	Reduce household costs; Increase government burden	Replace fuel subsidies with heater/building envelope subsidies; Fuel subsidies compromise energy and emission goals
Heater Subsidies	Impact depends on heaters	Impact depends on heaters	Design subsidies to promote efficient heaters and provide sufficient support to low-income communities
Building Envelope Subsidies	Decrease emissions	Impact depends on building envelope types	Offer subsidies for rural households and accelerate easy energy retrofits in rural areas; Incentivize developers for nearly zero-energy buildings
Mandatory Building Codes in New Rural Construction	Decrease emissions	May increase costs; Payback in <10 years if thermal comfort is high	Introduce gradually; Focusing on regions with higher-income rural communities; Ensuring availability of low-cost energy-efficient materials
Renewable Heating Share Targets	Decrease emissions	May increase household costs	Establishing provincial-level renewable heating portfolio standards can facilitate the adoption of low-carbon technologies
Current Building Energy Standards (2018-2022)	Significant emission reduction	Likely cost-effective with energy system savings	Ensure strict enforcement
Nearly Zero Energy Building Standards	Substantial emission reduction	Cost-effective if building envelope costs decrease	Accelerate demonstrations to reduce costs; Implement early for high emission reductions

Based on the findings from these three chapters, I make the following suggestions for future research in assessing the impact of decarbonization technologies and policies:

Firstly, the choice of an appropriate baseline is a fundamental prerequisite for meaningful and informed assessments of technology impact. For example, previous studies often highlighted the short-term benefits of improving coal-based district heating systems but overlooked the long-term risks of carbon lock-in (Gingerich & Mauter, 2015; IEA, 2019a; Jimenez-Navarro et al., 2020; Ramaswami et al., 2017; K. Tong et al., 2017; W. Zheng et al., 2020). This is because they assessed coal technologies against a frozen baseline (i.e., neglecting to include the coal power phasedown necessitated by climate targets) and/or against dirty alternative heating technologies such as coal and natural gas boilers (i.e., neglecting emerging clean low-carbon heating technologies such as heat pumps).

Secondly, it is crucial to understand the costs and benefits of energy technologies from a holistic system perspective. Many studies focus solely on the "direct" costs and benefits of these technologies, overlooking their broader impact on the overall system (Levesque et al., 2023). For instance, a promising strategy to reduce emissions from buildings is electrifying end uses with renewable energy. However, building electrification necessitates substantial grid infrastructure expansion, presenting challenges to grid operations and planning (Buonocore et al., 2022). Consequently, understanding strategies to mitigate the pressure on the power grid caused by building electrification becomes essential. Similarly, managing building energy use is pivotal for achieving global climate goals, as it not only directly reduces emissions but also facilitates other emission mitigation strategies (Levesque et al., 2021). For instance, enhancing building energy efficiency can lower water temperatures needed in district heat networks, resulting in a more

efficient use of electric heat pumps for heating. Unfortunately, these systemic benefits have not been thoroughly investigated to date. Additionally, expanding energy supply infrastructure has upstream environmental consequences, including increased mining and manufacturing. Therefore, eliminating emissions at the electricity generation stage does not eliminate all environmental impacts of power generation. Thus, future research is needed to comprehensively understand the system impact of low-carbon energy technologies, facilitating a smoother energy transition.

Third, there is a need for better representation of demand-side technologies in large-scale energy models. Currently, most existing large-scale models, including integrated assessment models, energy system models, and decision-making models, provide relatively detailed representations of supply-side solutions. However, demand-side approaches are often simply treated as fixed inputs (Loulou et al., 2016; Stehfest et al., 2014). In other words, few models account for the interactions and synergies between supply-side solutions and demand-side approaches. Consequently, these models may not capture the benefits of demand-side approaches that were discussed earlier, likely resulting in an underestimation of their advantages. Future research is required to enhance the representation of demand-side approaches in these models.

Reference:

Buonocore, J. J., Salimifard, P., Magavi, Z., & Allen, J. G. (2022). Inefficient Building Electrification Will Require Massive Buildout of Renewable Energy and Seasonal Energy Storage. Scientific Reports, 12(1), 11931. https://doi.org/10.1038/s41598-022-15628-2

Duan, H., Zhou, S., Jiang, K., Bertram, C., Harmsen, M., Kriegler, E., van Vuuren, D. P., Wang, S., Fujimori, S., Tavoni, M., Ming, X., Keramidas, K., Iyer, G., & Edmonds, J. (2021). Assessing China's efforts to pursue the 1.5°C warming limit. Science, 372(6540), 378–385. https://doi.org/10.1126/science.aba8767

Gingerich, D. B., & Mauter, M. S. (2015). Quantity, Quality, and Availability of Waste Heat from United States Thermal Power Generation. Environmental Science and Technology, 49(14), 8297–8306. https://doi.org/10.1021/es5060989

IEA. (2019). District Energy Systems in China.

Jimenez-Navarro, J. P., Kavvadias, K., Filippidou, F., Pavičević, M., & Quoilin, S. (2020). Coupling the heating and power sectors: The role of centralised combined heat and power plants and district heat in a European decarbonised power system. Applied Energy, 270. https://doi.org/10.1016/j.apenergy.2020.115134

Levesque, A., Pietzcker, R. C., Baumstark, L., & Luderer, G. (2021). Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5°C scenario. Environmental Research Letters, 16(5), 054071. https://doi.org/10.1088/1748-9326/abdf07

Loulou, R., Goldstein, G., Kanudia, A., Lettila, A., Remme, U., & Noble, K. (2016). Documentation for the TIMES Model PART I - Concepts and Theory. July, 151. https://iea-etsap.org/index.php/etsap-tools/model-generators/times

Myllyvirta, L., Zhang, X., & Dong, L. (2022). China's Climate Transition: Outlook 2022.

Ramaswami, A., Tong, K., Fang, A., Lal, R. M., Nagpure, A. S., Li, Y., Yu, H., Jiang, D., Russell, A. G., Shi, L., Chertow, M., Wang, Y., & Wang, S. (2017). Urban cross-sector actions for carbon mitigation with local health co-benefits in China. Nature Climate Change, 7(10), 736–742. https://doi.org/10.1038/nclimate3373

Stehfest, E., van Vuuren, D., Bouwman, L., & Kram, T. (2014). Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications. Netherlands Environmental Assessment Agency (PBL).

Tong, K., Fang, A., Yu, H., Li, Y., Shi, L., Wang, Y., Wang, S., & Ramaswami, A. (2017). Estimating the potential for industrial waste heat reutilization in urban district energy systems: Method development and implementation in two Chinese provinces. Environmental Research Letters, 12(12). https://doi.org/10.1088/1748-9326/aa8a17

Zheng, W., Zhang, Y., Xia, J., & Jiang, Y. (2020). Cleaner heating in Northern China: potentials and regional balances. Resources, Conservation and Recycling, 160(April), 104897. https://doi.org/10.1016/j.resconrec.2020.104897

Appendix for Chapter 2

Supplementary Note 1: Extended Methods

Heater costs and fuel prices

We consider four clean heaters widely adopted in northern rural China: natural gas heaters (NGH), electric resistance heaters (RH) with storage (RH*w*TS) and without storage (RH*wo*TS), and air-to-air heat pumps (AAHP). NGH use thermal energy from natural gas combustion with an efficiency of ~85%, while electric resistance heaters convert nearly all the incoming electric energy into heat. RH*w*TS have higher investment costs than RH*wo*TS, but RH*w*TS take advantage of the time-of-use electricity pricing and store thermal energy during off-peak hours at night when electricity rates are low. Therefore, RH*w*TS have lower operating costs than RH*wo*TS. AAHP have the highest upfront capital costs among all clean heaters. AAHP use electricity to operate a motor to move thermal energy from outdoor air into heated space. The efficiency of a heat pump is often expressed as the coefficient of performance (COP, defined as the ratio of useful heat provided to electricity consumed). The COP of a heat pump depends on the ambient temperature, and the higher the ambient temperature, the higher the COP will be for heating (M. Zhou et al., 2021). AAHP typically have a COP of 2.5-4, so AAHP have lower operating costs than other clean heaters except when electricity prices are high and natural gas prices are low.

We also include two coal heating technologies for comparison: dispersed coal with traditional stoves (DCTS) and clean coal briquettes with improved stoves (CCIS). Compared to DCTS, CCIS significantly reduces air pollutant and CO_2 emissions, and has lower costs because of the improved combustion efficiency (H. Liu & Mauzerall, 2020; M. Zhou et al., 2021); therefore, improved stoves have been promoted by many local governments since 2013 and were the most widely

adopted heater before the clean heating policy interventions (Peng et al., 2019). We do not consider the scenarios of a combination of coal stoves and improved building envelopes because improving airtightness may unintentionally deteriorate indoor air quality and increase the risk of dangerous carbon monoxide and fine particulate accumulation from coal burning.

We collect heater costs and fuel prices with and without subsidies from the literature, government documents, and conversations with heating device suppliers, rural residents, and gas/electricity distribution companies, as described in greater detail in Liu and Mauzerall (2020) and Zhou et al. (2021) (H. Liu & Mauzerall, 2020; M. Zhou et al., 2021). Capital costs of heaters depend on the required power capacity (kW) of each heater per household. We calculate household peak heating loads to keep indoor temperatures at 14 °C during the heating season using EnergyPlus to estimate the required sizes of various heaters.

Operating heating burden, payback periods, TACs and UCCs

The operating heating burden ($OHB_{c,f,d,e}$) of operating heater h using fuel f with envelope e in city c can be calculated as Eq. (S1)

$$OHB_{c,f,h,e} = AOC_{c,f,h,e}/HI_c \quad \text{(S1)}$$

where HI_c is the household income during the heating season in city c. Household incomes are calculated based on per capita disposable income in rural areas in each city in 2020 and rural household sizes, obtained from provincial statistical yearbooks.

For existing buildings, we calculate payback periods for increasing building envelope efficiency. Payback periods measure how long it takes for cumulative discounted savings to offset the initial

investment. We include two types of savings from improving building envelope efficiency: savings from reduced capital costs of clean heaters (one-time savings) and savings from reduced annual operating costs (annual net cash flow). Therefore, the discounted payback period ($PP_{h,e}$) for improving building envelope from baseline envelope (denoted as *0*) to improved building envelope e for households using fuel f and heater h in city c can be calculated as Eq. (S2) -(S4):

$$PP_{h,e} = \ln\left(\frac{1}{1-\frac{(BEC_e - SHC_{h,c,e})\times r}{SAOC_{c,f,h,e}}}\right) \div \ln(1+r) \quad \text{(S2)}$$

$$SHC_{h,c,e} = HC_{h,c,0} - HC_{h,c,e} \quad \text{(S3)}$$

$$SAOC_{c,f,h,e} = AOC_{c,f,h,0} - AOC_{c,f,h,e} \quad \text{(S4)}$$

where e denotes various improved building envelopes (i.e., easy, moderate, and large improvements) and h denotes various heaters. BEC_e denotes the upfront capital cost of improved building envelope e. $SHC_{h,c,e}$ is the savings from reduced capital costs of clean heaters, which is the difference between capital costs of heaters with the baseline envelope ($HC_{h,c,0}$) and costs with improved envelopes ($HC_{h,c,e}$). Similarly, $SAOC_{c,f,h,e}$ is the savings from reduced operating costs, which is the difference between operating costs of heaters with the baseline envelope ($AOC_{c,f,h,0}$) and costs with improved envelopes ($AOC_{c,f,h,e}$). r denotes the discount rate, which is 5% in our analysis. For existing buildings with clean heaters, the capital costs of clean heaters are sunk costs, so savings from reduced capital costs of clean heaters ($SHC_{h,c,e}$) is zero.

For new buildings, rural households must purchase clean heaters and decide the efficiency of their

building envelopes during the construction process. We calculate total annualized costs ($TAC_{c,f,h,e}$, annualized upfront capital costs plus annual operating costs) and upfront capital costs ($UCC_{c,f,h,e}$) of space heating using heater h using fuel f with envelope e in city c. We do not consider subsidies here. $TAC_{c,f,h,e}$and $UCC_{c,h,e}$ are calculated as Eq. (S5) -(S7):

$$TAC_{c,f,h,e} = ACC_{c,h,e} + AOC_{c,f,h,e} \quad \text{(S5)}$$

$$ACC_{c,h,e} = \frac{BEC_e}{(1+\frac{1}{1+r}+\cdots+\frac{1}{(1+r)^{n_e-1}})} + \frac{HC_{h,c,e}}{(1+\frac{1}{1+r}+\cdots+\frac{1}{(1+r)^{n_h-1}})} \quad \text{(S6)}$$

$$UCC_{c,h,e} = BEC_e + HC_{h,c,e} \quad \text{(S7)}$$

where $ACC_{c,h,e}$ denotes annualized capital costs and $AOC_{c,f,h,e}$ denotes annual operating costs.BEC_e denotes the capital cost of improved building envelope e for new constructions and $HC_{h,c,e}$ denotes capital costs of various heaters. r is the discounting rate (5%). n_e and n_h are lifetimes of the building envelop materials and heaters, respectively. We do not consider salvage values of heaters and envelopes due to their low present values (H. Liu & Mauzerall, 2020; M. Zhou et al., 2021).

Household heating related CO_2e emission calculations

Household heating related annual CO_2e emissions ($HAE_{c,f,h,e}$) using fuel f and heater h with envelope e in city c can be calculated using Eq. (S8) -(S10):

$$HAE_{c,f,h,e} = AEC_{c,f,h,e} \times EF_f + LR_{c,h=AAHP,e} + BE_e \quad \text{(S8)}$$

$$EF_{f=eletricity} = S_{coal} \times EF_{coal} + S_{gas} \times EF_{gas} + S_{non} \times 0 \quad \text{(S9)}$$

$$LR_{c,h=ASHP,e} = \frac{EC \times PC_{c,h=AAHP,e}}{n_{h=AAHP}} \quad \text{(S10)}$$

Where EF_f is the CO_2e emission factor of fuel *f*, including both on-site and upstream emissions (from fuel/electricity production, processing, transmission, and distribution, including natural gas leakages), as described in greater detail in Zhou et al. (2021) and Qin et al. (2018) (Qin et al., 2018; M. Zhou et al., 2021). CO_2e emission factors for electricity ($EF_{f=eletricity}$) depend on shares of coal (S_{coal}), natural gas (S_{gas}) and non-fossil fuel (S_{non}) in the power mix. In 2020, ~61% of electricity in China came from coal, ~3% from natural gas, and the remaining ~ 36% from non-fossil sources. EF_{coal} and EF_{gas} are CO_2e emission factors of coal and natural gas power generation, respectively. $LR_{c,h=AAHP,e}$is annual GHG emissions from the leakage of refrigerants in AAHP; EC is the GHG emission intensity (750 kg CO_2e per kW of installed AAHP power capacity under GWP_{100}) from the leakage of refrigerant liquids over the entire life span (Knobloch et al., 2020); $PC_{c,h=AAHP,e}$is the required power capacity of AAHP in city c with building envelope e; $n_{h=AAHP}$ is the life span of AAHP, which is assumed to be 15 years. When calculating CO_2e under GWP_{20}, we assume R134a is used as a refrigerant for heat pumps. R134a has a GWP_{20} of ~4144 and GWP_{100} of ~1526.

We also estimate embodied CO_2e emissions (denoted as BE_e) from the production of additional efficient building envelope materials (i.e., efficient windows, insulation layers). Those embodied CO_2e emissions depend on insulation material choices, insulation levels and production. Due to data deficiency, we use the average emission factors of building material production from the literature (Asdrubali et al., 2021; Grazieschi et al., 2021): for double-glazed windows with PVC

frames, the carbon intensity is ~68.4 kg CO_2e per m^2; for EPS insulation layers, the carbon intensity is ~4.65 kg CO_2e per kg EPS.

Clean heating policy scenarios from 2020 to 2030

We estimate CO_2e emission, total annualized costs (TACs), and upfront capital costs (UCCs) in 2030 under various policy scenarios in the "2+26" cities plus the Fen-Wei Plain region of northern. We design six policy scenarios (one current policy scenario plus five potential future policy scenarios) to represent plausible near-term climate actions from 2020 to 2030. We assume the Chinese rural residential building stock will be stable with a ~3.5% annual "turnover" rate from 2020 to 2030 (a continuation of the historical trend since 2000) (Tsinghua BERC, 2018).

Our current policy scenario (P_0 scenario) is designed based on China's action plan to peak carbon emissions by 2030 (State Council, 2021). The plan proposed a "no coal-zone" policy which aims to gradually reduce and eventually prohibit burning of coal. We therefore assume that, outside of Beijing, all coal stoves (including CCIS) in the "2+26" cities plus the Fen-Wei Plain region of northern China will be replaced by NGH and RH (particularly RH*w*TS) by 2030. We assume that very few households will install AAHP by 2030 because of high upfront costs. For Beijing where the local government provides generous subsidies, we assume ~50% of rural households will install AAHP (Natural Resources Defense Council, 2018). We also assume that the non-fossil share in the power mix will reach 43% by 2030, consistent with the IEA's stated policies scenario(International Energy Agency, 2020).We also present another power sector decarbonization scenario, in which the non-fossil share in the power mix will reach 59% by 2030, consistent with the IEA's sustainable development scenario. In terms of building energy efficiency, we assume that all new construction from 2020 to 2030 will adopt the "easy envelope

improvement", and ~0.15% of total existing residential buildings will be retrofitted with the "moderate envelope improvement" each year, as indicated by the Clean Winter Heating Plan(NDRC (National Development and Reform Commission of China), 2017).

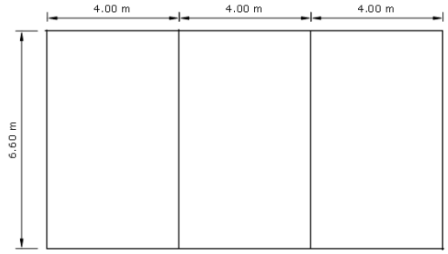
Our analysis indicates that current policies can be strengthened by (1) accelerating heat pump adoption and (2) increasing residential building envelope energy efficiency. Therefore, we design five policy scenarios to represent possible enhanced climate actions by 2030 (P_1-P_5 scenarios).

Heat pump deployment scenario (P_1 scenario) assumes that 50% of rural homes will install AAHP by 2030, consistent with the clean policy scenario in Ma et al. (2021)(Ma et al., 2021). Easy building envelope efficiency scenario (P_2 scenario) assumes that all existing and new buildings implement easy improvement retrofits by 2030. High building envelope efficiency scenario (P_3 scenario) assumes that all existing implement moderate improvement retrofits and all new constructions adopt large improvements in building envelopes between 2020 and 2030.

The other two scenarios are combined policy scenarios: P_4 scenario is a combination of heat pump deployment (P_1) and easy building envelope efficiency improvements (P_2), and P_5 scenario is a combination of heat pump deployment (P_1) and easy building envelope efficiency improvements (P_3). The emission mitigation potential of the combined policy scenarios will not be equivalent to the sum of potentials from individual policy scenarios. This is because clean heating actions are partly complementary; for example, with efficient AAHP, improving building envelope efficiency will become less effective.

Supplementary tables and figures

Table S1 Building prototypes and surface materials of the Chinese rural residential baseline building.

Building prototypes		
Building layout		Building characteristics
		Shape coefficient: 0.80 Heated area: 80 m^2 Window-to-wall ratio (WWR): 0.24 (south wall), 0.09 (north wall)
Building surfaces		
Building surface	Building surface materials	U-value (W/m^2K)
Exterior walls	330 mm solid clay brick wall	1.7
Exterior door	Door without insulation	4.5
Exterior windows	Single-glazed	5.8
Roof	Plaster concrete	2.2

Notes: We design the baseline building to represent a typical rural house in northern China based on Shan et al. (2020) (M. Shan et al., 2020). The baseline building is a detached single-story house, consisting of one living room and two bedrooms with a total heating floor area of ~80 m^2. We did not include non-heated rooms in our simulation, e.g., restrooms, storage rooms, etc. Chinese rural residential buildings often have an area of 100-200 m^2, with ~60% of total area heated in winter (Building Energy Research Center of Tsinghua University, 2012).

Shape coefficient (SC) is an important factor affecting building energy use. SC is the ratio between the external envelope area of a building and its inclusive volume. Smaller SC means less heat loss via building envelopes and resulting less energy consumption. Chinese rural residential buildings often have very high SCs, ~0.8 (Building Energy Research Center of Tsinghua University, 2012; Y. Cui et al., 2020).

We choose building surface materials for the baseline building based on the previous literature (Building Energy Research Center of Tsinghua University, 2012; Y. Cui et al., 2020; Fan & Zhao, 2019; M. Fu et al., 2019; B. Li et al., 2020; J. Liu, 2019; X. Meng et al., 2015; Rui et al., 2019; M. Shan et al., 2020; Xu et al., 2020; Y. Zheng, 2020b). Exterior walls are usually made of solid bricks. The depth of exterior walls in the studied region varies from 240 mm~370 mm (Building Energy Research Center of Tsinghua University, 2012), and U-values of walls used in previous studies vary from 1.0 to 2.0. Roofs are often made of plaster concrete or tile bricks, and U-values of roofs used in previous studies vary from 1.5 to 4.0. Windows are often made with a single layer of glass and wooden/aluminum frames. U-values of windows and doors often vary from 4.7 to 6.8.

Previous surveys reported that only very limited rural residential buildings installed insulation, while more households adopted insulation in recent years. A survey conducted in 2007 showed that only 2.3% rural households installed insulation during that time (Building Energy Research Center of Tsinghua University, 2012). The government Clean Winter Heating Plan reported that ~20% rural buildings adopted some level of insulations in 2016 (NDRC (National Development and Reform Commission of China), 2017).

Table S2 Sensitivity analyses to explore the impacts of air changes per hour (ACH) on annual heating energy consumption in the rural baseline building at 14°C and 18°C outdoor temperatures.

ACH (h^{-1})	Increase in annual heating energy use (%) compared to ACH=0.5 h^{-1} (14 °C)	Increase in annual heating energy use (%) compared to ACH=0.5 h^{-1} (18 °C)
1	~33%	~23%
2	~98%	~69%
3	~163%	~114%
4	~228%	~160%
5	~293%	~208%

Notes: Air changes per hour (abbreviated ACH) in the baseline building is assumed to be 1.0 h^{-1} based on the literature (M. Shan et al., 2015; Tsinghua BERC, 2018). The recommended ACH rate from the Chinese rural building energy efficiency standard is 0.5 h^{-1}, but ACH rates in rural houses are commonly larger than 1 h^{-1} and can be ~5 h^{-1} with windows closed in winter because of poor building airtightness (Jian & Zhu, 2010; M. Shan et al., 2015; Tsinghua BERC, 2018).

We run EnergyPlus to calculate annual heating loads for each ACH rate to maintain the indoor temperature at 14/18 °C during the heating season. To reduce the computing time, here we use the average annual energy use in Beijing, Tianjin, Taiyuan, Zhengzhou, Jinan, Shijiazhuang, and Xi'an.

Table S3 Unsubsidized Market Prices of various heaters in 2020.

Devices	Types and prices
Air-to-air heat pump (AAHP)	~5,500 RMB for a 1.5 horsepower AAHP ~6,000 RMB for a 2.0 horsepower AAHP
Resistance heaters with thermal storage (RH*w*TS)	~2,400 RMB for a 1.6 kW RH*w*TS ~2,900 RMB for a 2.4 kW RH*w*TS ~3,800 RMB for a 3.2 kW RH*w*TS
Resistance heaters without thermal storage (RH*wo*TS)	~1,050 RMB for a ~4.1 kW RH*wo*TS ~1,400 RMB for a ~5.5 kW RH*wo*TS
Natural gas heaters (NGH)	~3,000 RMB for a ~4.8 kW NGH ~3,200 RMB for a ~6.4 kW NGH
Improved coal stoves (CCIS)	~1,400 RMB for a rural house.

Notes: Prices and installation fees for heating devices are collected from our conversations with residents in northern China and market suppliers, as described in greater detail in Liu and Mauzerall (2020) and Zhou et al. (2021) (H. Liu & Mauzerall, 2020; M. Zhou et al., 2021). We calculate household peak heating loads to keep indoor temperatures at 14/18 °C during the heating season using EnergyPlus to estimate the required sizes (power capacity, kW) of various heaters. As the sizes of the devices are not continuous, we use linear interpolation to estimate the households' upfront capital costs. For example, we estimate the cost for a household requiring a 3kW RH*w*TS by interpolating between the cost of a 2.4kW and 3.2kW RH*w*TS:

$Cost(3) = Cost(2.4) + (3 - 2.4) \times \frac{\times(Cost(3.2) - Cost(2.4))}{(3.2 - 2.4)}$.

Table S4 Thermal efficiencies, lifetimes of heaters, heating values and emission factors of fuels

Heater type	Thermal efficiencies	Lifetime (years)	Fuel type	Heating values	CO_2e emission factors
Traditional coal stove	35% (Q. Li et al., 2016; Y. Liu, Zhang, et al., 2018b; Shen, 2016)	10 (M. Zhou et al., 2021)	Dispersed coal	20.9 MJ/kg	Upstream: 19 CO_2e g/MJ (GWP_{100}); 43 CO_2e g/MJ (GWP_{20}); Downstream: 2.66 kg CO_2e/kg (Qin et al., 2018; M. Zhou et al., 2021)
Improved coal stove	71% (Q. Li et al., 2016; Y. Liu, Zhang, et al., 2018b; Qin et al., 2017)	10 (M. Zhou et al., 2021)	Clean coal briquettes	28.4 MJ/kg	Upstream: 19 CO_2e g/MJ (GWP_{100}); 43 CO_2e g/MJ (GWP_{20}); Downstream: 3.091 kg CO_2e/kg (Qin et al., 2018; M. Zhou et al., 2021)
Natural gas heater (NGH)	85% (Qin et al., 2017)	8 (M. Zhou et al., 2021)	Natural gas	34 MJ/m^3	Upstream: CO_2e g/MJ (GWP_{100}); 43 CO_2e g/MJ (GWP_{20}) Downstream: 55.80 g CO_2e/MJ^2 (Qin et al., 2018; M. Zhou et al., 2021)
Resistance heater with thermal storage (RH*w*TS)	99% (Q. Zhang, Zhang, et al., 2017)	15 (M. Zhou et al., 2021)	Electricity (upstream)	3.6 MJ/kWh	2020 Grid (67% fossil) 0.593 kg CO_2e /kWh (Qin et al., 2018; M. Zhou et al., 2021)
Resistance heater with thermal storage (RH*wo*TS)	99% (Q. Zhang, Zhang, et al., 2017)	10 (M. Zhou et al., 2021)			2030 Stated Policy (57% fossil) 0.503 kg CO_2e /kWh (Qin et al., 2018; M. Zhou et al., 2021)
Air-to-air heat pump (AAHP)	0.07*ambient temperature (℃) +2.69 (X. Yang, 2018)	15 (M. Zhou et al., 2021)			2030 Sustainable Development (41% fossil) 0.350 kg CO_2e /kWh (Qin et al., 2018; M. Zhou et al., 2021)

Notes: We adopt the Stated Policy Scenario and Sustainable Development Scenario in the World Energy Outlook 2020 for the 2030 power mix projection (International Energy Agency, 2020). "Downstream" means on-site coal and natural gas burning and "upstream" represents fuel/electricity production, processing, transmission, distribution, and natural gas leakages, as described in greater detail in Qin et al. (2018) and Zhou et al. (2021) (Qin et al., 2018; M. Zhou et al., 2021).

Table S5 Various building envelope efficiency improvement measures and associated costs and energy savings.

Envelope	Material	Window frame	U-value (W/m^2K)	SHGC (for windows)	Cost for existing building retrofits	Cost for new buildings	Energy saving (18 ˚C)	Energy saving (14 ˚C)
All windows	Low-e Win 3	Wooden	4.098	0.853	2161	1901	20%	27%
All windows	Win 3+6A+3	Wooden	3.147	0.759	3111	2851	22%	29%
All windows	Low-e Win 3+6A+3	Wooden	2.68	0.761	4180	3920	23%	30%
All windows	Low-e Win 3	Aluminum	4.098	0.853	2992	2732	20%	27%
All windows	Low-e Win 5	Aluminum	4.05	0.853	3111	2851	20%	27%
All windows	Win 3+6A+3	Aluminum	3.147	0.759	3943	3683	22%	28%
All windows	Win 4+6A+4	Aluminum	3.121	0.759	4180	3920	22%	28%
All windows	Win 5+6A+5	Aluminum	3.096	0.759	4418	4158	22%	29%
All windows	Win 5+12A+5	Aluminum	2.686	0.761	4596	4336	23%	30%
All windows	Low-e Win 3+6A+3	Aluminum	2.68	0.761	4537	4277	23%	30%
All windows	Low-e Win 4+6A+4	Aluminum	2.661	0.762	4774	4514	23%	30%
All windows	Low-e Win 5+6A+5	Aluminum	2.643	0.762	5012	4752	23%	30%
All windows	Low-e Win 5+12A+5	Aluminum	2.07	0.764	5071	4811	25%	32%
All windows	Win 5+9A+5+9 A+5	Aluminum	1.886	0.677	5131	4871	24%	31%
All windows	Low-e Win 5+9A+5+9 A+5	Aluminum	1.606	0.672	5606	5346	25%	32%
All windows	Low-e Win 3	PVC	4.098	0.853	2636	2376	20%	27%
All windows	Low-e Win 5	PVC	4.05	0.853	2755	2495	21%	27%
All windows	Win 3+6A+3	PVC	3.147	0.759	2161	1901	22%	29%
All windows	Win 4+6A+4	PVC	3.121	0.759	2398	2138	22%	29%
All windows	Win 5+6A+5	PVC	3.096	0.759	2636	2376	22%	29%
All windows	Win 5+12A+5	PVC	2.686	0.761	2874	2614	23%	30%
All windows	Low-e Win 3+6A+3	PVC	2.68	0.761	3111	2851	24%	31%

All windows	Low-e Win 4+6A+4	PVC	2.661	0.762	3468	3208	24%	31%
All windows	Low-e Win 5+6A+5	PVC	2.643	0.762	3824	3564	24%	31%
All windows	Low-e Win 5+12A+5	PVC	2.07	0.764	4062	3802	25%	33%
All windows	Win 5+9A+5+9 A+5	PVC	1.886	0.677	4062	3802	24%	31%
All windows	Low-e Win 5+9A+5+9 A+5	PVC	1.606	0.672	4774	4514	25%	32%
All windows	Low-e Win 3	Insulated aluminum	4.098	0.853	4537	4277	20%	27%
All windows	Low-e Win 5	Insulated aluminum	4.05	0.853	5368	5108	20%	27%
All windows	Win 3+6A+3	Insulated aluminum	3.147	0.759	5012	4752	22%	29%
All windows	Win 4+6A+4	Insulated aluminum	3.121	0.759	5250	4990	22%	29%
All windows	Win 5+6A+5	Insulated aluminum	3.096	0.759	5725	5465	22%	29%
All windows	Win 5+12A+5	Insulated aluminum	2.686	0.761	5962	5702	23%	30%
All windows	Low-e Win 3+6A+3	Insulated aluminum	2.68	0.761	5487	5227	23%	30%
All windows	Low-e Win 4+6A+4	Insulated aluminum	2.661	0.762	5725	5465	23%	30%
All windows	Low-e Win 5+6A+5	Insulated aluminum	2.643	0.762	6200	5940	23%	30%
All windows	Low-e Win 5+12A+5	Insulated aluminum	2.07	0.764	6438	6178	25%	33%
All windows	Win 5+9A+5+9 A+5	Insulated aluminum	1.886	0.677	6438	6178	24%	31%
All windows	Low-e Win 5+9A+5+9 A+5	Insulated aluminum	1.606	0.672	6913	6653	25%	32%
North wall	30EPS		0.723		3194	2408	7%	9%
North wall	30XPS		0.645		3331	2544	7%	10%
North wall	30PUR		0.536		3649	2863	8%	11%
North wall	40EPS		0.61		3386	2600	8%	10%
North wall	40XPS		0.536		3538	2751	8%	11%
North wall	40PUR		0.438		4068	3282	9%	12%
North wall	50EPS		0.527		3522	2736	8%	11%
North wall	50XPS		0.459		3811	3024	9%	12%
North wall	50PUR		0.371		4250	3464	10%	13%
North wall	80EPS		0.375		4361	3575	10%	13%
North wall	80XPS		0.321		4862	4075	10%	13%
North wall	80PUR		0.253		5362	4576	11%	14%
North wall	100EPS		0.315		4780	3994	10%	13%

North wall	100XPS	0.267	5508	4722	11%	14%
North wall	100PUR	0.209	6054	5268	11%	15%
Roof	30EPS	0.686	7722	5821	14%	18%
Roof	30XPS	0.615	8052	6151	15%	20%
Roof	30PUR	0.516	8822	6921	17%	23%
Roof	40EPS	0.583	8186	6285	16%	21%
Roof	40XPS	0.516	8552	6652	17%	23%
Roof	40PUR	0.425	9836	7935	19%	25%
Roof	50EPS	0.508	8516	6615	18%	23%
Roof	50XPS	0.444	9212	7312	19%	25%
Roof	50PUR	0.361	10276	8375	21%	27%
Roof	80EPS	0.365	10543	8642	21%	27%
Roof	80XPS	0.314	11753	9852	22%	29%
Roof	80PUR	0.249	12963	11062	23%	30%
Roof	100EPS	0.307	11557	9656	22%	29%
Roof	100XPS	0.262	13317	11416	23%	30%
Roof	100PUR	0.206	14637	12736	24%	32%
Other walls	30EPS	0.723	6107	4604	10%	12%
Other walls	30XPS	0.645	6368	4865	11%	13%
Other walls	30PUR	0.536	6977	5474	12%	15%
Other walls	40EPS	0.61	6474	4971	11%	14%
Other walls	40XPS	0.536	6764	5261	12%	15%
Other walls	40PUR	0.438	7779	6276	13%	17%
Other walls	50EPS	0.527	6735	5232	12%	15%
Other walls	50XPS	0.459	7286	5783	13%	16%
Other walls	50PUR	0.371	8127	6624	14%	18%
Other walls	80EPS	0.375	8339	6835	14%	18%
Other walls	80XPS	0.321	9296	7792	15%	19%
Other walls	80PUR	0.253	10253	8749	16%	20%
Other walls	100EPS	0.315	9141	7637	15%	19%
Other walls	100XPS	0.267	10533	9029	16%	19%
Other walls	100PUR	0.209	11577	10073	16%	20%

Notes: We collect building energy efficiency measures that can be widely adopted in rural houses from the peer-reviewed literature, government technical guides, and building material suppliers.

We consider three types of measures: window replacements, wall insulation, and roof insulation. We consider efficient windows with various glass (single, double, or triple; various thicknesses), coating (whether low emissivity coating is applied), and frames (aluminium, polyvinyl chloride, or insulated aluminium). Air sealing is assumed to be performed when replacing old windows with new ones (Feng et al., 2014). We assume the ACH rate will reduce to 0.5 h^{-1} after air sealing according to building retrofit requirements and case studies (M. Shan et al., 2015; S. Zhao et al., 2015).

We select the three most common materials used for insulation: expanded polystyrene (EPS), extruded polystyrene (XPS), and polyurethane (PU). We do not include sunrooms, false ceilings, window shrink films, door-draft stoppers, and other technologies in our analysis because data are not available or of low quality. Finally, we include 84 individual energy efficiency measures in our analysis.

Costs of increasing building envelope efficiency for existing buildings are 5-20% higher than those for new buildings because of additional demolition costs during the retrofit.

The thermal properties of efficient windows and insulation materials are obtained from building material standards and building material suppliers (Ministry of Housing and Urban-Rural Development of China, 2016).

We run EnergyPlus to calculate the energy-saving potential (compared with our baseline building) of each measure. To reduce the computing time, here we use the average energy-saving potentials in Beijing, Tianjin, Taiyuan, Zhengzhou, Jinan, Shijiazhuang, and Xi'an.

The most cost-effective (largest energy-saving per yuan) measures for each envelope are highlighted in the table.

Our building envelope scenarios are designed to represent a step-by-step envelope efficiency improvement strategy for rural homes, so we consider the costs of each measure. For example, roof insulation has a larger energy-saving potential than north wall insulation, but roof insulation is much more expensive than north wall insulation. Therefore, we suggest rural households with a limited budget first implement north wall insulation.

Retrofitting the north wall has a larger energy-saving potential than retrofitting other walls in rural buildings in north China. This is because the south wall usually absorbs more heat from solar radiation than the north wall. Such heat can be conducted into the home through the south wall. To take advantage of the heat from solar exposure, it is usually better to have a higher level of insulation on the north wall than on the south wall.

Terminology and acronyms are: Low-e (low emissivity coating is applied); Win 3+6A+3 (double glazed windows use two panes of glass both 3mm apart and 6mm air between the two panes); 30EPS (30mm EPS insulation); EPS (expanded polystyrene); XPS (extruded polystyrene); PU (polyurethane); SHGC (Solar heat gain coefficient).

Table S6 City-level fuel prices without subsidies in the "2+26" cities and the Fen-Wei Plain region.

Areas	Electricity prices (RMB/kWh)		Natural gas prices (RMB/m^3)	Clean coal briquettes (RMB/ton)	Raw coal (RMB/ton)
	Peak hours	Off-peak hours			
Beijing	0.4883	0.3	2.63	1180	535
Tianjin	0.49	0.3	2.63	1210	535
Shijiazhuang	0.55	0.3	2.68	1310	535
Xingtai	0.55	0.3	2.4	1310	535
Hengshui	0.55	0.3	2.68	1310	535
Cangzhou	0.55	0.3	2.63	1310	525
Handan	0.55	0.3	2.68	1310	525
Tangshan	0.55	0.3	2.15	1310	525
Baoding	0.55	0.3	2.68	1310	525
Langfang	0.55	0.3	2.47	1310	525
Jinan	0.5769	0.3469	<216, 3.3 216-360, 3.9 >360, 4.8	1226	525
Zibo	0.5769	0.3469	<360, 2.7 360-1080, 2.85 >1080, 3.5	1226	525
Jining	0.5769	0.3469	<200, 2.4 200-275, 2.88 >275, 3.6	1226	525
Dezhou	0.5769	0.3469	<1200, 2.45 >1200, 2.89	1226	525
Liaocheng	0.5769	0.3469	<900, 2.43 900-1400, 2.916 >1400, 3.645	1226	525
Binzhou	0.5769	0.3469	<360, 2.3 >360, 2.75	1226	525
Heze	0.5769	0.3469	<15, 2.52 15-45, 2.71 >45, 3.39	1226	525
Taiyuan	0.507	0.2862	<26, 2.26 26-38, 2.71 >38, 3.39	645	525
Changzhi	0.507	0.2862	<380, 2.26 >380, 2.71	645	525
Yangquan	0.507	0.2862	<1900, 2.75 >1900, 3.03	645	525
Jinzhong	0.507	0.2862	<390, 2.61 >390, 3.13	645	525
Linfen	0.507	0.2862	<400, 2.7 >400, 2.97	645	525
Luliang	0.507	0.2862	<370, 2.61 >370, 2.71	645	525
Yuncheng	0.507	0.2862	<300, 2.65 >300, 3.09	645	525

Jincheng	0.507	0.2862	<380, 2.26 >380, 2.71	645	525
Zhengzhou	0.64	0.49	<50,2.56 >50, 3.33	1200	525
Kaifeng	0.64	0.49	<50, 2.6 >50, 3.38	1200	525
Luoyang	0.64	0.49	<50, 2.58 >50, 3.35	1200	525
Anyang	0.64	0.49	<50, 2.57 >50, 3.34	1200	525
Hebi	0.64	0.49	<50, 2.42 >50,3.15	1200	525
Xinxiang	0.64	0.49	<50, 2.57 >50, 3.34	1200	525
Jiaozuo	0.64	0.49	<50, 2.37 >50, 3.08	1200	525
Puyang	0.64	0.49	<50, 2.44 >50, 3.17	1200	525
Sanmenxia	0.64	0.49	<50, 2.58 >50, 3.35	1200	525
Xi'an	0.5483	0.2862	<2000, 2.07 2000-3000, 2.48 >3000, 3.11	1200	525
Baoji	0.5483	0.2862	<2000, 2.06 2000-3000, 2,47 >3000, 3.09	1280	525
Xianyang	0.5483	0.2862	<2000, 2.05 2000-3000, 2.46 >3000, 3.08	1280	525
Tongchuan	0.5483	0.2862	<2000, 2.18 2000-3000, 2.61 >3000, 3.27	1280	525
Weinan	0.5483	0.2862	<2000, 2.06 2000-3000, 2.47 >3000, 3.09	1280	525

Notes: Peak hours are 8pm-8am in the "2+26" cities and the Fen-Wei Plain region. Data are collected from local governments, natural gas companies, and utility companies, as described in greater detail in Liu and Mauzerall (2020) and Zhou et al. (2021) (H. Liu & Mauzerall, 2020; M. Zhou et al., 2021).

Table S7 Subsidies for operating costs of natural gas and electricity (in effect 2018-2020).

Cities	Electricity Subsidies		Natural gas Subsidies	
	Rate (RMB/kWh)	Ceiling (kWh per year)	Rate (RMB/m^3)	Ceiling (m^3 per year)
Beijing	0.2 (off-peak)	10000	0.73	820
Tianjin	0.2 (off-peak)	8000	1.2	1000
Shijiazhuang	0.12	10000	0.8	1200
Xingtai	0.12	10000	0.8	1200
Hengshui	0.174	10000	0.8	1200
Cangzhou	0.12	10000	0.8	1200
Handan	0.12	10000	0.8	1200
Tangshan	0.12	10000	0.8	1200
Baoding	0.12	10000	0.8	1200
Langfang	0.12	10000	0.8	1200
Jinan	NA	1200	NA	1200
Zibo	0.2	6000	1	1200
Jining	0.2	5000	NA	NA
Dezhou	NA	1000	NA	1000
Liaocheng	NA	NA	NA	NA
Binzhou	0.2	6000	1	1200
Heze	NA	1000	NA	1000
Taiyuan	0.2	12000	1.10, <500 m^2, 1.36 > 500 m^2	
Changzhi	0.2 (off-peak)	12000	1	2400
Yangquan	0.2 (off-peak)	12000	0.5	900
Jinzhong	0.2	10000	1	1120
Linfen	0.2 (off-peak)	12000	1	900
Luliang	0.2	10000	1	2400
Yuncheng	0.2 (off-peak)	12000	NA	NA
Jincheng	0.2 (off-peak)	12000	NA	NA
Zhengzhou	0.2	3000	1	600
Kaifeng	0.3	3000	1	900
Luoyang	NA	NA	NA	NA
Anyang	0.2	3000	1	600
Hebi	0.2	3000	1	600
Xinxiang	0.2	3000	1	600
Jiaozuo	0.4	2500	120	1000
Puyang	NA	NA	1.10, <150 m^2	
Sanmenxia	0.2	2500	NA	NA
Jiyuan shi	0.2	3000	1	600
Xi'an	0.25	4000	NA	1000RMB
Baoji	NA	NA	NA	NA
Xianyang	NA	NA	NA	NA
Tongchuan	NA	NA	NA	NA
Weinan	NA	NA	NA	NA

Table S8 Estimated clean heater adoption in 2020 in the "2+26" cities and the Fen-Wei Plain region.

Provinces/cities	Natural gas heaters (NGH)	Resistance heaters (RH)	Air-to-air heat pumps (AAHP)	Coal stoves
Beijing	~18%	~32%	~50%	~0%
Tianjin	~56%	~44%	~0%	~0%
Hebei	~53%	~7%	~0%	~40%
Shanxi	~50%	~10%	~0%	~40%
Shandong	~45%	~15%	~0%	~40%
Henan	~8%	~52%	~0%	~40%
Shaanxi	~10%	~50%	~0%	~40%

Notes: Because data of clean heater adoption in 2020 is not available, we estimate the share of various heaters in rural households in the "2+26" cities and the Fen-Wei Plain region of northern China based on the stated 2021 targets in the clean heating plan and the clean heater replacement progress by 2018 (NDRC (National Development and Reform Commission of China), 2017; Z. Zhang et al., 2021). We assume all the coal stoves in Beijing and Tianjin have been replaced, where ~40% rural households in other provinces are still using coal stoves (mainly CCIS), as indicated by the clean heating plan targets (NDRC (National Development and Reform Commission of China), 2017). We assume that very few households will install AAHP by 2030 because of high upfront costs. For Beijing where the local government provides generous subsidies, we assume ~50% of rural households installed AAHP according to the survey data (Natural Resources Defense Council, 2018). We estimate NGH and RH adoptions based on the government report in 2018 (Z. Zhang et al., 2021).

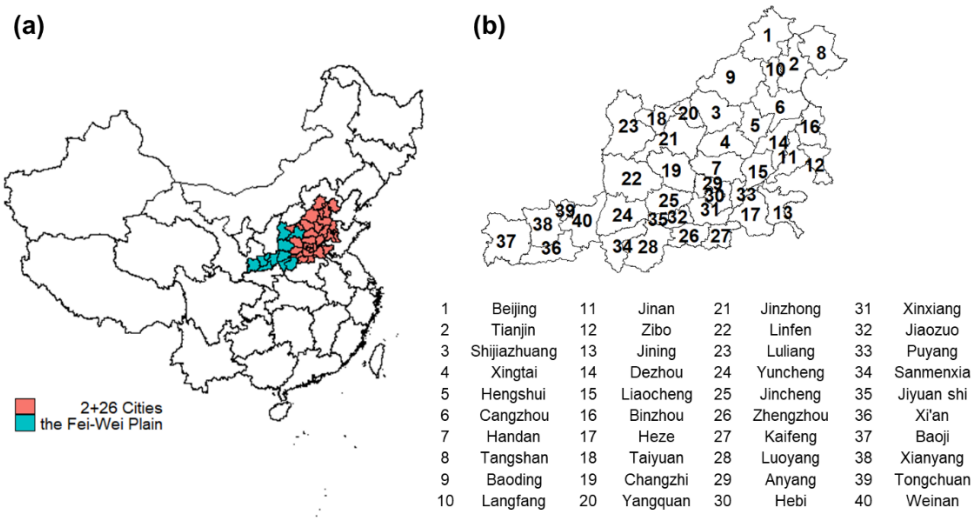


Figure S1. Map of the "2+26" cities and the Fen-Wei Plain over China. (a) The red and blue areas denote the "2+26" cities and the Fen-Wei Plain region, respectively (b) City names and locations in the studied region. Jiyuan shi, a county-level city directly managed by the Henan provincial government, is also a part of the "2+26" cities region.

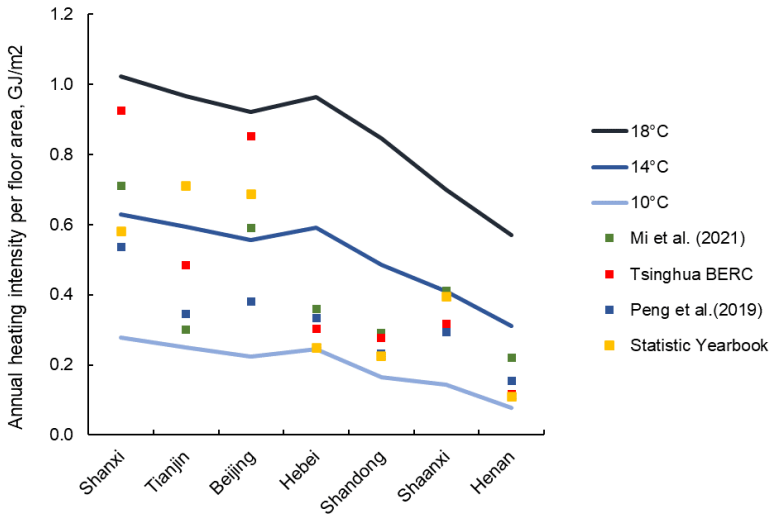


Figure S2. Simulated (solid lines) and surveyed (dots) annual rural residential heating intensities per floor area in seven northern Chinese provinces for three desired indoor temperatures. We validate our baseline simulations by comparing our simulated rural residential heating intensities with various survey data. We simulate city-level annual heating energy intensities using EnergyPlus based on our baseline building and estimate population-weighted provincial average heating intensities. We also estimated provincial-level average heating energy intensities based on rural energy use survey data from four Chinese rural household energy consumption datasets: Zhou et al. (2021), Tsinghua's Building Energy Research Center (BERC)'s Annual Report 2012, Peng et al. (2019), and China Energy Statistical Yearbook (CESY) 2010v(Building Energy Research Center of Tsinghua University, 2012; Peng et al., 2019; M. Zhou et al., 2021). Previous studies reported that the indoor temperatures in most rural homes are usually at 10-14 °C, indicating our simulated heating loads are valid(Building Energy Research Center of Tsinghua University, 2012; China's Ministry of Housing and Urban-Rural Development, 2013; Evans et al., 2014; B. jie He et al., 2014). The surveyed heating intensities in Tianjin and Beijing are higher than those in other provinces because of higher household incomes and resulting higher indoor temperatures; and the heating intensity in Shanxi is higher because of lower coal prices and resulting higher indoor temperatures.

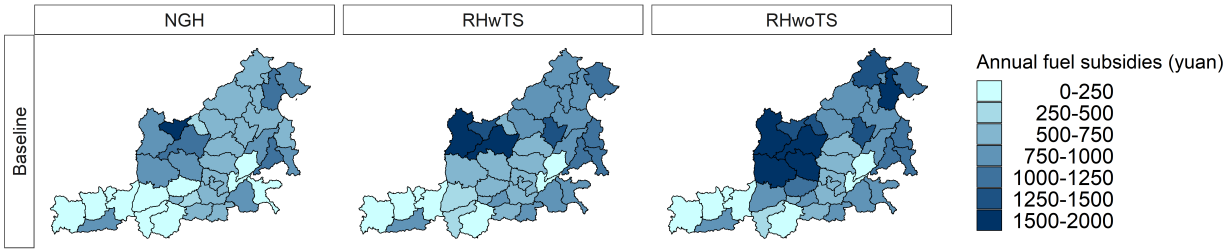


Figure S3. Estimated household operating fuel subsidies with various clean heaters (across top) in the baseline building in the "2+26" cities plus the Fen-Wei Plain region of northern China. Household operating fuel subsidies are estimated based on heating loads simulated by EnergyPlus to maintain the indoor temperature at 14°C during the heating season and city-level fuel subsidy policies listed in Table S7. See Table 1 for definition of heater acronyms.

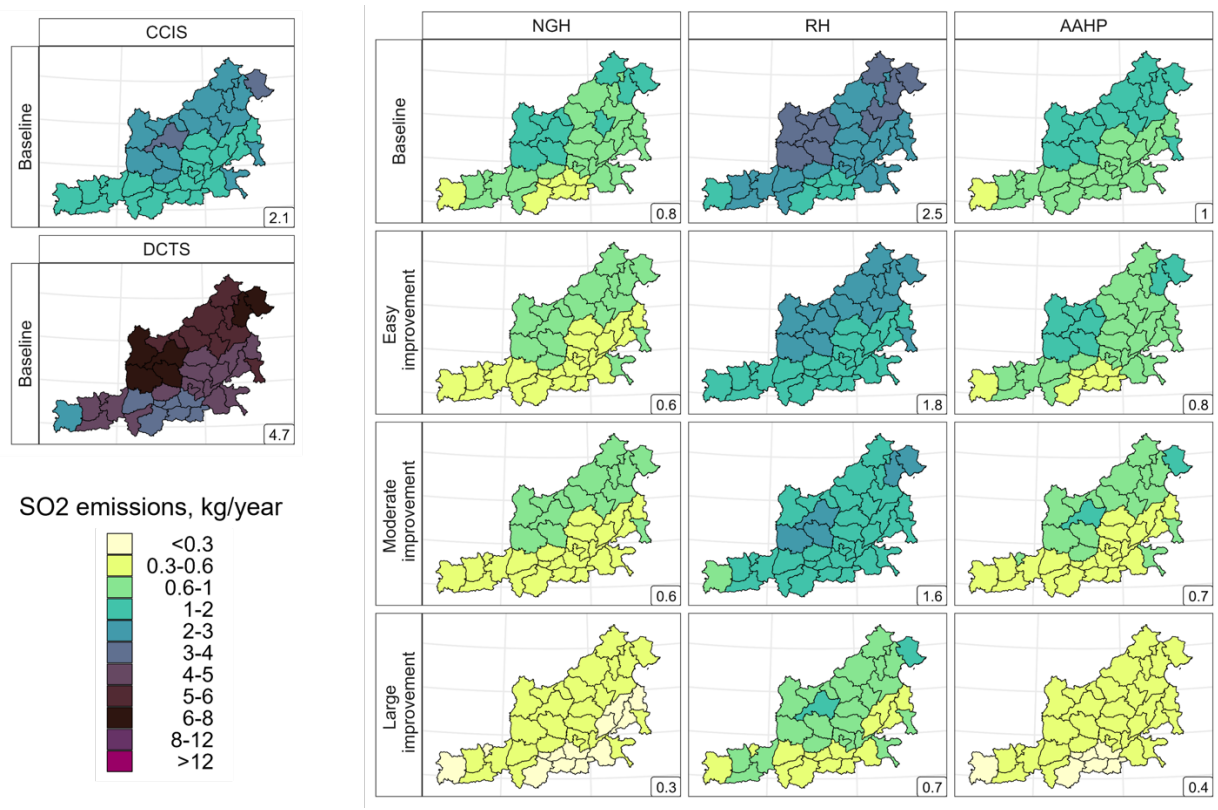


Figure S4. Household heating related SO_2 emissions with various heaters (across top) and building envelopes (down columns) in the "2+26" cities plus the Fen-Wei Plain region of northern China. Both direct emissions from coal and natural gas burning and indirect emissions from fuel/electricity production, processing, transmission, and distribution are included. The figure shows the emissions related to household space heating to maintain indoor temperatures at 14 °C during the heating season. The numbers at the bottom right of each subfigure denote the average household emissions in the studied region. See Table 1 for definition of heater acronyms.

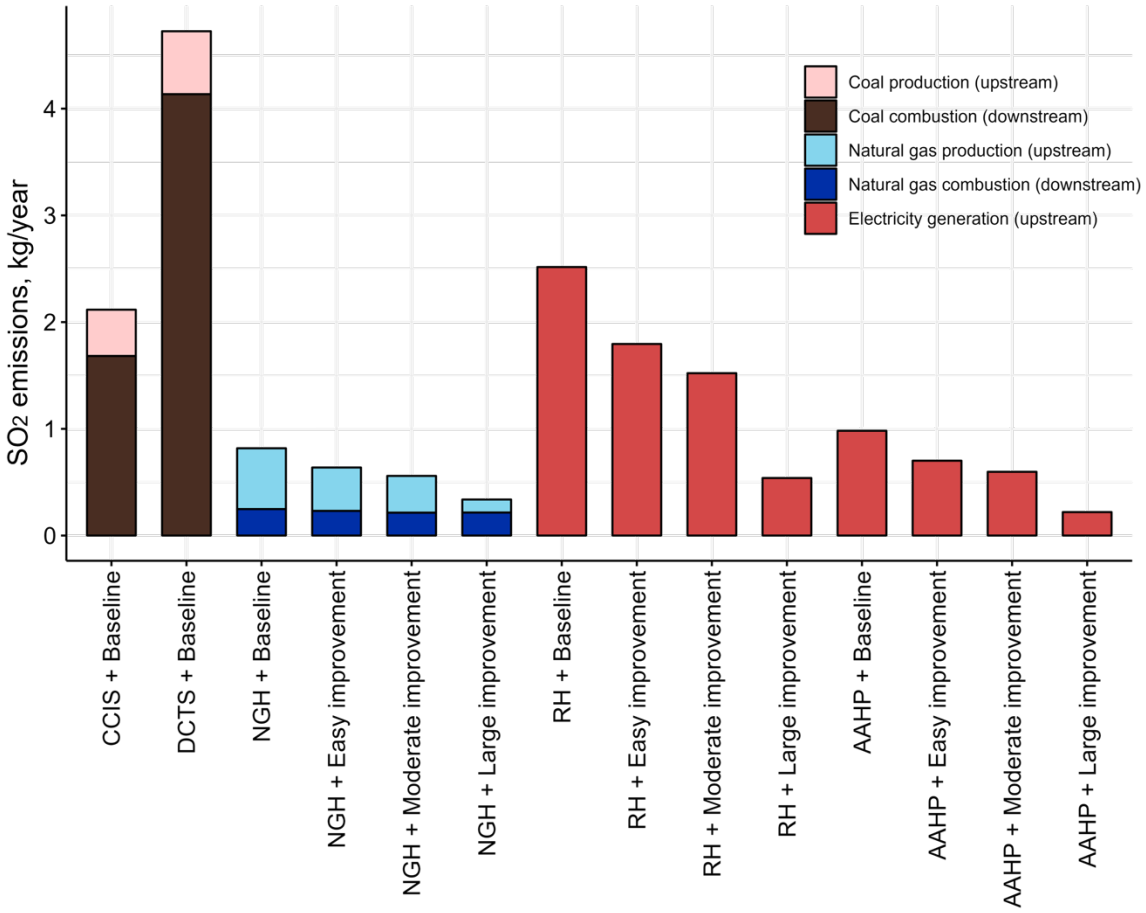


Figure S5. Average household heating related SO_2 emissions by sources in the "2+26" cities plus the Fen-Wei Plain region of northern China. The figure shows the emissions related to household space heating to maintain indoor temperatures at 14 °C during the heating season. See Table 1 for definition of heater acronyms.

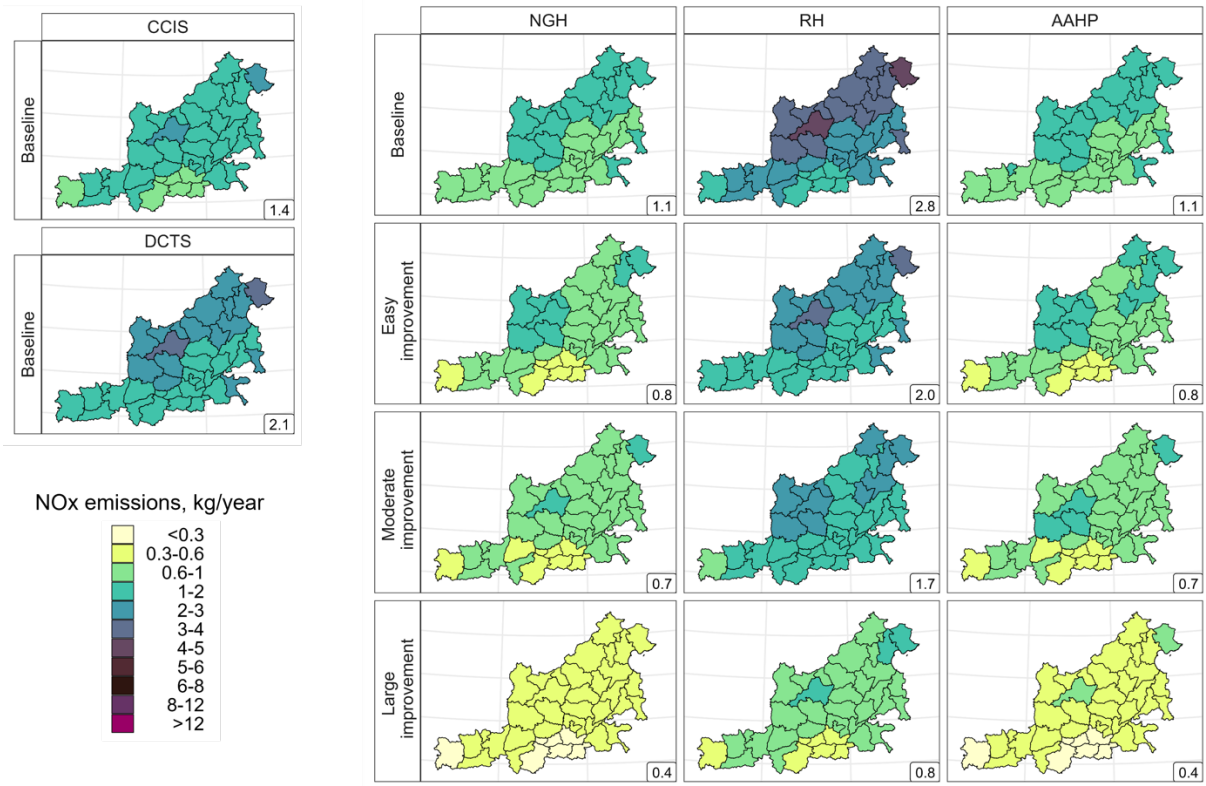


Figure S6. Household heating related NOx emissions with various heaters (across top) and building envelopes (down columns) in the "2+26" cities plus the Fen-Wei Plain region of northern China. Both direct emissions from coal and natural gas burning and indirect emissions from fuel/electricity production, processing, transmission, and distribution are included. The figure shows the emissions related to household space heating to maintain indoor temperatures at 14 °C during the heating season. The numbers at the bottom right of each subfigure denote the average household emissions in the studied region. See Table 1 for definition of heater acronyms.

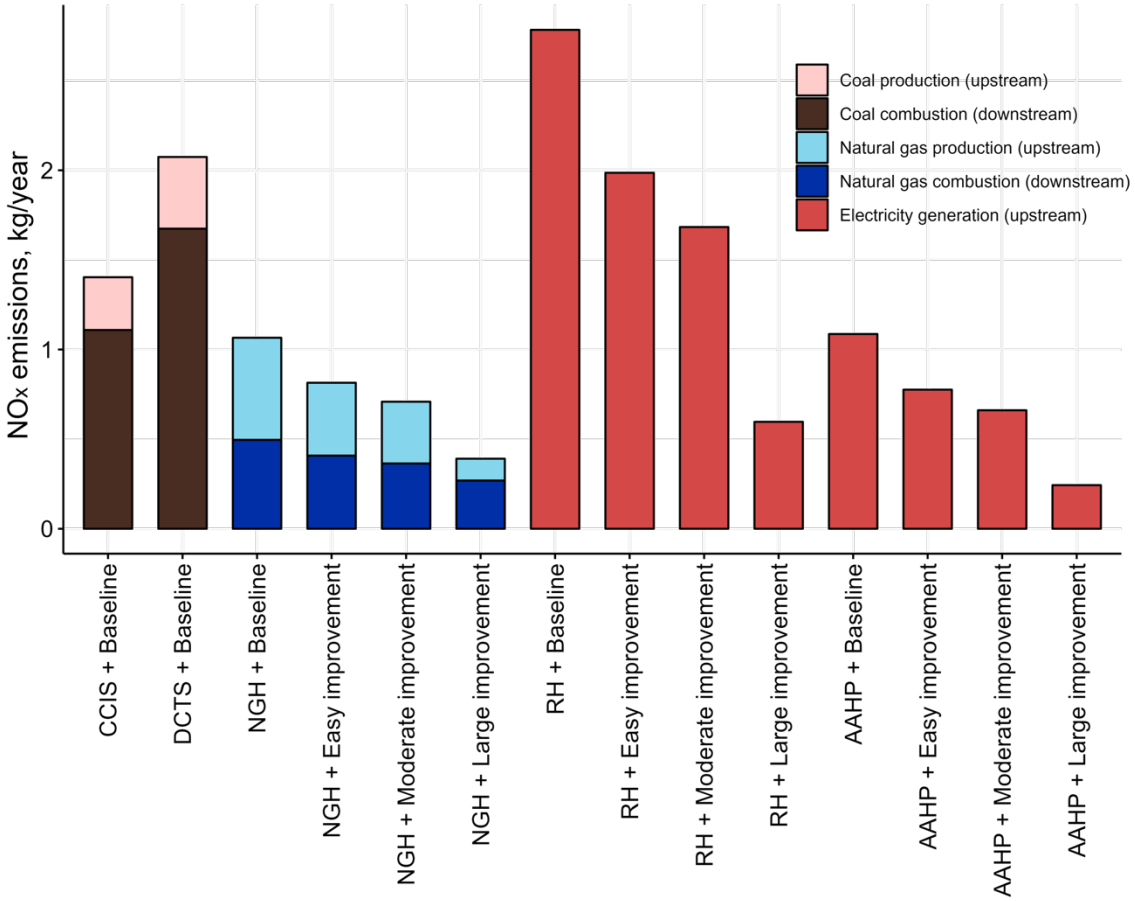


Figure S7. Average household heating related NOx emissions by sources in the "2+26" cities plus the Fen-Wei Plain region of northern China. The figure shows the emissions related to household space heating to maintain indoor temperatures at 14 °C during the heating season. See Table 1 for definition of heater acronyms.

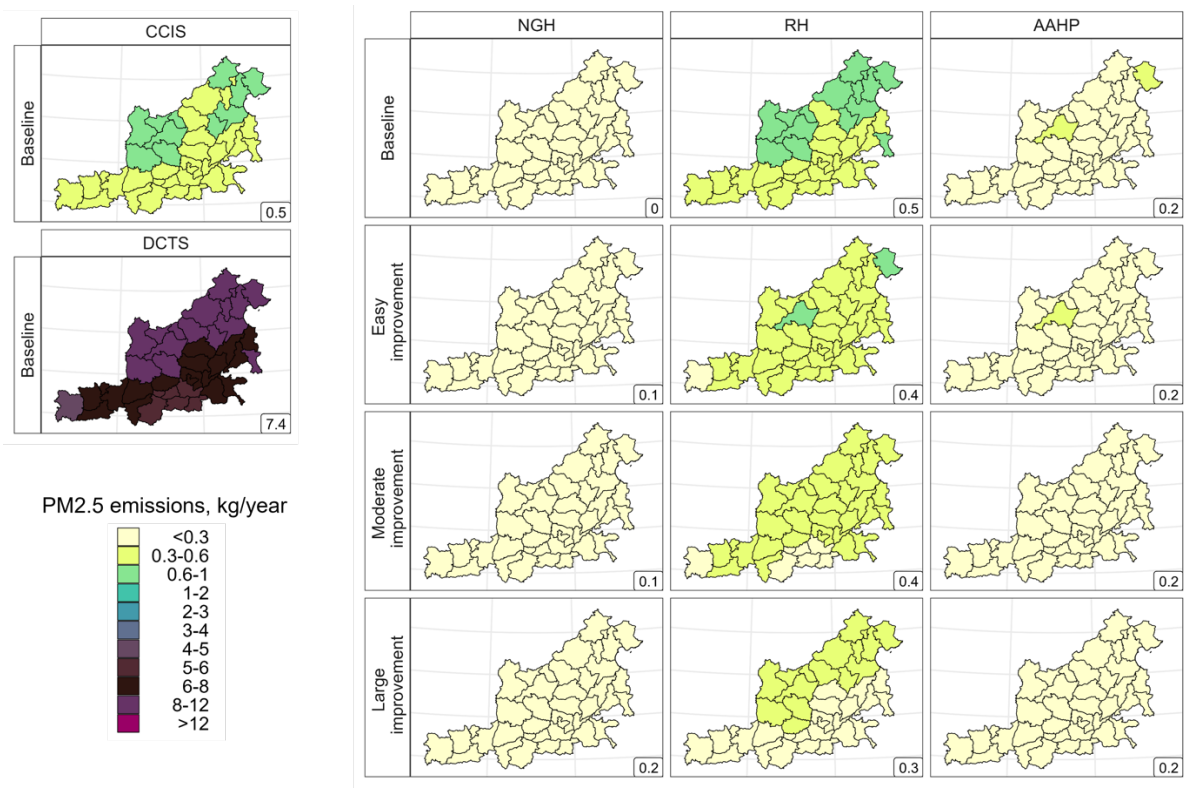


Figure S8. Household heating related $PM_{2.5}$ emissions with various heaters (across top) and building envelopes (down columns) in the "2+26" cities plus the Fen-Wei Plain region of northern China. Both direct emissions from coal and natural gas burning and indirect emissions from fuel/electricity production, processing, transmission, and distribution are included. The figure shows the emissions related to household space heating to maintain indoor temperatures at 14 °C during the heating season. The numbers at the bottom right of each subfigure denote the average household emissions in the studied region. See Table 1 for definition of heater acronyms.

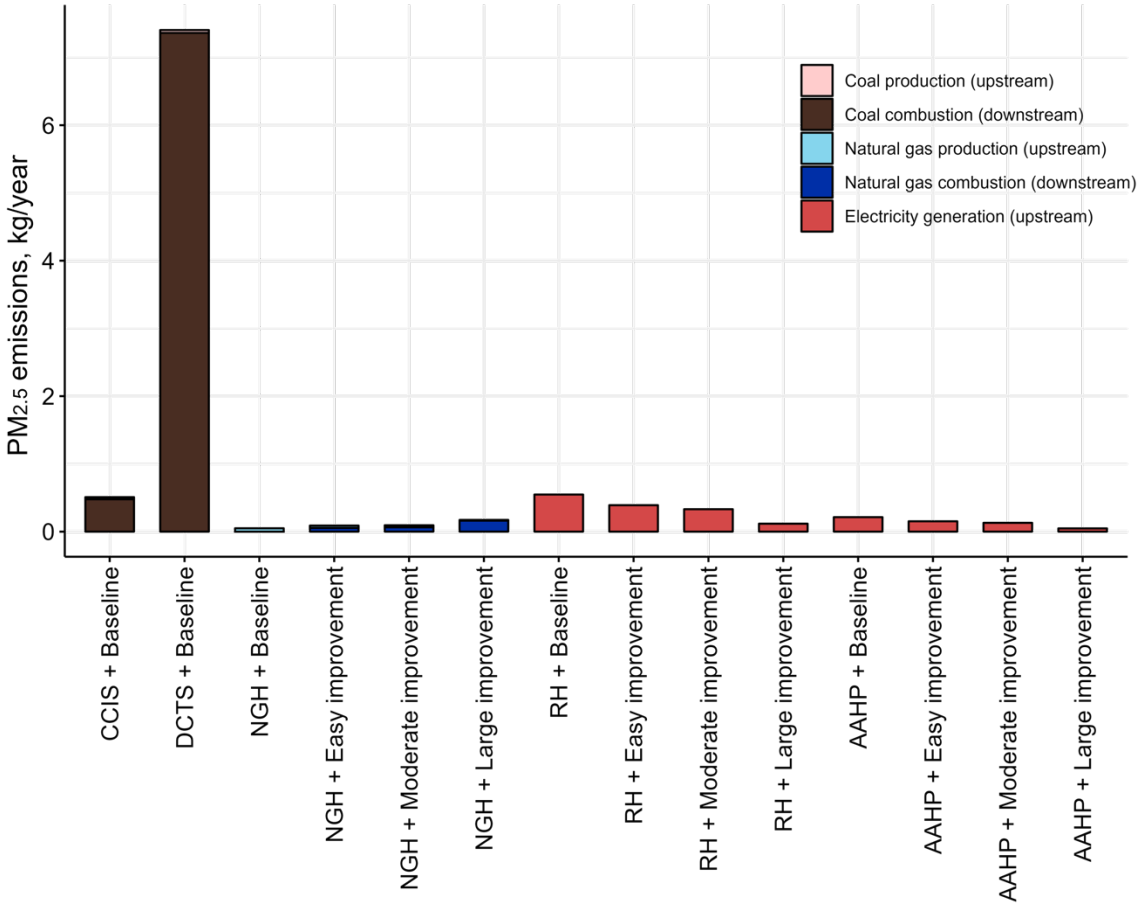


Figure S9. Average household heating related $PM_{2.5}$ emissions by sources in the "2+26" cities plus the Fen-Wei Plain region of northern China. The figure shows the emissions related to household space heating to maintain indoor temperatures at 14 °C during the heating season. See Table 1 for definition of heater acronyms.

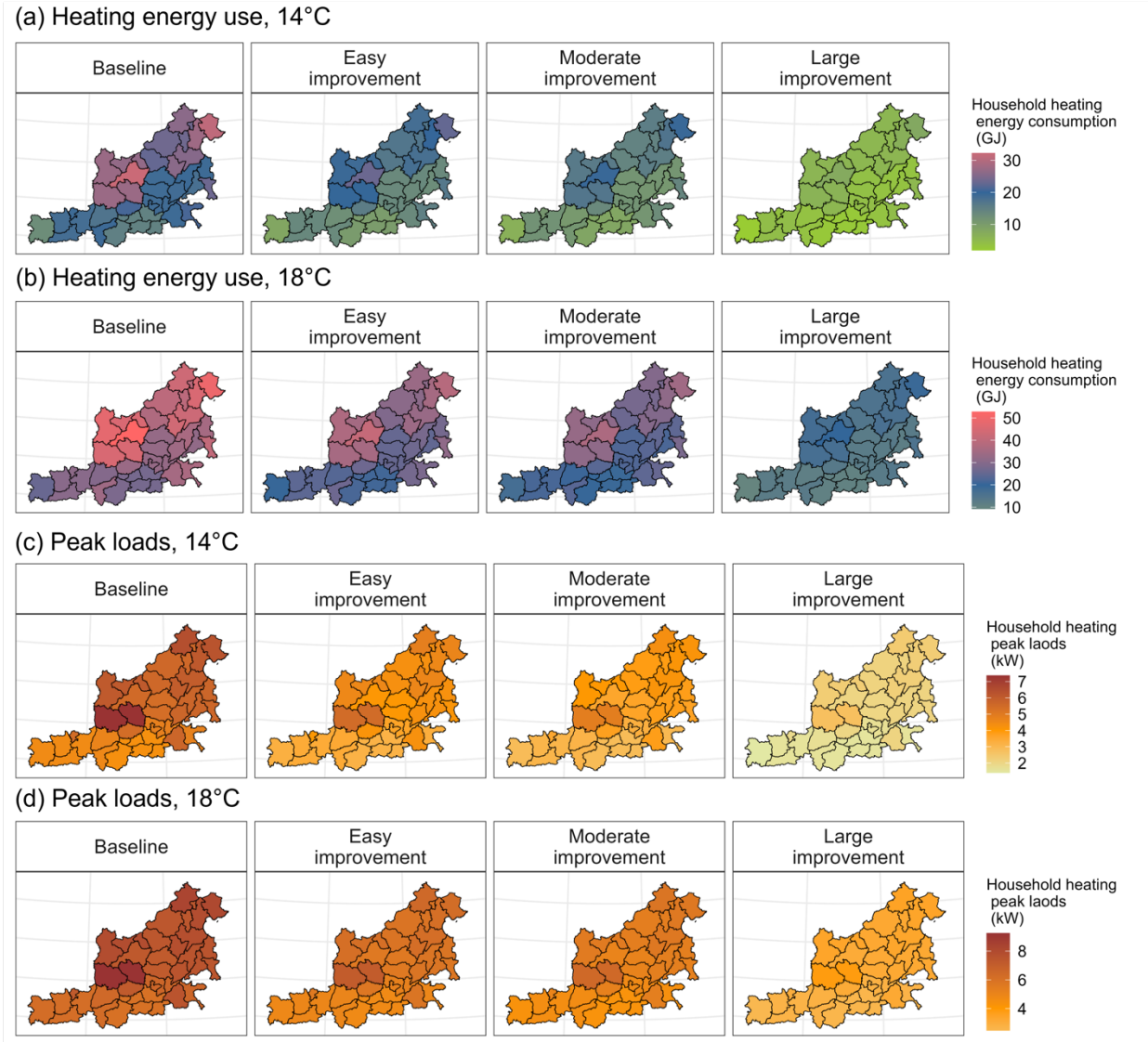


Figure S10. Household heating energy use and peak loads with various building envelopes in the "2+26" cities plus the Fen-Wei Plain region of northern China. (a) heating energy use with the indoor temperature of 14°C; (b) heating energy use with the indoor temperature of 18°C; (c) peak loads with the indoor temperature of 14°C; (d) peak loads with the indoor temperature of 18°C.

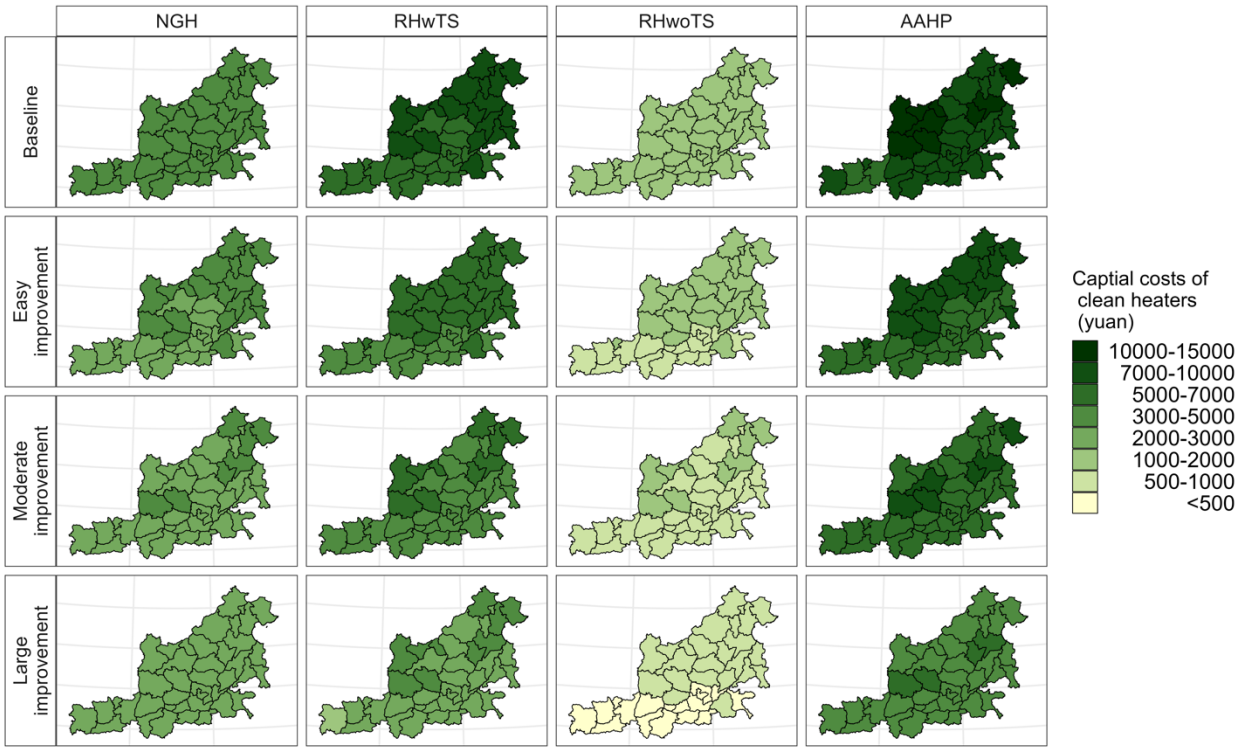


Figure S11. Household upfront capital costs of various heaters (across top) with improved building envelopes (down columns) in the "2+26" cities plus the Fen-Wei Plain region of northern China. We calculate household peak heating loads to keep indoor temperatures at 14 °C during the heating season using EnergyPlus to estimate the required sizes (power capacity, kW) of various heaters. No subsidies are included. See Table 1 for definition of heater acronyms.

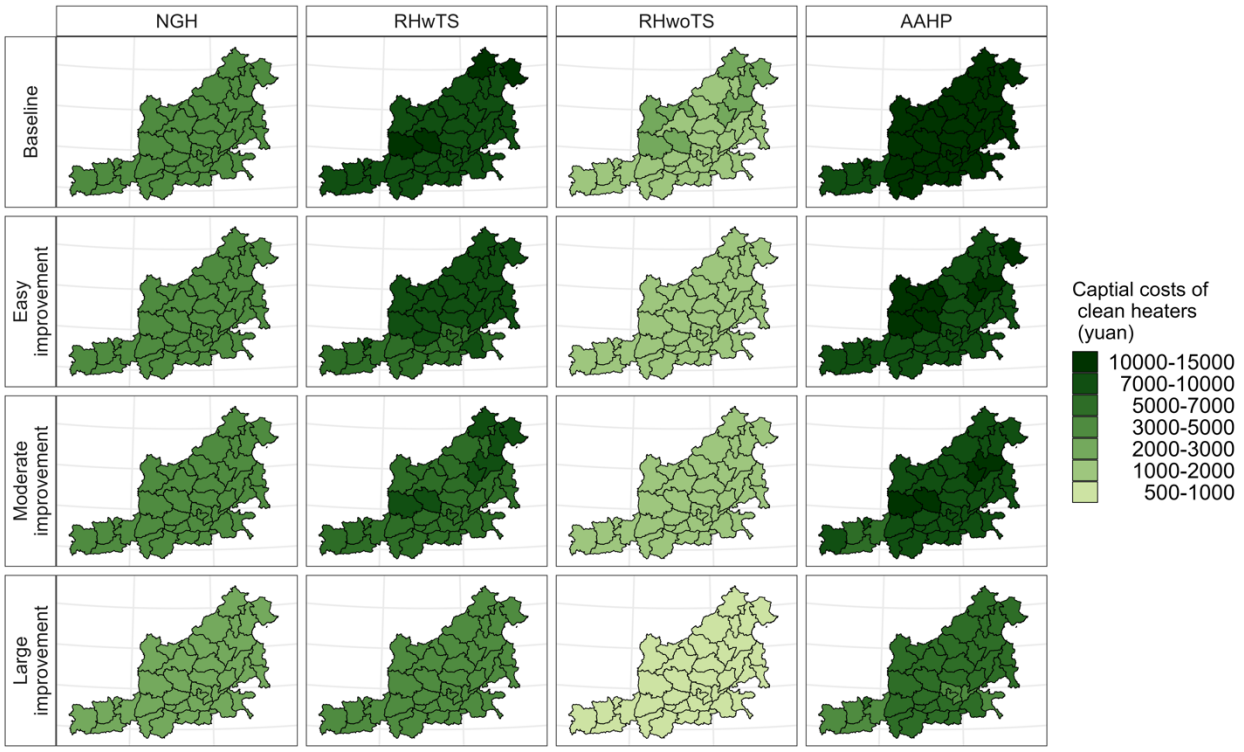


Figure S12. Household upfront capital costs of various heaters (across top) with improved building envelopes (down columns) in the "2+26" cities plus the Fen-Wei Plain region of northern China. We calculate household peak heating loads to keep indoor temperatures at 18 °C during the heating season using EnergyPlus to estimate the required sizes (power capacity, kW) of various heaters. No subsidies are included. See Table 1 for definition of heater acronyms.

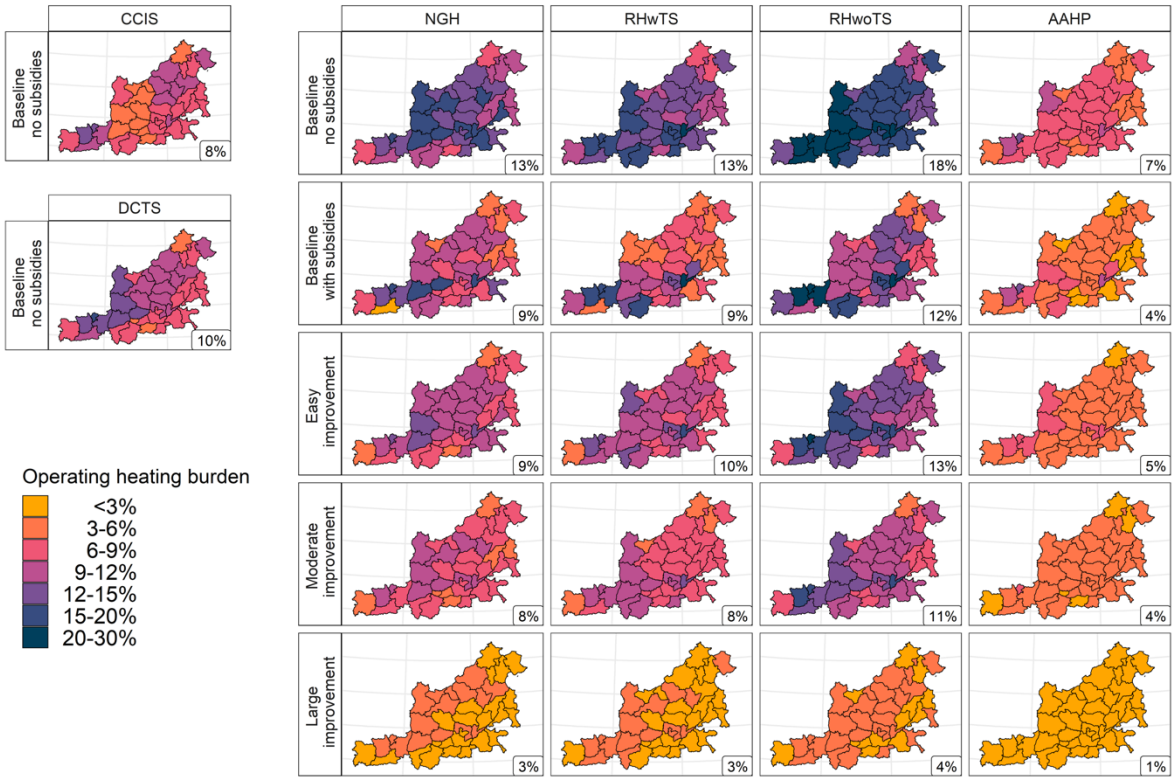


Figure S13. Household operating heating burdens with various heaters (across top) and building envelopes (down column) in the "2+26" cities plus the Fen-Wei Plain region of northern China. Household operating heating burden is defined as the percentage of household income spent on operating heating costs to maintain the indoor temperature at 14 °C during the heating season. The numbers at the bottom right of each subfigure denote the average operating heating burden in the studied region. No capital costs (heater and envelope costs) are considered here. We consider government fuel subsidies in the "Baseline with subsidies" scenario. No subsidies are included in building envelope improvement scenarios. See Table 1 for definition of heater acronyms.

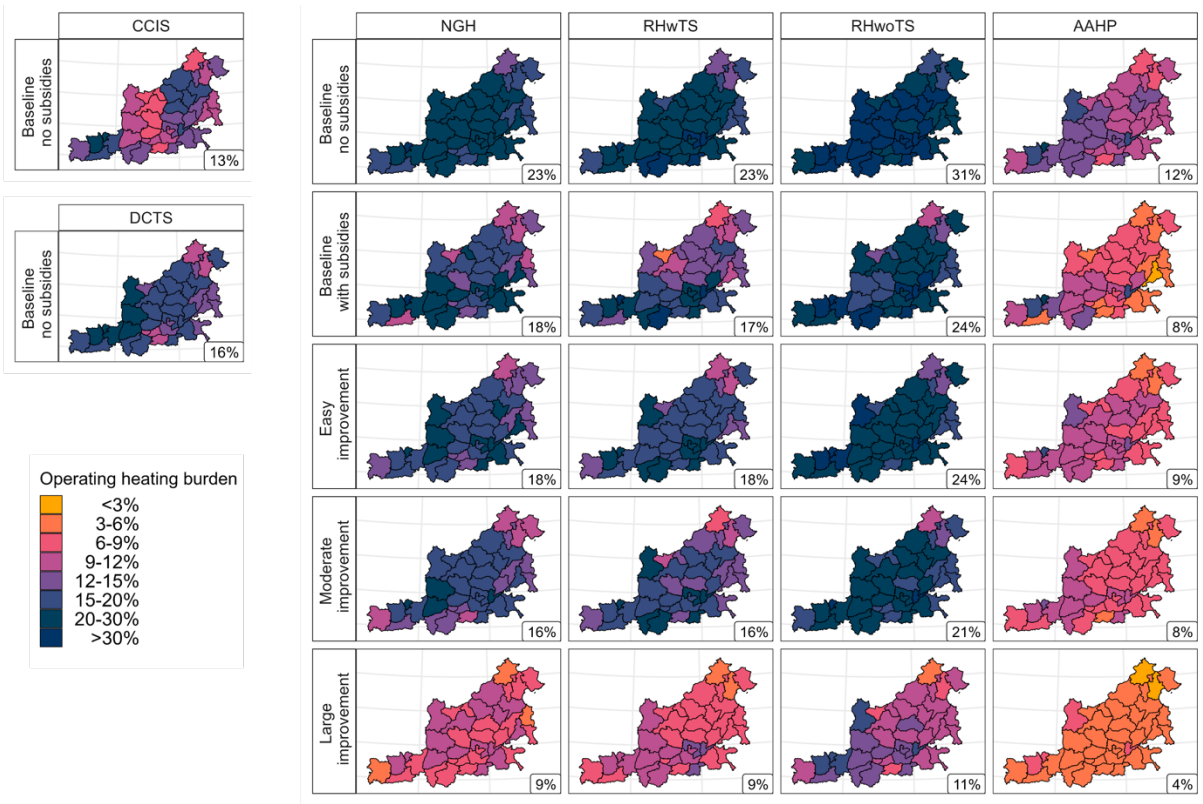


Figure S14. Household operating heating burdens with various heaters (across top) and building envelopes (down column) in the "2+26" cities plus the Fen-Wei Plain region of northern China. Household operating heating burden is defined as the percentage of household income spent on operating heating costs to maintain the indoor temperature at 18 °C during the heating season. The numbers at the bottom right of each subfigure denote the average operating heating burden in the studied region. No capital costs (heater and envelope costs) are considered here. We consider government fuel subsidies in the "Baseline with subsidies" scenario. No subsidies are included in building envelope improvement scenarios. See Table 1 for definition of heater acronyms.

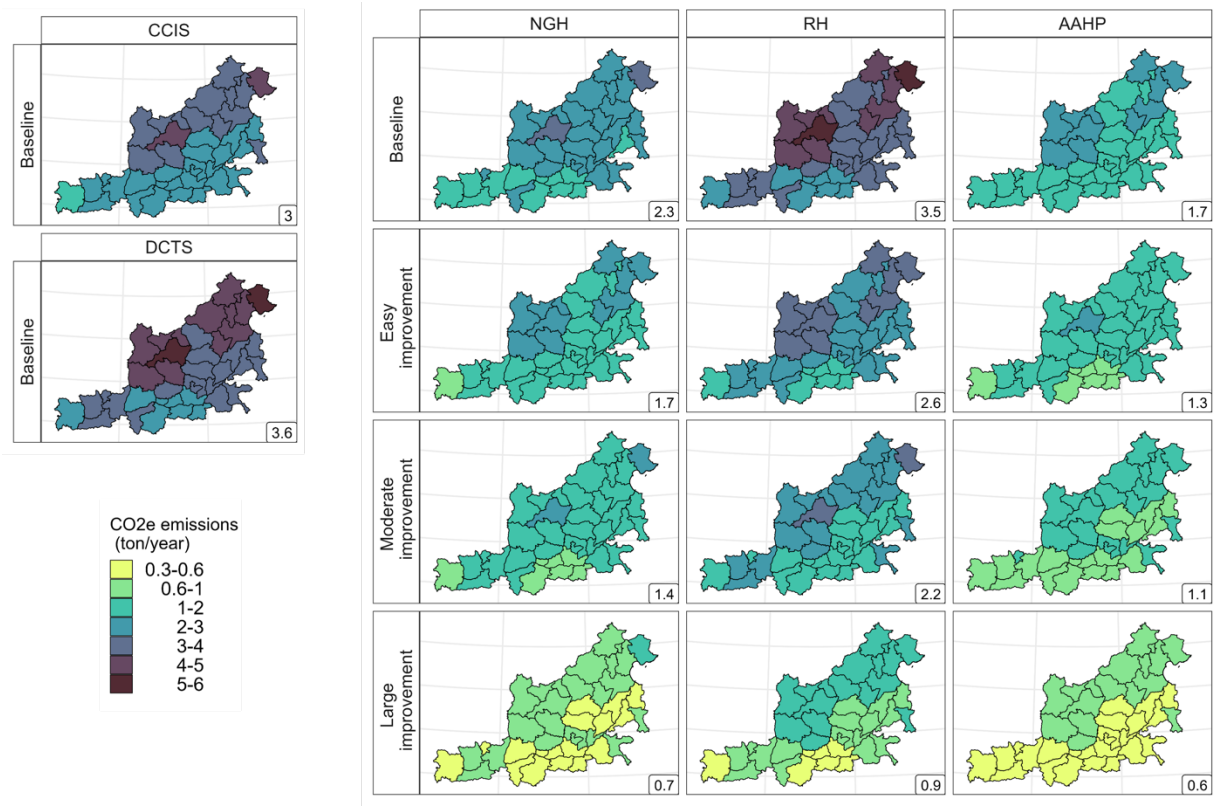


Figure S15. Household heating related CO_2e emissions under GWP_{20} with various heaters (across top) and building envelopes (down column) in the "2+26" cities plus the Fen-Wei Plain region of northern China. Both direct emissions from coal and natural gas burning and indirect emissions from fuel/electricity production, processing, transmission, and distribution are included. The figure shows the CO_2e emissions related to household space heating to maintain indoor temperatures at 14 °C during the heating season. The numbers at the bottom right of each subfigure denote the average household CO_2e emissions in the studied region. Results for an indoor temperature of 14 °C are presented in Figure S6. See Table 1 for definition of heater acronyms.

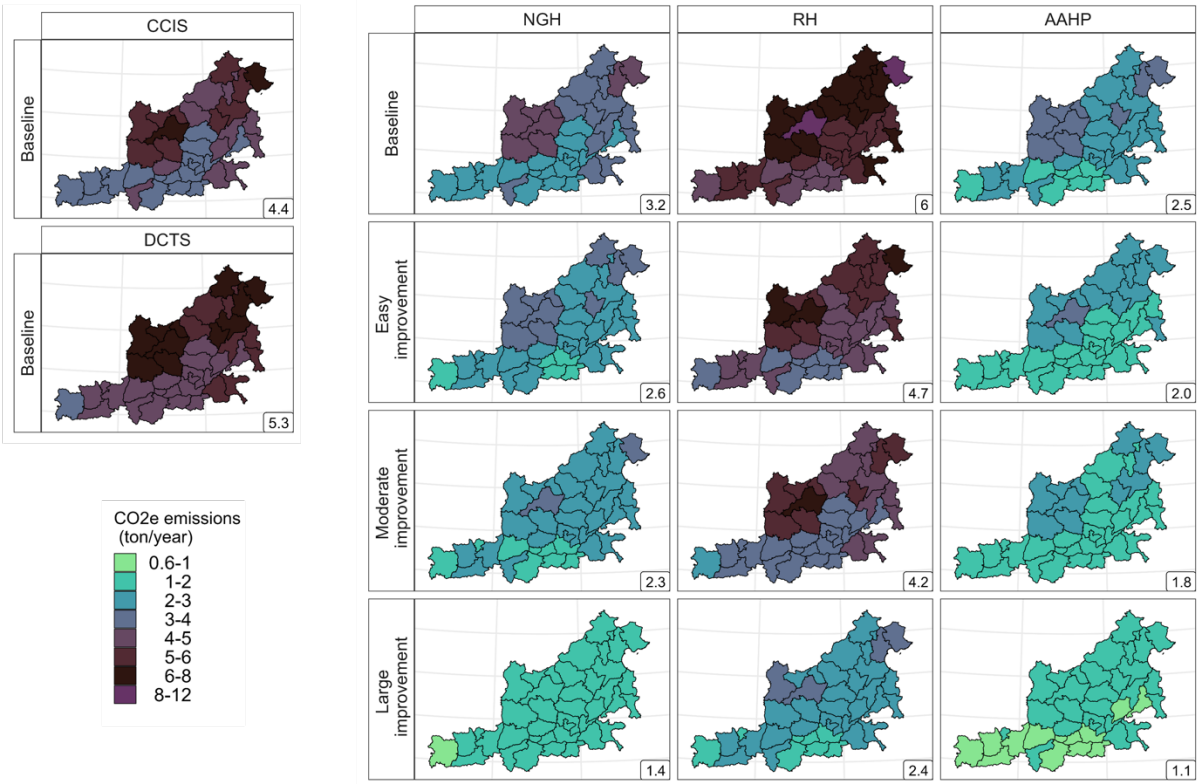


Figure S16. Household heating related CO_2e emissions under GWP_{100} with various heaters (across top) and building envelopes (down column) in the "2+26" cities plus the Fen-Wei Plain region of northern China. Both direct emissions from coal and natural gas burning and indirect emissions from fuel/electricity production, processing, transmission, and distribution are included. The figure shows the CO_2e emissions related to household space heating to maintain indoor temperatures at 18 °C during the heating season. The numbers at the bottom right of each subfigure denote the average household CO_2e emissions in the studied region. See Table 1 for definition of heater acronyms.

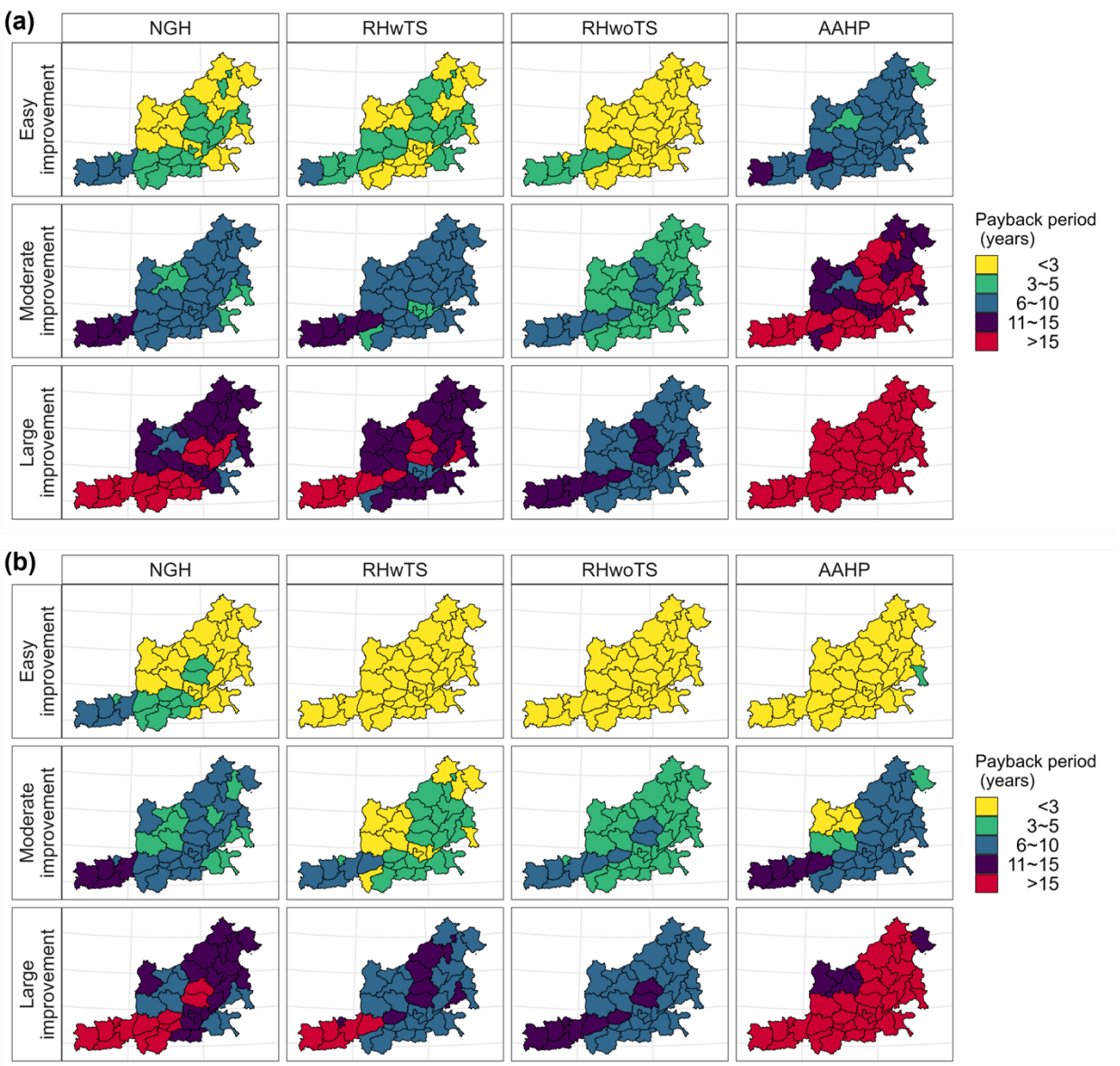


Figure S17. Payback periods for building envelope efficiency improvements to (a) existing buildings using various clean heaters and (b) existing buildings that will soon install various clean heaters in the "2+26" cities plus the Fen-Wei Plain region of northern China. This figure shows payback periods when rural households maintain the indoor temperature at 18 °C during the heating season. The discount rate is 5%. In subfigure (a), only savings from reduced annual operating costs are considered because capital costs of clean heaters are sunk costs. In contrast, in subfigure (b), both savings from reduced capital costs of clean heaters and savings from reduced annual operating costs are considered. See Table 1 for definition of heater acronyms.

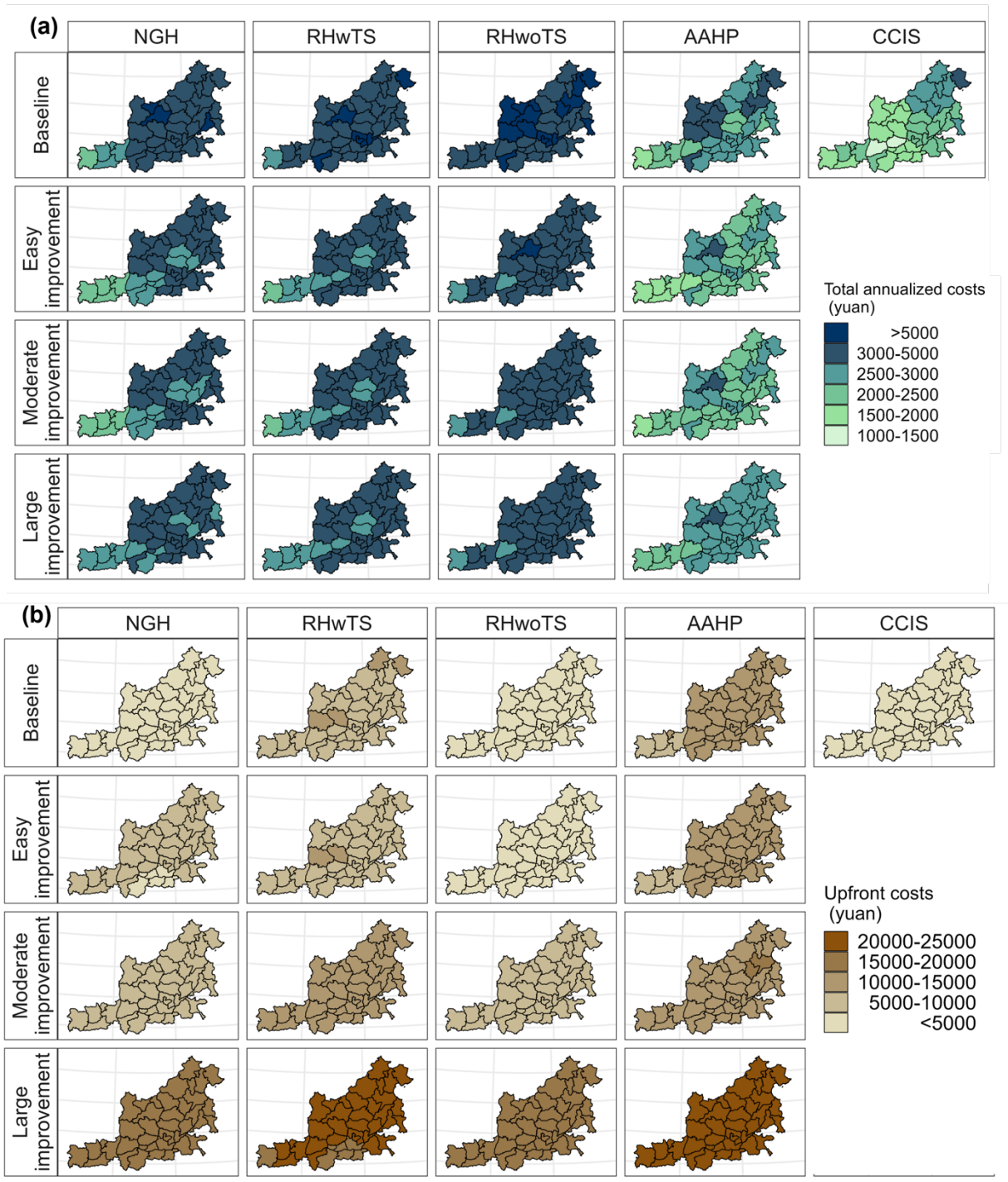


Figure S18. Household (a) total annual costs and (b) upfront capital costs of space heating with various building envelopes and heaters in new buildings in the "2+26" cities plus the Fen-Wei Plain region of northern China. The figure shows costs when rural households maintain indoor temperatures at 18 °C during the heating season. Discount rate is 5%. The expected lifetime of new building envelopes is assumed to be 15 years. See Table 1 for definition of heater acronyms.

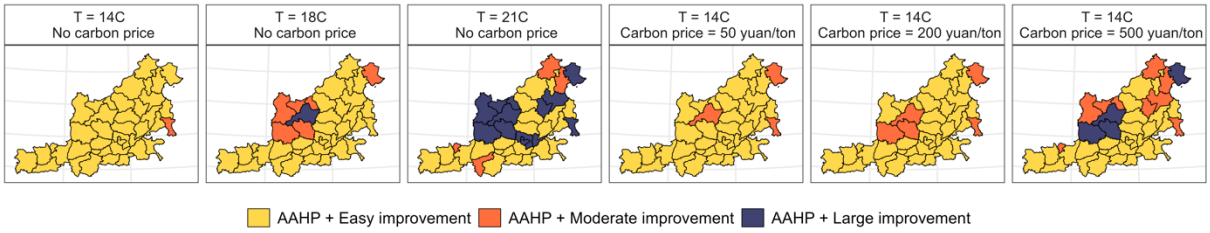


Figure S19. Household lowest total annualized cost heater and building envelope efficiency level options of space heating under various indoor temperatures and carbon prices in new buildings in the "2+26" cities plus the Fen-Wei Plain region of northern China. Note: AAHP always have the lowest total annualized cost of all heater options. The expected lifetime of new building envelopes is assumed to be 15 years. See Table 1 for definition of heater acronyms.

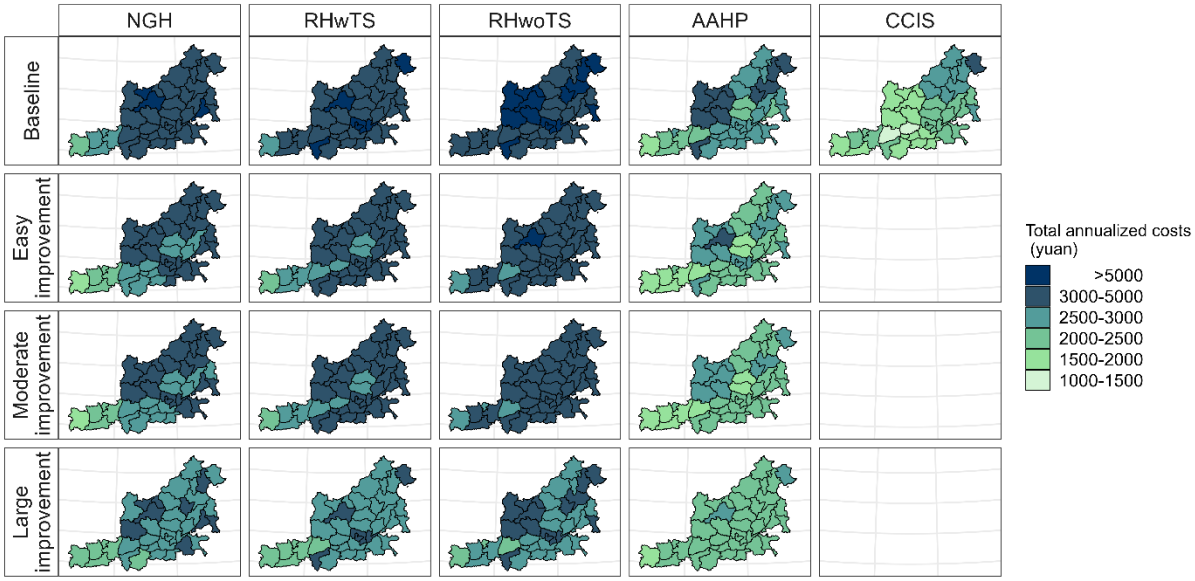


Figure S20. Household total annual costs space heating with various building envelopes and heaters in new buildings in the "2+26" cities plus the Fen-Wei Plain region of northern China. The figure shows costs when rural households maintain indoor temperatures at 18 °C during the heating season. The discount rate is 5%. The expected lifetime of new building envelopes is assumed to be 25 years. See Table 1 for definition of heater acronyms.

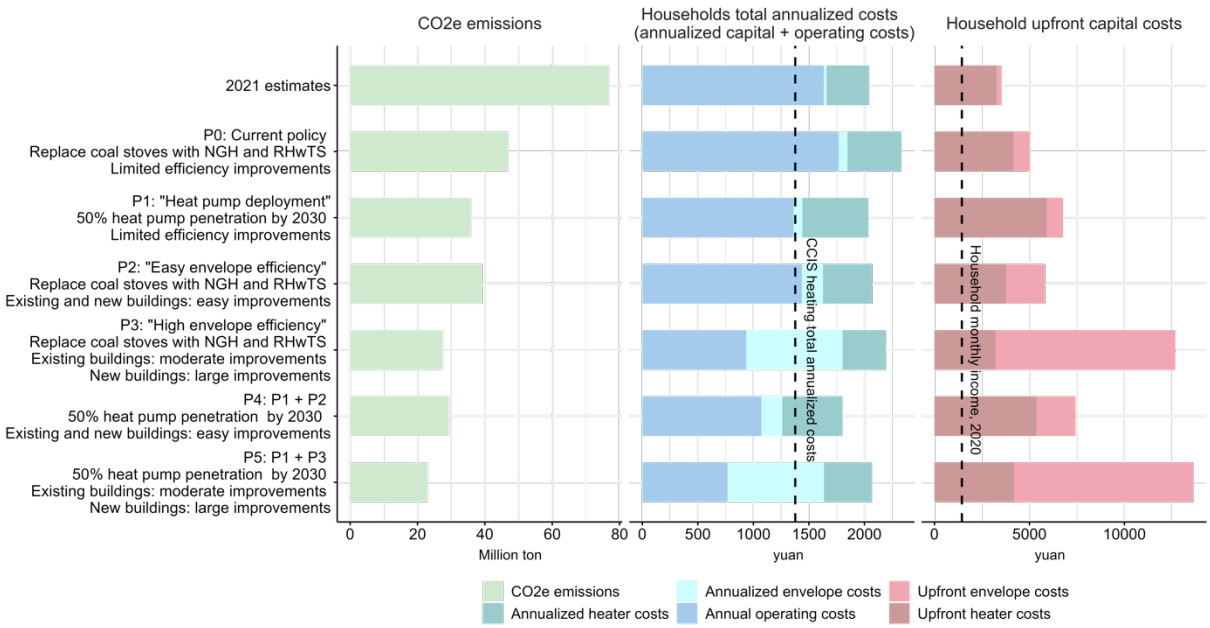


Figure S21. CO_2e emissions, population-weighted household total annualized costs (TACs), and upfront capital costs (UCCs) in 2030 under various policy scenarios in the "2+26" cities and the Fen-Wei Plain region of northern China. The vertical dashed lines denote the TAC of CCIS and household monthly income in 2020 for comparison. P_0 represents the current "no-coal zone" policy, while P_1-P_5 are various possible improved clean heating policy scenarios implemented between 2020 and 2030. In this figure, we follow the sustainable development scenario in IEA reports to estimate the carbon intensity of the power grid (see Table S5).

Reference:

Asdrubali, Francesco, Marta Roncone, and Gianluca Grazieschi. 2021. “Embodied Energy and Embodied Gwp of Windows: A Critical Review.” Energies 14(13).

Building Energy Research Center of Tsinghua University. 2012. 2012 Annual Report on China Building Energy Efficiency. China Architecture & Building Press.

China’s Ministry of Housing and Urban-Rural Development. 2013. Design Standard for Energy Efficiency of Rural Residential Buildings.

Cui, Yanqiu, Ninghan Sun, Hongbin Cai, and Simeng Li. 2020. “Indoor Temperature Improvement and Energy-Saving Renovations in Rural Houses of China’s Cold Region—a Case Study of Shandong Province.” Energies 13(4). doi: 10.3390/en13040870.

Evans, Meredydd, Sha Yu, Bo Song, Qinqin Deng, Jing Liu, and Alison Delgado. 2014. “Building Energy Efficiency in Rural China.” Energy Policy 64:243–51. doi: 10.1016/j.enpol.2013.06.040.

Fan, Pingping, and Ziqin Zhao. 2019. “Energy Saving Reconstruction of Enclosure Structure of Existing Country Residential Buildings in Northwest China (in Chinese).” Energy Conservation & Environmental Protection 1003(8965):26–27.

Feng, Wei, Ke Huang, Mark Levine, Nan Zhou, and Lawrence Berkeley. 2014. “Evaluation of Energy Savings of the New Chinese Commercial Building Energy Standard.” The American Council for An Energy-Efficient Economy 2014 Summer Study on Energy Efficiency 121–32.

Fu, Mengfei, Chuanzhi Liang, Yongheng Du, and Xucan Sun. 2019. “Interpretation of the Compilation of the Technical Guidelines for Improving Energy Efficiency in Existing Agricultural Houses in Henan Province(Trial).” Construction Science and Technology 384:61–64. doi: 10.16116/j.cnki.jskj.2019.10.011.

Grazieschi, Gianluca, Francesco Asdrubali, and Guilhem Thomas. 2021. “Embodied Energy and Carbon of Building Insulating Materials: A Critical Review.” Cleaner Environmental Systems 2. doi: 10.1016/j.cesys.2021.100032.

He, Bao jie, Li Yang, Miao Ye, Ben Mou, and Yanan Zhou. 2014. “Overview of Rural Building Energy Efficiency in China.” Energy Policy 69:385–96. doi: 10.1016/j.enpol.2014.03.018.

International Energy Agency. 2020. World Energy Outlook 2020.

Jian, Yiwen, and Zan Zhu. 2010. “Sealing Performance of Rural Housing in Beijing (in Chinese).” Pp. 760–64 in The Second China Energy Scientist Forum.

Knobloch, Florian, Steef v. Hanssen, Aileen Lam, Hector Pollitt, Pablo Salas, Unnada Chewpreecha, Mark A. J. Huijbregts, and Jean Francois Mercure. 2020. “Net Emission Reductions from Electric Cars and Heat Pumps in 59 World Regions over Time.” Nature Sustainability 3(6):437–47. doi: 10.1038/s41893-020-0488-7.

Li, Baiyi, Liyao You, Min Zheng, Yao Wang, and Ziguang Wang. 2020. “Energy Consumption Pattern and Indoor Thermal Environment of Residential Building in Rural China.” Energy and Built Environment 1(3):327–36. doi: 10.1016/j.enbenv.2020.04.004.

Li, Qing, Jingkun Jiang, Juan Qi, Jianguo Deng, Deshan Yang, Jianjun Wu, Lei Duan, and Jiming Hao. 2016. “Improving the Energy Efficiency of Stoves to Reduce Pollutant Emissions from Household Solid Fuel Combustion in China.” Environmental Science and Technology Letters 3(10):369–74. doi: 10.1021/acs.estlett.6b00324.

Liu, Hongxun, and Denise L. Mauzerall. 2020. “Costs of Clean Heating in China: Evidence from Rural Households in the Beijing-Tianjin-Hebei Region.” Energy Economics. doi: https://doi.org/10.1016/j.eneco.2020.104844.

Liu, Jinghan. 2019. “DeST-Based Analysis of Energy-Saving Renovation Measures for Rural Residential Buildings in Shandong Province (in Chinese).” CC&AC (3):61–63.

Liu, Yafei, You Zhang, Chuang Li, Yun Bai, Daoming Zhang, Chunyu Xue, and Guangqing Liu. 2018. “Air Pollutant Emissions and Mitigation Potential through the Adoption of Semi-Coke Coals and Improved Heating Stoves: Field Evaluation of a Pilot Intervention Program in Rural China.” Environmental Pollution 240:661–69. doi: 10.1016/j.envpol.2018.04.110.

Ma, Sining, Siyue Guo, Dingqian Zheng, Shiyan Chang, and Xiliang Zhang. 2021. “Roadmap towards Clean and Low Carbon Heating to 2035: A Provincial Analysis in Northern China.” Energy 225:120164. doi: 10.1016/j.energy.2021.120164.

Meng, Xi, Weijie Liang, Pei Ding, Suo Wang, Yanru Li, and Enshen Long. 2015. “Survey Research on Living Environment and Energy Consumption in the West Rural Areas of China.” Pp. 1044–50 in Procedia Engineering. Vol. 121. Elsevier Ltd.

Ministry of Housing and Urban-Rural Development of China. 2016. “Code for Thermal Design of Civil Building.”

Natural Resources Defense Council. 2018. “China Dispersed Coal Governance Report 2018.”

NDRC (National Development and Reform Commission of China). 2017. “Clean Winter Heating Planning for Northern Areas (2017–2021).” Retrieved (http://www.gov.cn/xinwen/2017-12/20/content_5248855.htm).

Peng, Liqun, Qiang Zhang, Zhiliang Yao, Denise L. Mauzerall, Sicong Kang, Zhenyu Du, Yixuan Zheng, Tao Xue, and Kebin He. 2019. “Underreported Coal in Statistics: A Survey-Based Solid Fuel Consumption and Emission Inventory for the Rural Residential Sector in China.” Applied Energy 235(November 2018):1169–82. doi: 10.1016/j.apenergy.2018.11.043.

Qin, Yue, Lena Höglund-Isaksson, Edward Byers, Kuishuang Feng, Fabian Wagner, Wei Peng, and Denise L. Mauzerall. 2018. “Air Quality–Carbon–Water Synergies and Trade-Offs in China’s Natural Gas Industry.” Nature Sustainability 1(9):505–11. doi: 10.1038/s41893-018-0136-7.

Qin, Yue, Fabian Wagner, Noah Scovronick, Wei Peng, Junnan Yang, Tong Zhu, Kirk R. Smith, and Denise L. Mauzerall. 2017. “Air Quality, Health, and Climate Implications of China’s Synthetic Natural Gas Development.” Proceedings of the National Academy of Sciences 114(19):4887–92. doi: 10.1073/pnas.1703167114.

Rui, Jingwen, Huibo Zhang, Chengnan Shi, Deng Pan, Ya Chen, and Chunyu Du. 2019. “Survey on the Indoor Thermal Environment and Passive Design of Rural Residential Houses in the HSCW Zone of China.” Sustainability (Switzerland) 11(22). doi: 10.3390/su11226471.

Shan, Ming, Pengsu Wang, Jiarong Li, Guangxi Yue, and Xudong Yang. 2015. “Energy and Environment in Chinese Rural Buildings: Situations, Challenges, and Intervention Strategies.” Building and Environment 91:271–82. doi: 10.1016/j.buildenv.2015.03.016.

Shan, Ming, Liu Yanqing, Ma Rongjiang, Deng Mengsi, Ding Xingli, Yang Xudong, Zhang Yongjie, and Ye Jiandong. 2020. “Comparison of Economic and Emission Performances of Different Technologies from Coal to Clean Energy in Northern Rural China (in Chinese).” Environment and Sustainable Developemnt 3:43–49.

Shen, Guofeng. 2016. “Changes from Traditional Solid Fuels to Clean Household Energies - Opportunities in Emission Reduction of Primary PM2.5 from Residential Cookstoves in China.” Biomass and Bioenergy 86:28–35. doi: 10.1016/j.biombioe.2016.01.004.

State Council. 2021. “China’s Action Plan for Carbon Dioxide Peaking Before 2030.”

Tsinghua BERC. 2018. China Building Energy Use 2018. China Building Industry Press.

Xu, Zhen-Hong, Xing-Yu Li, Hong-Yu Wang, and Jun-Hong Liu. 2020. “Investigation and Study on Energy Conservation Retrofitting of Rural Existing Residential Buildings in Shandong (in Chinese).” Journal of Building Energy Efficiency 48(352):126–31.

Yang, Xudong. 2018. “Current Situations and Technical Routes of Rural Clean Heating (in Chinese).” in The 14th session of Building Energy Efficiency Academic Week in Tsinghua University: Clean Heating Forum, Beijing.

Zhang, Qunli, Lin Zhang, Jinzhe Nie, and Yinlong Li. 2017. “Techno-Economic Analysis of Air Source Heat Pump Applied for Space Heating in Northern China.” Applied Energy 207:533–42. doi: 10.1016/j.apenergy.2017.06.083.

Zhang, Zongxi, Yuguang Zhou, Nan Zhao, Huan Li, Bahargul Tohniyaz, Philbert Mperejekumana, Quan Hong, Rucong Wu, Gang Li, Muhammad Sultan, Ali Mohammed Ibrahim Zayan, Jinxin Cao, Riaz Ahmad, and Renjie Dong. 2021. “Clean Heating during Winter Season in Northern China: A Review.” Renewable and Sustainable Energy Reviews 149(May):111339. doi: 10.1016/j.rser.2021.111339.

Zhao, Shanguo, Wei Feng, Shicong Zhang, Jing Hou, Nan Zhou, and Mark Levine. 2015. “Energy Savings and Cost-Benefit Analysis of the New Commercial Building Standard in China.” Procedia Engineering 121(December):317–24. doi: 10.1016/j.proeng.2015.08.1074.

Zheng, Ying. 2020. “Study on Energy Conservation Reform and Economy of Rural Existing Residential Buildings (in Chinese).” Architecture Technology 51(4):469–71.

Zhou, Mi, Hongxun Liu, Liqun Peng, Yue Qin, Dan Chen, Lin Zhang, and Denise L. Mauzerall. 2021. “Environmental Benefits and Household Costs of Clean Heating Options in Northern China.” Nature Sustainability. doi: 10.1038/s41893-021-00837-w.

Appendix for Chapter 3

Table S9 Sensitivity test scenario design and descriptions.

Sensitivity factors	Scenarios
Building envelope costs	Main scenarios: learning rate = 10% High building envelope cost scenario: learning rate = 5% Low building envelope cost scenario: learning rate = 20% (similar to solar PV)
Building floor area	Main scenarios: average building lifetime = 35 years (historical average), per capita floor area in 2050 = 50 m^2 (~2015 US levels) Low new building construction scenario: average building lifetime = 50 years (historical average), per capita floor area in 2050 = 35 m^2 (IEA shift scenario)
Future district heating electrification rate	Main scenarios: linearly increase from 7% in 2020 to 70% in 2050. High heat electrification scenario: 7% in 2020, 60% in 2030, 90% in 2050. Low heat electrification scenario: linearly increase from 7% in 2020 to 30% in 2050.
Thermal comfort	Main scenarios: 21°C for heating, 26°C for cooling High thermal comfort scenario: 22°C for heating, 25°C for cooling
Future power sector decarbonization	Main scenarios: carbon emissions will linearly reduce from the peak in 2030 to zero in 2050. 80% power sector emission reduction by 2035 scenario: carbon emissions will reduce by 80% from 2020 to 2035, and to zero in 2050.
Electricity consumption growth in other sectors	Main scenarios: projected electricity demand in other sectors based on IEA reports and the DPEC (see Methods) Low electric demand growth in other sectors scenario: 20% lower than those in the main scenario High electric demand growth in other sectors scenario: 20% higher than those in the main scenario
Social costs of carbon	Main scenarios: carbon price = ¥300/$45 per ton CO_2 High carbon prices scenario: carbon price = ~¥1300/$185 per ton CO_2 (estimated social cost of carbon)
Future renewable costs	Main scenarios: BloombergNEF New Energy Outlook database Low renewable costs scenario: 20% lower than those in the main scenario High renewable costs scenario: 20% higher than those in the main scenario
Future energy storage costs	Main scenarios: BloombergNEF New Energy Outlook database Low energy storage costs scenario: 20% lower than those in the main scenario High energy storage costs scenario: 20% higher than those in the main scenario
Future CCS costs	Main scenarios: BloombergNEF New Energy Outlook database Low CCS costs scenario: 20% lower than those in the main scenario High CCS costs scenario: 20% higher than those in the main scenario

Appendix for Chapter 4

Supplementary Notes 2: Technical Background

In coal-fired power plants, electricity is produced by combusting coal in a boiler to produce high-pressure high-temperature steam. The steam is then expanded in multiple stages through a series of turbines, including high, medium, and low-pressure turbines, to convert the thermal energy into mechanical energy. The high-pressure turbine operates at the highest pressure and temperature, while the medium and low-pressure turbines operate at lower pressure/temperature levels, allowing the steam to expand gradually and maximize the energy conversion efficiency. The steam drives a generator to produce electricity, which is then cooled and condensed back into water, completing the cycle, and allowing the process to repeat.

CHP plants generate both electricity and heat. There are multiple ways to produce district heat in CHP plants:

(1) Extraction-condensing. Extraction-condensing is currently commonly used in China's large CHP plants. This technology extracts hot steam before it enters the low-pressure turbine. The steam then goes to the steam-to-water heat exchanger to transfer heat to the district heating system.

(2) Back-pressure: The back-pressure process begins with hot steam entering a back-pressure steam turbine. Different from extraction-condensing technology, the outlet steam from the back-pressure steam turbine leaves at "overpressure" (a.k.a. "a high back pressure") and is then reused for process steam applications, such as district heating or drying.

The back-pressure technology is more efficient than extraction-condensing technology for district

heat production. Back-pressure CHP plants do not require a separate condensing system, as the steam exhausted from the turbine is used directly for district heat. This eliminates the energy losses in the condenser. Back-pressure CHP plants also have a simpler design, which results in lower capital and maintenance costs.

However, back-pressure CHP technology is generally less flexible than extraction-condensing technology in operation. This is because back-pressure turbines are designed to maintain a constant pressure in the steam cycle, which limits their ability to adjust to changing load demands. Additionally, back-pressure CHP plants have a limited turndown ratio, meaning they can only operate over a narrow range of power output levels. As a result, back-pressure CHP plants are better suited for applications with a consistent and stable demand for heat and power and are ideal for small-scale CHP plants that do not need to offer much flexibility to the power grid.

Therefore, for large power plants, back-pressure technology may not be the most efficient option. Maintaining a minimum output to ensure a heat supply can limit a CHP plant's ability to provide peak-shaving services and integrate more renewable energy, resulting in renewable curtailment. In our main analysis, we assume all small CHP plants adopt the back-pressure technology.

(3) **Compression heat pumps:** Compression heat pumps utilize electricity as the primary source of energy to operate. Their function is to transfer heat from one location to another by using a refrigerant. The process includes compression, condensation, expansion, and evaporation. During the compression stage, the refrigerant is pressurized by a compressor, increasing its temperature and pressure. From there, the hot, high-pressure refrigerant travels to the condenser, releasing heat to the surrounding air or water, and then condensing into a liquid. Next, the liquid refrigerant passes through an expansion valve, which reduces pressure and temperature. The cool, low-

pressure refrigerant then enters the evaporator, where it absorbs heat from the surrounding air or water, evaporating into a gas. The cycle repeats, with the gas refrigerant returning to the compressor for compression once more.

Compression heat pumps can enhance the temperature of low-temperature waste heat from sources like coal-fired power plants and industrial facilities, making them suitable for district heating networks. Industrial compression heat pumps typically have a COP (coefficient of performance, defined as the ratio of useful heat provided to electricity consumed) ranging from 2 to 6, influenced significantly by the temperature difference between the heat source and sink.

In our main analysis, we assume compression heat pumps must raise the temperature from around 40°C to 90°C (a temperature difference of about 50°C) for district heating. Therefore, we use a COP value of around 3, based on a previous review study(Jesper et al., 2021). This also emphasizes that improvements in energy efficiency on the demand side can make adopting heat pumps in district heating systems more feasible. For instance, if building energy efficiency increases by 30%, the temperature difference could also decrease by 30%, leading to a ~40% increase in the COP of compression heat pumps.

(4) **Absorption heat pumps:** Absorption heat pumps work differently from conventional compression heat pumps, as they are powered by hot steam or natural gas and utilize an absorption process for heat transfer. The main components of an absorption heat pump system include an evaporator, generator, condenser, and absorber. In the generator, hot steam heats the absorbent solution, causing it to evaporate into a low-temperature vapor (refrigerant). The refrigerant moves to the condenser, releasing heat to the district heating system and condensing back into a liquid. The liquid then goes through a pump and an expansion valve, becoming low-pressure and low

temperature. It flows to the evaporator where it is heated by the waste heat from the power plant condenser. The liquid absorbs this heat, vaporizing in the process. The vapor returns to the absorber, where it forms an absorbent solution with the absorbent, and then returns to the generator as a high-concentration solution. The cycle repeats. Absorption heat pumps have a COP of ~1.7 (Y. Li et al., 2016; Z. Yun & Bin, 2016).

The most common working fluid used in absorption heat pumps is a mixture of water and lithium bromide (LiBr). LiBr has a high solubility for water, making it an effective absorbent, and the water-LiBr solution has a relatively low boiling point, allowing it to easily vaporize and absorb heat. Other working fluids, such as ammonia-water or sodium chloride-water, are also used in some absorption heat pump systems.

Supplementary Notes 3: Extended Methods

2.1 Availability, cost, and emissions of alternative district heating technologies

CHP and industrial waste heat

We calculate the citygate levelized total heating costs ($LTC_{CHP/IWH,t}$) of coal-fired CHP plants and industrial waste heat in year *t* using the following formula:

$$LTC_{CHP/IWH,t} = (I_{CHP/IWH}/AF_{CHP/IWH} + OC_{CHP/IWH,t})/H_{CHP/IWH,t}$$

$I_{CHP/IWH}$ denotes the initial investment costs, which include retrofit costs, heat transport pipeline costs, heat pump costs, and water pump costs. $AF_{CHP/IWH}$ denotes the annuity factor. The discount rate is set at 7%. The assumed lifespan is 30 years for CHP plants and 20 years for industrial heat pumps. For existing CHP plants and pipelines, CHP conversion costs, pipeline costs, and water pump costs are considered sunk costs and equal zero. CHP projects that utilize the extraction-condensing technology do not require heat pumps, therefore heat pump costs for these projects are also zero. When an industrial plant serves multiple cities, the CHP conversion and heat pump costs are evenly distributed among each plant-city linkage.

$OC_{CHP/IWH,t}$ denotes the operating costs, including fuel and heat transport operating costs. The extraction-condensing and absorption heat pump systems operate using the hot steam in the turbine, which results in a reduction in electricity generation. The fuel costs are therefore evaluated as the opportunity cost of this decreased generation, with a ratio of 1 kWh of steam extracted resulting in ~0.22 kWh of reduced electricity generation (Y. Li et al., 2016). Compression heat pumps used for waste heat recovery are powered by grid-based electricity. The operating costs of

grid-based compression heat pumps are calculated based on the COP and provincial-level electricity prices. Heat transport operating costs depend on the distance of the pipeline and the amount of heat supplied. $H_{CHP/IWH,t}$ represents the amount of heat delivered (excluding heat loss) in year *t*, which is determined using our matching optimization model.

Details of the calculation methods for heat generation potential and emissions can be found in the Methods section. We assume that crude steel production from steel plants will decrease by 15% from 2020 to 2030 based on previous steel production projections (Z. Li & Hanaoka, 2022).

Municipal solid waste (MSW) incineration

We estimate the city-level district heat potential from MSW incineration using the following formula:

$$DHP_{c,MSW} = \frac{heating\ days}{365} \cdot TMSW_c \cdot \sum_i MSWC_{c,i} \cdot LHV_{MSW,i} \cdot \eta_{E,MSWI} \cdot HtER_{MSWI}$$

where $DHP_{c,MSW}$ represents the district heat potential from MSW incineration for a specific city *c*. The total amount of MSW during the heating season in city *c* in 2020, denoted by $TMSW_c$, is obtained from the *Chinese Urban Construction Statistical Yearbook*. We consider seven categories of MSW: food waste, paper, textile, wood, plastic, rubber, and others. $MSWC_{c,i}$ represents the proportion of each MSW type in city *c*. LHV_i denotes the lower heating values for each type of MSW. We estimate the heating value of Chinese MSW to be 3.8~4.8 GJ/ton. This estimation aligns with the findings reported in previous studies (Y. Guo et al., 2018; Y. Liu et al., 2017; Shapiro-Bengtsen et al., 2020). We assume that China's MSW incineration power plants have an electricity generation efficiency (η_{MSWI}) of approximately 25% (W. Huang & Marefati, 2023). This

efficiency is relatively lower compared to European countries, primarily due to the higher moisture content in Chinese MSW. The heat-to-electricity ratio for MSW incineration power plants, denoted as $HtER_{MSWI}$, is assumed to be ~2 (W. Zheng et al., 2020) (the efficiency of MSW incineration CHP can reach about 75%). Shapiro-Bengtsen et al. (2020) found that the future availability of MSW for the Chinese energy sector will increase with rising income and urbanization (Shapiro-Bengtsen et al., 2020); however, this increase can be offset by implementing better waste management practices, such as sorting and recycling. Therefore, we assume a constant potential for China's MSW incineration resources between 2020 and 2030.

We calculate the levelized total costs of district heat production MSW incineration ($LCOH_{MSW}$) using the following formula:

$$ATC_{MSW} = I_{MSW}/AF_{MSW} + O\&M_{MSW,t} - WDF_{MSW,t}$$

where I_{MSW} denotes the investment costs of MSW incineration CHP facilities. Previous studies have estimated the investment costs of MSW incineration CHP facilities to range between 1000 and 1600 yuan per annual treated ton (J. He & Lin, 2019; Shao & Ma, 2020; Xin-gang et al., 2016). We use the average value of ~1300 yuan per annual treated ton in this study. The lifespan of an MSW incineration plant (T_{MSW}) is assumed to be 23 years (Xin-gang et al., 2016). The annual O&M costs of MSW incineration CHP facilities, denoted as $O\&M_{MSW,t}$, are assumed to be 9% of the investment costs (J. He & Lin, 2019; Shao & Ma, 2020; Xin-gang et al., 2016). MSW incineration facilities generate revenue through waste disposal fees ($WDF_{MSW,t}$), which is assumed to be ~70 yuan per ton (Shao & Ma, 2020).

We estimate CO_2e emissions (E_{MSW}) from MSW incineration using the following equations (Kang

et al., 2022; Y. Liu et al., 2017; N. Yang et al., 2012):

$$CI_{MSW} = (CI_{MSW,CO2} + CI_{MSW,CH4} + CI_{MSW,N2O})$$

$$CI_{MSW,CO2} = \sum_i MSWC_i \cdot DMC_i \cdot TCC_i \cdot FCC_i \cdot OF \cdot \frac{44}{12}$$

$$CI_{MSW,CH4} = GWP_{100,CH4} \cdot EF_{MSW,CH4}$$

$$CI_{MSW,N2O} = GWP_{100,N2O} \cdot EF_{MSW,N2O}$$

where $CI_{MSW,CO2}$, $CI_{MSW,CH4}$ and $CI_{MSW,N2O}$ denote the CO_2, CH_4 and N_2O emissions from MSW incineration when providing 1 GJ energy input, respectively. Only fossil carbon in MSW is accounted for in CO_2 emissions, while biogenic carbon is assumed to be carbon neutral. DMC_i, TCC_i, and FCC_i represent the respective percentages of dry matter content in the total quantity of MSW, total carbon content in the dry matter content, and fossil carbon content in the total carbon content for each specific MSW type. OF is the oxidation factor, set at 95% (Kang et al., 2022). $EF_{MSW,CH4}$ and $EF_{MSW,N2O}$ are emission factors of CH_4 and N_2O for MSW incineration, which are 6.5 kg/ton and 0.06 kg/ton (Kang et al., 2022), respectively. The global warming potentials for CH_4 and N_2O, denoted as $GWP_{100,CH4}$ and $GWP_{100,N2O}$ are 29.8 and 273, respectively, according to *IPCC Sixth Assessment Report*. Since MSW incineration CHP plants simultaneously produce heat and electricity, we allocate the total costs and emissions to heat and electricity utilizing an efficiency-based approach, as detailed in a previous study (Y. Guo et al., 2018).

Wastewater source heat pumps (WSHPs)

We estimate the city-level district heat potential from sewage wastewater source heat pumps using the following formula:

$$DHP_{c,WSHP} = \frac{heating\ days}{365} \cdot TWW_c \cdot C_w \cdot \Delta T \cdot \frac{COP_{WSHP}}{COP_{WSHP} - 1}$$

Where $DHP_{c,WSHP}$ represents the district heat potential from wastewater source heat pumps for a specific city, TWW_c denotes the quality of treatment wastewater in city c. C_w is the specific heat capacity of water, which is 4.2 J/g°C, and ΔT is the temperature changes in wastewater during the heat exchange process, which is assumed to be 5°C (W. Zheng et al., 2020). COP_{WSHP} denotes the COP of WSHPs. Previous studies found that COP of wastewater source heat pumps vary from 3 to 12 in China (Hepbasli et al., 2014). We assume that the COP of wastewater source heat pumps is 4.5 in our analysis.

We calculate the levelized total costs per unit heat of WSHPs (LTC_{WSHP}) using the following formula:

$$LTC_{WSHP} = \frac{I_{WSHP}/AF_{WSHP} + O\&M_{WSHP,t} + H_{WSHP,t}/COP_{WSHP} \cdot ep_{grid}}{H_{WSHP,t}}$$

where I_{WSHP} denotes the upfront costs of WSHP facilities. Previous studies have estimated the upfront costs of WSHP facilities to range between 1800 and 4300 yuan/kW when providing heat to its neighborhood communities. Such projects require limited pipeline infrastructure costs. To be conservative, we use the highest value of 4300 yuan/W in our analysis. The lifespan of an WSHP plant (T_{WSHP}) is assumed to be 25 years (Xin-gang et al., 2016). The annual O&M costs of

WSHP facilities, denoted as $O\&M_{WSHP,t}$, are assumed to be 2.5% of the upfront costs (J. He & Lin, 2019; Shao & Ma, 2020; Xin-gang et al., 2016).

Air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs)

ASHPs are commonly viewed as a viable, cost-efficient, and energy-efficient technology for reducing emissions in residential heating systems (IEA, 2020b; Rosenow et al., 2022; M. Zhou et al., 2021). GSHPs are more suitable for non-residential buildings as it can be used for both district heating and cooling. Residential buildings usually do not have district cooling system in China. Using for both district heating and cooling also help GSHPs as it can make the soil temperature be stable. In the heating dominated regions (where heating demand is larger than cooling demand), COPs of GSHPs maybe decrease over years with the decrease in soil temperature. Using other complementary heating technologies, such as solar collector or dual-fuel GSHPs, can help stabilize the soil temperature thus keeping the efficiency of GSHPs. Also, space outdoors is needed to install a GSHP in the ground. While GSHPs don't have aboveground components that will take up space outdoors, wells and loops will need to be installed underground—under a yard, a parking lot, or other landscaped area.

We calculate the levelized total costs per unit heat of grid-based ASHPs/GSHPs ($LTC_{ASHP/GSHP}$) using the following formula:

$$LTC_{ASHP/GSHP} = \frac{I_{ASHP}/AF_{ASHP} + O\&M_{ASHP/GSHP,t} + H_{ASHP/GSHP,t}/COP_{ASHP/GSHP} \cdot ep_{grid}}{H_{ASHP/GSHP,t}}$$

where I_{WSHP} denotes the upfront costs of ASHPs/GWHPs. Upfront costs of ASHPs are obtained from a previous study (M. Zhou et al., 2021). For upfront costs of GSHPs, previous studies have estimated the upfront costs of GWHPs to range between 6000 and 10000 yuan/kW, or 40-100% higher than the upfront costs of ASHPs in China. GSHPs with vertical boreholes have lower space requirement and more expansive. Considering the limited space resources in compact urban areas in China, we assume the upfront costs of GWHPs 10000 yuan/kW in this study, The lifespan of an ASHP (T_{ASHP}) is assumed to be 15 years, and GSHPs (T_{GSHP}) is assumed to be 25 years. The annual O&M costs of ASHPs/GWHPs, denoted as $O\&M_{ASHP/GSHP,t}$, are assumed to be 3% and 1% of the investment costs, respectively.

The COP of a ASHP depends on the ambient temperature, and the higher the ambient temperature, the higher the COP will be for heating. ASHPs typically have a seasonal COP of 1.5-3 in northern China. GSHPs usually have a higher and stable COP compared to ASHPs. Previous studies have found GSHPs have a COP of 2.5-4.3 in northern China, particularly depending on local soil temperature (Chang et al., 2017; Gao et al., 2013; J. Huang et al., 2020; Z. Liu et al., 2017; Qiao et al., 2020; K. Zhou et al., 2022). In this study, we assume a seasonal COP of GSHPs to be 2.5 in the severely cold region and 3 in the cold region.

Previous research has suggested that the costs associated with emerging technologies, particularly ASHPs and GSHPs, are likely to decrease over time due to improvements in efficiency, economies of scale, and learning effects. In line with this, we assume cost reduction between 2020 and 2030 of 9% for ASHPs and 6% for GSHPs, as estimated by a UK study (Heptonstall & Winskel, 2023). A recent report showed that there was an annual reduction of over 3% in costs for air/ground-source heat pumps in Europe between 2016 and 2019 (IRENA, 2022). In Sweden, consumer prices for

ground-source heat pumps in district heating systems halved over ~20 years (Gross & Hanna, 2019). Also, previous studies indicate that China's learning rates in energy technologies are higher than the rates measured in other regions (Helveston et al., 2022; Y. Wang et al., 2023).

Biomass

We calculate the district heating generation potential from burning agricultural and forestry residues using the biomass resource map developed by a previous study (R. Wang et al., 2023). Since biomass has much lower energy density compared to fossil fuels, transporting it over long distances from production and processing sites is usually not economically efficient. Therefore, we calculate the biomass resources available within each city and consider 50% of the total biomass resources suitable for district heating (IEA, 2021).

We are being cautious by not including extensive biomass heating in our scenario design. This is because biomass combustion, without proper emission controls, releases harmful pollutants that can affect health (D. Wu et al., 2022). Additionally, using bioenergy extensively could lead to changes in land use, causing carbon emissions and loss of biodiversity (Goetz et al., 2018).

Heating demand in 2030

To estimate the future demand for urban district heating, we use a formula that considers the projected population and per capita heating demand as follows:

$$HD_{i,j} = HD_{i,2020} \times \frac{UP_{i,j}}{UP_{i,2020}} \times \frac{PHD_{i,j}}{PHD_{i,2020}}$$

where $HD_{i,j}$ represents the urban district heating demand in city i in year j. $HD_{i,2020}$ is the urban

district heating demand in city *i* in 2020. Similarly, $UP_{i,j}$ is the urban population in city *i* in year *j*. We use the population projection from a previous study (Y. Chen et al., 2020) to estimate the future urban population in each city. $PHD_{i,j}$ is per capita heating demand in city *i* in year *j*. We assume that per capita heating demand will increase by ~20% from 2020 to 2030, based on a previous study (S. Guo et al., 2022). We therefore estimate that the total district heating demand in northern China will increase by ~25% between 2020 and 2030. Our estimates are consistent with the previous estimates (S. Guo et al., 2022; Z. Wang et al., 2023).

Heat loss calculation

We calculate heat loss from heat transport using the following formula based on a previous study (J. Chen et al., 2021).

$$Q_{loss} = \frac{t_p - t_g}{\frac{1}{2\pi\lambda_i}\ln\frac{d+2\delta}{d} + \frac{1}{2\pi\lambda_e}\ln\left(\frac{2H}{d+2\delta} + \sqrt{\left(\frac{2H}{d+2\delta}\right)^2 - 1}\right)} \cdot (1+\beta) \cdot L$$

where Q_{loss} represents heat loss measured in kilowatts. t_p and t_g represent the temperatures of the hot water and the ground surface, respectively, which are assumed to be ~100°C and 0°C. λ_i and λ_e are the coefficients of thermal conductivity of the insulating material and earth, respectively, which are 0.023 and 2 W/(m*K). The variable d represents the thickness of the insulating layer, which is set to 60 mm in this study. H is the depth of the pipe and is fixed at 2 m, while *L* denotes the length of the heat transport pipeline. Finally, β is a coefficient associated with the pipeline components, and its value is 0.15 in this study. We further calculate heat loss factors (in the unit of GJ/km per year) using on local heating days.

Water pump capacity and electricity consumption

Water pumps are needed to transport heat. We calculate water pump capacity (P_{wp}) and associated electricity consumption (Q_{wp}) required for each plant-city linkage from heat transport using the following formula based on a previous study (J. Chen et al., 2021).

$$P_{wp} = \frac{P_{supply}}{\eta c_p \Delta T}\left[\frac{R(1+\theta)}{\rho}\right] \cdot L$$

$$Q_{wp} = \frac{Q_{supply}}{\eta c_p \Delta T}\left[\frac{R(1+\theta)}{\rho}\right] \cdot L$$

where P_{supply} and Q_{supply} the maximum heat transport capacity and the amount of heat transported, respectively. c_p, which is equal to 4.2 kJ/kg/K, denotes the specific heat capacity of water. ΔT represents the temperature difference between the supply and return waste, set at 50K for this study. The variable L denotes the length of the pipe. θ, which is equal to 20%, is a coefficient that accounts for pipeline components. R, which represents the specific frictional resistance, is set at 30, and ρ, which denotes the water density, is 960 kg/m^3. We further use electricity prices to calculate heat transport costs.

Supplementary Tables

Table S10 Government policies on coal-based district heating infrastructure improvements

Year	Policy	Measures
2016	Management Measures for Combined Heat and Power Generation	- Meet >60% of the district heating demand through CHP generation in large and medium-sized cities. - Plan and construct new CHP projects based on heating demands. - Replace inefficient coal-fired boilers and outdated small-scale CHP units with large and efficient CHP facilities. - The electricity generated by cogeneration units is prioritized for purchase by power grid companies, following the principle of "dispatching electricity generation based on heating demand".
2017-2021	The Clean Winter Heating Plan	- Utilize CHP plants to replace small coal-fired boilers that are within the range of CHP heat supply. - Promote medium- and long-distance heat transport. - Encourage CHP units to recover waste heat from exhaust steam and circulating cooling water to increase heat production capacity. - Convert electricity-only power units (particularly those located near the city and in operation for less than 15 years) into CHP plants.
2021-2025	The Coal Power Plant Upgrade Plan	- Convert 50 GW electricity-only units (particularly those located near the city and in operation for less than 15 years) to CHP units by 2025 to replace coal-fired boilers. - Encourage the adoption of back-pressure turbines, industrial heat pumps, and other advanced CHP technologies. - Increase coal-fired power plants (including CHP plants) flexibility to integrate renewable energy sources.
2021-2025	14th Five-year Plan for Energy Conservation and Emission Reduction	- Promote clean heating in northern regions based on local conditions and accelerate the large-scale use of industrial waste heat and renewable energy in urban district heating. - Convert large electricity-only power units into CHP plants. Maximize the utilization of power plant resources to eliminate coal-fired boilers and scattered coal use within the coverage of urban heating networks. - Accelerate the phase-out of outdated coal-fired boilers and small coal-fired cogeneration units, and promote the utilization of industrial waste heat, power plant waste heat, and clean energy.
2021-2025	14th Five-Year Plan for a Modern Energy System	- Optimize the use of natural gas and prioritize ensuring residential needs and clean heating during winter in northern regions. - Promote the use of nuclear energy in the clean heating sector. - Develop biomass energy for clean heating according to local conditions. - Actively promote the use of deep geothermal energy for heating and cooling in the Beijing-Tianjin-Hebei region, Shanxi, Shaanxi, Henan, and Hubei. - Convert large electricity-only power units into CHP plants and promote the use of industrial waste heat for heating. - Gradually phase out small coal-fired boilers and scattered coal within the coverage of heating networks.

		- Encourage public institutions and residents to use non-coal, efficient heating products. - Eliminate the use of scattered coal in key atmospheric pollution prevention areas and phase out coal-fired boilers with a capacity below 35 tons/hour by 2025.
2021-2025	14th Five-Year Plan on Urban Infrastructure	- Improve the efficiency of heat transport and distribution. - Promote CHP technologies, along with the utilization of industrial waste heat, natural gas, electricity, and renewable energy for urban district heating based on local conditions. - Develop low-carbon energy sources for district heating. - Replace small and polluting coal heat sources with clean coal-fired heat sources, supporting the low-carbon transition of urban heating. - Support cities in upgrading heating networks, conducting pilot projects for multi-heat source district heating systems, and enhancing the safety of urban heating systems.

Table S11 District heat demand and generation potential by sources in 2020 in northern China.

Unit: PJ	Demand	Large coal-fired CHP			MSW	Biomass	WHR, industrial facilities			Waste water
		Extraction	Absorption	WHR			Steel	Chemical	Nuclear	
BTH	723	507	640	681	16	7	576	2	0	30
Gansu	129	328	428	361	2	2	32	1	0	4
Heilongjiang	448	176	219	230	5	28	28	2	0	11
Henan	195	363	480	411	6	12	77	4	0	9
Jilin	279	131	165	171	4	26	44	0	0	12
Liaoning	632	263	334	340	7	12	210	0	113	23
Inner Mongolia	354	1298	1668	1639	4	6	103	30	0	7
Ningxia	64	344	444	401	1	1	5	12	0	2
Qinghai	52	31	39	38	1	0	8	6	0	2
Shaanxi	155	481	632	537	4	2	22	15	0	6
Shandong	525	684	868	867	12	24	159	5	30	21
Shanxi	268	680	874	821	4	3	169	5	0	6
Xinjiang	192	623	790	709	3	6	35	7	0	4
Total	4019	5912	7586	7208	71	128	1472	88	143	139

Table S12 Emission factors of electricity and steam

Fuel	Unit	Emission factors
Coal-fired electricity	kg-CO_2/kwh	0.968 (Qin et al., 2018)
Natural gas-fired electricity	kg-CO_2/kwh	0.410 (Qin et al., 2018)
Coal-fired CHP-produced steam	ton-CO_2/TJ	126 (In-depth observation of the carbon market, 2021)

Table S13 Costs and CO_2 emissions of coal boilers, natural gas boilers and biomass boilers.

	Coal boiler	Natural gas boiler	Biomass boilers
Efficiency	50-85% (W. Zheng et al., 2020)	80-90% (W. Zheng et al., 2020)	80-90%
Heating value	27.5 (M. Zhou et al., 2021) MJ/kg	34 (M. Zhou et al., 2021) MJ/m^3	14.7 (R. Wang et al., 2023) MJ/kg
CO_2 emission factor	2746.5 (M. Zhou et al., 2021) g-CO_2 /kg coal	55.8 (M. Zhou et al., 2021) g-CO_2/MJ	1.7 (R. Wang et al., 2022) ton-CO_2/TJ
Fuel market price	500-1200 yuan/ton coal	2-4 yuan/m^3	700-1100 yuan/ton biomass
Total costs per unit heat	44-64 yuan/GJ (*residential coal price ~660 yuan/ton)	65-147 yuan/GJ	75-99 yuan/GJ
Carbon intensity	117-200 ton-CO_2/TJ	62-70 ton-CO_2/TJ	~2 (R. Wang et al., 2022) ton-CO_2/TJ

Table S14 Municipal solid waste (MSW) composition and carbon content in China.

	Food waste	Paper	Textile	Wood	Plastic	Rubber	Others
MSW composition for different regions							
NE	59.90%	7.30%	1.54%	2.30%	6.50%	1.60%	20.86%
NC	53.25%	7.67%	3.26%	3.21%	6.80%	5.50%	20.31%
NW	39.26%	5.00%	2.38%	3.92%	12.1%	0.8%	36.54%
LHV (GJ/ton)	1.9	9.4	5.8	9.0	21.5	21.5	0
Dry matter content (%)	40	90	80	85	100	84	-
Total carbon content (% of dry matter)	38	46	50	50	75	67	-
Fossil carbon content (% of total carbon)	0	1	20	0	100	20	0

Abbreviations: NE, Northeast, including Heilongjiang, Jilin, Liaoning; NC, North China, including Beijing, Tianjin, Hebei, Shandong, Henan, Shanxi, Shaanxi; NW, Northwest, including Xinjiang, Neimenggu, Gansu, Qinghai, Ningxia; LHV: lower heating values.

Data sources: (Z. Zhao et al., 2020), (Y. Liu et al., 2017)

Table S15 Renewable (including hydro) ratio of electricity generation in 15 provinces in northern China.

Province	2020	2030 Current Policy	2030 Accelerated Power Sector Decarbonization
Beijing	16.40%	45.00%	67.00%
Gansu	52.50%	52.50%	67.00%
Hebei	14.20%	45.00%	67.00%
Heilongjiang	23.40%	45.00%	67.00%
Henan	21.60%	45.00%	67.00%
Jilin	30.30%	45.00%	67.00%
Liaoning	17.20%	45.00%	67.00%
Inner Mongolia	21.10%	45.00%	67.00%
Ningxia	26.70%	45.00%	67.00%
Qinghai	84.70%	84.70%	84.70%
Shaanxi	24.80%	45.00%	67.00%
Shandong	12.40%	45.00%	67.00%
Shanxi	18.80%	45.00%	67.00%
Tianjin	16.10%	45.00%	67.00%
Xinjiang	20.54%	45.00%	67.00%

Notes: China has set a renewable portfolio standard (RPS) to 40% of electricity consumption by 2030. This RPS policy aims to ensure a "fair and equitable distribution of the responsibility for renewable energy development and consumption". This means all provinces achieve a renewable ratio of >40% by 2030 (they can purchase renewables from other provinces), despite significant differences in their starting points in 2020. Our gird-based emission factors are designed based on this RPS policy and the IEA analysis (IEA, 2019b).

Table S16 Heating days, electricity prices, COPs of air source heat pumps, and the share of natural gas heating in 15 provinces in northern China.

Province	Heating days	On-gird electricity tariff yuan/MWh	Residential electricity tariff yuan/MWh	COP of ASHP	The proportion of natural gas in district heating in 2020
Beijing	114	351.9	371.7	2.44	88%
Gansu	148	248.7	402.5	2.35	15%
Hebei	114	320.9	425.0	2.47	32%
Heilongjiang	181	373.5	438.9	1.58	2%
Henan	90	356.2	515.0	2.98	16%
Jilin	167	365.4	455.2	1.95	1%
Liaoning	145	370.6	460.0	2.37	3%
Neimenggu	181	272.5	435.5	1.74	6%
Ningxia	142	248.7	394.4	2.42	14%
Qinghai	204	280.2	377.1	1.95	26%
Shaanxi	99	326.8	423.3	2.70	42%
Shandong	105	411.0	461.9	2.85	22%
Shanxi	126	321.6	396.6	2.51	16%
Tianjin	118	351.9	395.0	2.65	14%
Xinjiang	140	215.1	390.0	2.04	38%

Data source: (M. Zhou et al., 2021), (Building Energy Research Center Tsinghua University, 2023)

Table S17 Maximum heat to power ratios of various CHP technologies

Power plant capacity/CHP technology	Cooling technology	Max heat to power ratio
~300MW, extraction-condensing	Dry	1.55 (W. Zheng et al., 2020)
~300MW, extraction-condensing	Cooling	1.53 (W. Zheng et al., 2020)
>600MW, extraction-condensing	Dry	1.44 (W. Zheng et al., 2020)
>600MW, extraction-condensing	Cooling	1.31 (W. Zheng et al., 2020)
Absorption heat pumps	-	1.8 (S. Yin et al., 2020)
Back pressure technology	-	1.5 (W. Zheng et al., 2020)
Nuclear power plants	-	1.6 (J. Chen et al., 2021)

Table S18 Process heat distributions in coal-fired power plants

Combustion technology	Power	Condenser	Exhaust	Other losses
Subcritical	30%	50%	10%	10%
Supercritical	38%	42%	10%	10%
Ultra-supercritical	45%	35%	10%	10%

Data source: (Gingerich & Mauter, 2015)

Table S19 District heat generation and costs from steel and chemical plants

Technology	District heat production potential	Fixed costs	Utilization factors
Steel plants	~5290 MJ/ ton-crude steel (Lin, 2021)	1.24 million yuan per MW (Lin, 2021)	0.8
Chemical plants	~2851 MJ/ton-methanol (W. Zheng et al., 2020) ~2000 MJ/ton-oil (W. Zheng et al., 2020)	1.15 million yuan per MW (Lin, 2021)	0.76

Table S20 Investment costs of pipelines and heat pumps

Investment	Unit	Investment costs
Heat transport pipeline	million yuan/km	25(Lin, 2021)[*]
Electricity-only to CHP conversion costs	million yuan per generation unit	33(J. Chen et al., 2018)
Compression heat pump	million yuan/ MW	1.44(Xue et al., 2008)[**]
Absorption heat pump	million yuan/ MW	0.72[***]
Water pump	million yuan/ MW	0.70(Lin, 2021)

[*]The costs of heat transport pipelines vary significantly across project reports and studies. For example, the reported costs per kilometer range from 1.449(J. Hu et al., 2015) million yuan/km to 90(Taiyuan Thermal Power Group Co., 2021) million yuan/km, with other reported costs being 2.96(K. Tong et al., 2017) million yuan/km, 2.5(Z. Wang & Yan, 2018) million yuan/km, and 25(Lin, 2021) million yuan/km. High pipeline costs will impact the cost-effectiveness of new linkages, particularly those with long plant-city distances.

[**]The cost range of previous reports and studies compression heat pump was 0.5-4(IRENA, 2022; Lin, 2021; Xue et al., 2008) million yuan/ MW.

[***]The cost range of previous reports and studies for absorption heat pump was 0.25-1.00 million yuan/ MW. We here assume that absorption heat pumps cost roughly half as much as compression heat pumps(Lin, 2021).

Supplementary Figures

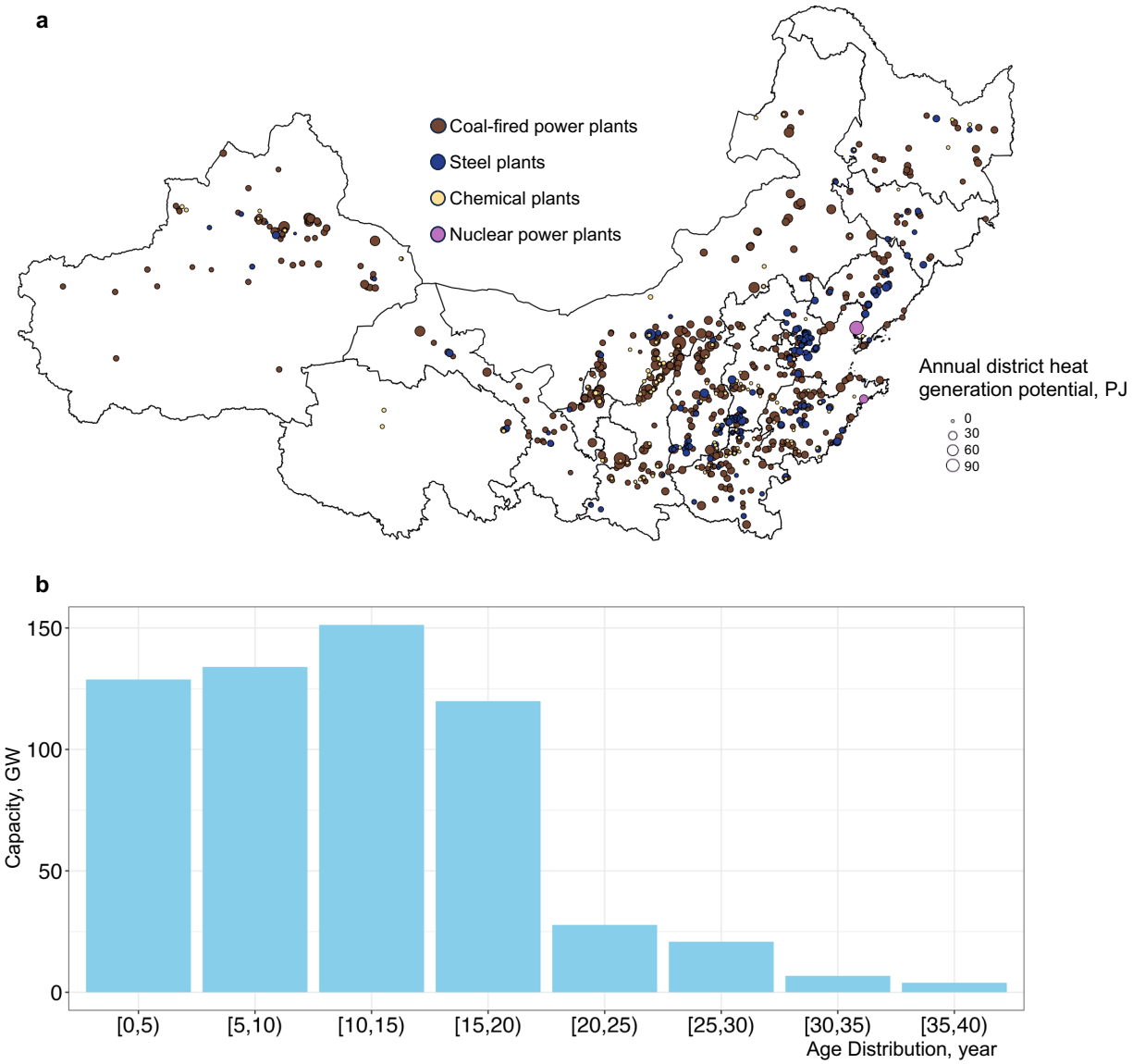


Figure S22. Geological and age distribution of industrial facilities in northern China.
a, Map showing coal-fired power plants, steel plants, chemical plants, and nuclear power plants in northern China. Dot size represents the annual district heat generation potential in 2020.
b, Age distribution of large coal-fired power plants in China in 2023.

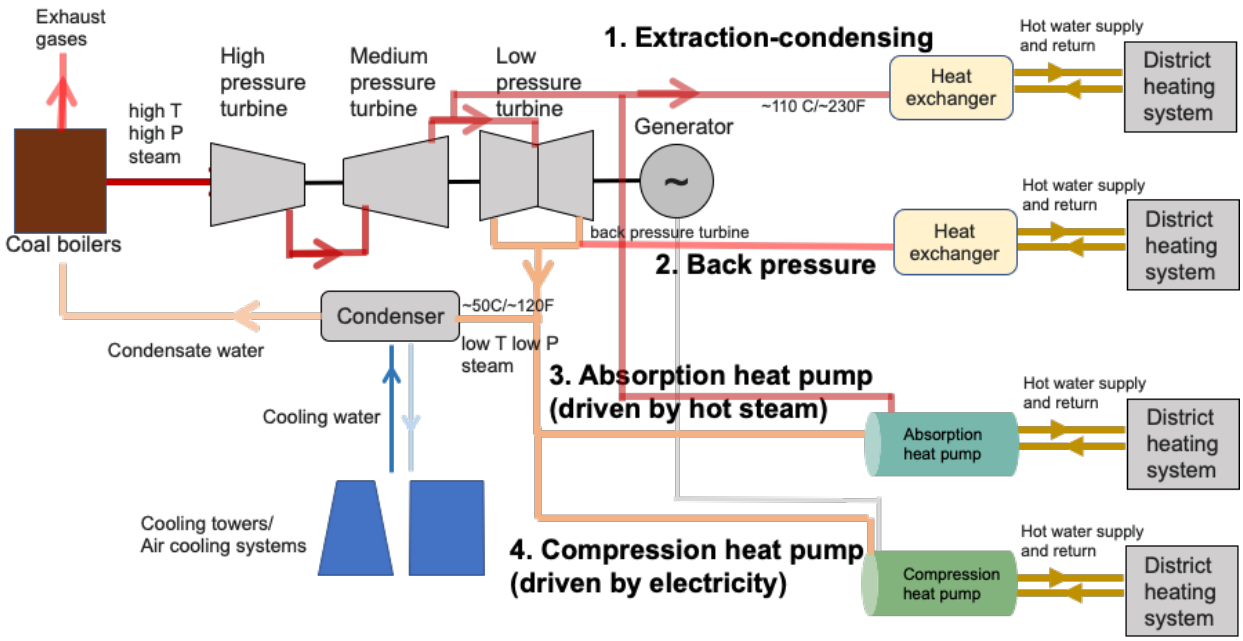


Figure S23. Workflow diagram of coal-fired power plants and various CHP technologies.

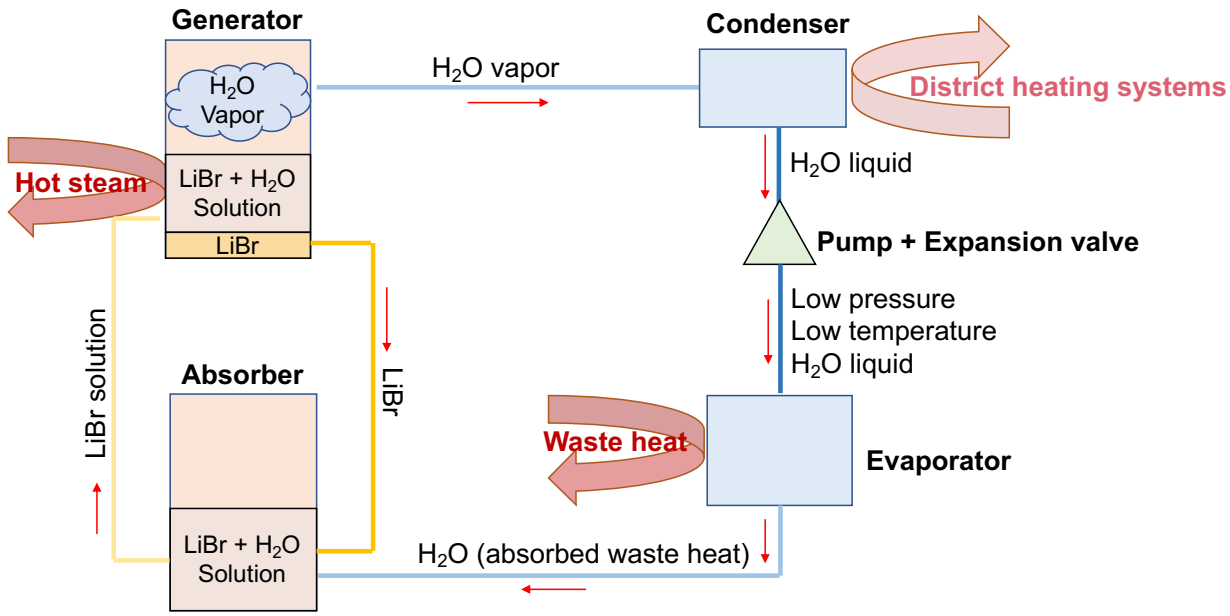


Figure S24. Workflow diagram of absorption heat pumps.

Reference:

Building Energy Research Center Tsinghua University. (2023). China Building Energy Efficiency Annual Development Research Report.

Chang, J., Liu, H., Wang, C., & Liu, M. (2017). The applications and economic analysis of Ground Source Heat Pump (GSHP) in certain national games sports centre. Procedia Engineering, 205, 863–870. https://doi.org/10.1016/j.proeng.2017.10.029

Chen, J., Deng, M., & Gao, X. (2018). Technical and economical comparison and selection of 1000 MW pure condensing unit for heat supply. Energy Conservation, 1, 65–67.

Chen, J., Zheng, W., Kong, Y., Yang, X., Liu, Z., & Xia, J. (2021). Case study on combined heat and water system for nuclear district heating in Jiaodong Peninsula. Energy, 218, 119546. https://doi.org/10.1016/j.energy.2020.119546

Chen, Y., Guo, F., Wang, J., Cai, W., Wang, C., & Wang, K. (2020). Provincial and gridded population projection for China under shared socioeconomic pathways from 2010 to 2100. Scientific Data, 7(1), 83. https://doi.org/10.1038/s41597-020-0421-y

Gao, Y., Peng, Y., & Liu, J. (2013). Comprehensive Benefit Analysis of Direct Expansion Ground Source Heat Pump System. Energy and Power Engineering, 05(02), 76–81. https://doi.org/10.4236/epe.2013.52a009

Gingerich, D. B., & Mauter, M. S. (2015). Quantity, Quality, and Availability of Waste Heat from United States Thermal Power Generation. Environmental Science and Technology, 49(14), 8297–8306. https://doi.org/10.1021/es5060989

Goetz, A., Searchinger, T., Beringer, T., German, L., McKay, B., Oliveira, G. de L. T., & Hunsberger, C. (2018). Reply to commentary on the special issue Scaling up biofuels? A critical look at expectations, performance and governance. Energy Policy, 118, 658–665. https://doi.org/10.1016/j.enpol.2018.03.046

Gross, R., & Hanna, R. (2019). Path dependency in provision of domestic heating. Nature Energy, 4(5), 358–364. https://doi.org/10.1038/s41560-019-0383-5

Guo, S., Jiang, Y., & Hu, S. (2022). The Pathways toward Carbon Peak and Carbon Neutrality in China's Building Sector. Chinese Journal of Urban and Environmental Studies, 10(02). https://doi.org/10.1142/S2345748122500117

Guo, Y., Glad, T., Zhong, Z., He, R., Tian, J., & Chen, L. (2018). Environmental life-cycle assessment of municipal solid waste incineration stocks in Chinese industrial parks. Resources, Conservation and Recycling, 139, 387–395. https://doi.org/10.1016/j.resconrec.2018.05.018

He, J., & Lin, B. (2019). Assessment of waste incineration power with considerations of subsidies and emissions in China. Energy Policy, 126, 190–199. https://doi.org/10.1016/j.enpol.2018.11.025

Helveston, J. P., He, G., & Davidson, M. R. (2022). Quantifying the cost savings of global solar photovoltaic supply chains. Nature, 612(7938), 83–87. https://doi.org/10.1038/s41586-022-05316-6

Hepbasli, A., Biyik, E., Ekren, O., Gunerhan, H., & Araz, M. (2014). A key review of wastewater source heat pump (WWSHP) systems. Energy Conversion and Management, 88, 700–722. https://doi.org/10.1016/j.enconman.2014.08.065

Heptonstall, P., & Winskel, M. (2023). Decarbonising Home Heating: An Evidence Review of Domestic Heat Pump Installed Costs Technology and Policy Assessment Research Report.

Hu, J., Luo, X., Chen, Y., Mo, S., & Hua, B. (2015). Exergy and economic analysis for a retrofitted heat pump system. HV&AC, 45(4), 95–100.

Huang, J., Fan, J., & Furbo, S. (2020). Demonstration and optimization of a solar district heating system with ground source heat pumps. Solar Energy, 202, 171–189. https://doi.org/10.1016/j.solener.2020.03.097

Huang, W., & Marefati, M. (2023). Development, exergoeconomic assessment and optimization of a novel municipal solid waste-incineration and solar thermal energy based integrated power plant: An effort to improve the performance of the power plant. Process Safety and Environmental Protection, 172, 562–578. https://doi.org/10.1016/j.psep.2023.02.016

IEA. (2019). World Energy Outlook 2019. https://doi.org/10.6027/9789289329996-1-en

IEA. (2020). The Future of Heat Pumps.

IEA. (2021). Implementation of bioenergy in China Country Reports. http://english.www.gov.cn/policies/latest_releases/2018/07/03/content_281476207708632.htm

In-depth observation of the carbon market. (2021). Who worries and who cares when quotas arrive for power generation enterprises. http://m.tanpaifang.com/article/79409.html

IRENA. (2022). Renewable solutions in end-uses: Heat pump costs and markets. www.irena.org

Jesper, M., Schlosser, F., Pag, F., Walmsley, T. G., Schmitt, B., & Vajen, K. (2021). Large-scale heat pumps: Uptake and performance modelling of market-available devices. Renewable and Sustainable Energy Reviews, 137, 110646. https://doi.org/10.1016/j.rser.2020.110646

Kang, Y., Yang, Q., Wang, L., Chen, Y., Lin, G., Huang, J., Yang, H., & Chen, H. (2022). China's changing city-level greenhouse gas emissions from municipal solid waste treatment and driving factors. Resources, Conservation and Recycling, 180, 106168. https://doi.org/10.1016/j.resconrec.2022.106168

Li, Y., Chang, S., Fu, L., & Zhang, S. (2016). A technology review on recovering waste heat from the condensers of large turbine units in China. Renewable and Sustainable Energy Reviews, 58, 287–296. https://doi.org/10.1016/j.rser.2015.12.059

Li, Z., & Hanaoka, T. (2022). Plant-level mitigation strategies could enable carbon neutrality by 2060 and reduce non-CO2 emissions in China's iron and steel sector. One Earth, 5(8), 932–943. https://doi.org/10.1016/j.oneear.2022.07.006

Lin, J. (2021). Study on utilization of low grade waste heat potential in steel plant for heating. North China Electric Power University.

Liu, Y., Sun, W., & Liu, J. (2017). Greenhouse gas emissions from different municipal solid waste management scenarios in China: Based on carbon and energy flow analysis. Waste Management, 68, 653–661. https://doi.org/10.1016/j.wasman.2017.06.020

Liu, Z., Xu, W., Zhai, X., Qian, C., & Chen, X. (2017). Feasibility and performance study of the hybrid ground-source heat pump system for one office building in Chinese heating dominated areas. Renewable Energy, 101, 1131–1140. https://doi.org/10.1016/j.renene.2016.10.006

Qiao, Z., Long, T., Li, W., Zeng, L., Li, Y., Lu, J., Cheng, Y., Xie, L., & Yang, L. (2020). Performance assessment of ground-source heat pumps (GSHPs) in the Southwestern and Northwestern China: In situ measurement. Renewable Energy, 153, 214–227. https://doi.org/10.1016/j.renene.2020.02.024

Qin, Y., Höglund-Isaksson, L., Byers, E., Feng, K., Wagner, F., Peng, W., & Mauzerall, D. L. (2018). Air quality–carbon–water synergies and trade-offs in China's natural gas industry. Nature Sustainability, 1(9), 505–511. https://doi.org/10.1038/s41893-018-0136-7

Rosenow, J., Gibb, D., Nowak, T., & Lowes, R. (2022). Heating up the global heat pump market. Nature Energy, 7(10), 901–904. https://doi.org/10.1038/s41560-022-01104-8

Shao, L., & Ma, D. (2020). Insights into the Waste-to-Energy Industry: Review and Outlook.

Shapiro-Bengtsen, S., Andersen, F. M., Münster, M., & Zou, L. (2020). Municipal solid waste available to the Chinese energy sector – Provincial projections to 2050. Waste Management, 112, 52–65. https://doi.org/10.1016/j.wasman.2020.05.014

Taiyuan Thermal Power Group Co., Ltd. (2021). Taiyuan-Gujiao long-distance heating project. https://www.tyrl.com/browse/NewInfo.aspx?ID=1f26df5b-76b0-4c3b-8348-4456306f3e9d

Tong, K., Fang, A., Yu, H., Li, Y., Shi, L., Wang, Y., Wang, S., & Ramaswami, A. (2017). Estimating the potential for industrial waste heat reutilization in urban district energy systems: Method development and implementation in two Chinese provinces. Environmental Research Letters, 12(12). https://doi.org/10.1088/1748-9326/aa8a17

Wang, R., Cai, W., Yu, L., Li, W., Zhu, L., Cao, B., Li, J., Shen, J., Zhang, S., Nie, Y., & Wang, C. (2023). A high spatial resolution dataset of China's biomass resource potential. Scientific Data, 10(1), 384. https://doi.org/10.1038/s41597-023-02227-7

Wang, R., Li, H., Cai, W., Cui, X., Zhang, S., Li, J., Weng, Y., Song, X., Cao, B., Zhu, L., Yu, L., Li, W., Huang, L., Qi, B., Ma, W., Bian, J., Zhang, J., Nie, Y., Fu, J., … Wang, C. (2022). Alternative Pathway to Phase Down Coal Power and Achieve Negative Emission in China. Environmental Science & Technology, 56(22), 16082–16093. https://doi.org/10.1021/acs.est.2c06004

Wang, Y., Wang, R., Tanaka, K., Ciais, P., Penuelas, J., Balkanski, Y., Sardans, J., Hauglustaine, D., Liu, W., Xing, X., Li, J., Xu, S., Xiong, Y., Yang, R., Cao, J., Chen, J., Wang, L., Tang, X., & Zhang, R. (2023). Accelerating the energy transition towards photovoltaic and wind in China. Nature, 619(7971), 761–767. https://doi.org/10.1038/s41586-023-06180-8

Wang, Z., Li, H., Zhang, B., Wang, B., Li, H., Tian, X., Lin, J., & Feng, W. (2023). Unequal residential heating burden caused by combined heat and power phase-out under climate goals. Nature Energy. https://doi.org/10.1038/s41560-023-01308-6

Wang, Z., & Yan, W. (2018). Discussion on economy of small capacity and advanced steam conditions coal-fired co-generation units (in Chinese). Energy Conservation Technology, 36(6), 505–509.

Wu, D., Zheng, H., Li, Q., Jin, L., Lyu, R., Ding, X., Huo, Y., Zhao, B., Jiang, J., Chen, J., Li, X., & Wang, S. (2022). Toxic potency-adjusted control of air pollution for solid fuel combustion. Nature Energy, 7(2), 194–202. https://doi.org/10.1038/s41560-021-00951-1

Xin-gang, Z., Gui-wu, J., Ang, L., & Yun, L. (2016). Technology, cost, a performance of waste-to-energy incineration industry in China. Renewable and Sustainable Energy Reviews, 55, 115–130. https://doi.org/10.1016/j.rser.2015.10.137

Xue, Y., Xiao, Y., Li, B., & Yuan, Q. (2008). Economic analysis of medium/high temperature heat pump assisted geothermal indirect heating systems. Journal of Shandong Jianzhu University, 23(6), 496–500.

Yang, N., Zhang, H., Chen, M., Shao, L.-M., & He, P.-J. (2012). Greenhouse gas emissions from MSW incineration in China: Impacts of waste characteristics and energy recovery. Waste Management, 32(12), 2552–2560. https://doi.org/10.1016/j.wasman.2012.06.008

Yin, S., Xia, J., & Jiang, Y. (2020). Characteristics analysis of the heat-to-power ratio from the supply and demand sides of cities in northern China. Energies, 13(1). https://doi.org/10.3390/en13010242

Yun, Z., & Bin, Z. H. U. (2016). An Economic Comparison of Absorption Heat Pump and Compression Heat Pump in Central Heating Area of Power Plant. 4–7.

Zhao, Z., Bian, R., Zhao, F., & Chai, X. (2020). Implications of municipal solid waste disposal methods in China on greenhouse gas emissions. Environmental Progress & Sustainable Energy, 39(3). https://doi.org/10.1002/ep.13372

Zheng, W., Zhang, Y., Xia, J., & Jiang, Y. (2020). Cleaner heating in Northern China: potentials and regional balances. Resources, Conservation and Recycling, 160(April), 104897. https://doi.org/10.1016/j.resconrec.2020.104897

Zhou, K., Mao, J., Zhang, H., Li, Y., Yu, X., Chen, F., & Li, M. (2022). Design strategy and techno-economic optimization for hybrid ground heat exchangers of ground source heat pump system. Sustainable Energy Technologies and Assessments, 52. https://doi.org/10.1016/j.seta.2022.102140

Zhou, M., Liu, H., Peng, L., Qin, Y., Chen, D., Zhang, L., & Mauzerall, D. L. (2021). Environmental benefits and household costs of clean heating options in northern China. Nature Sustainability. https://doi.org/10.1038/s41893-021-00837-w