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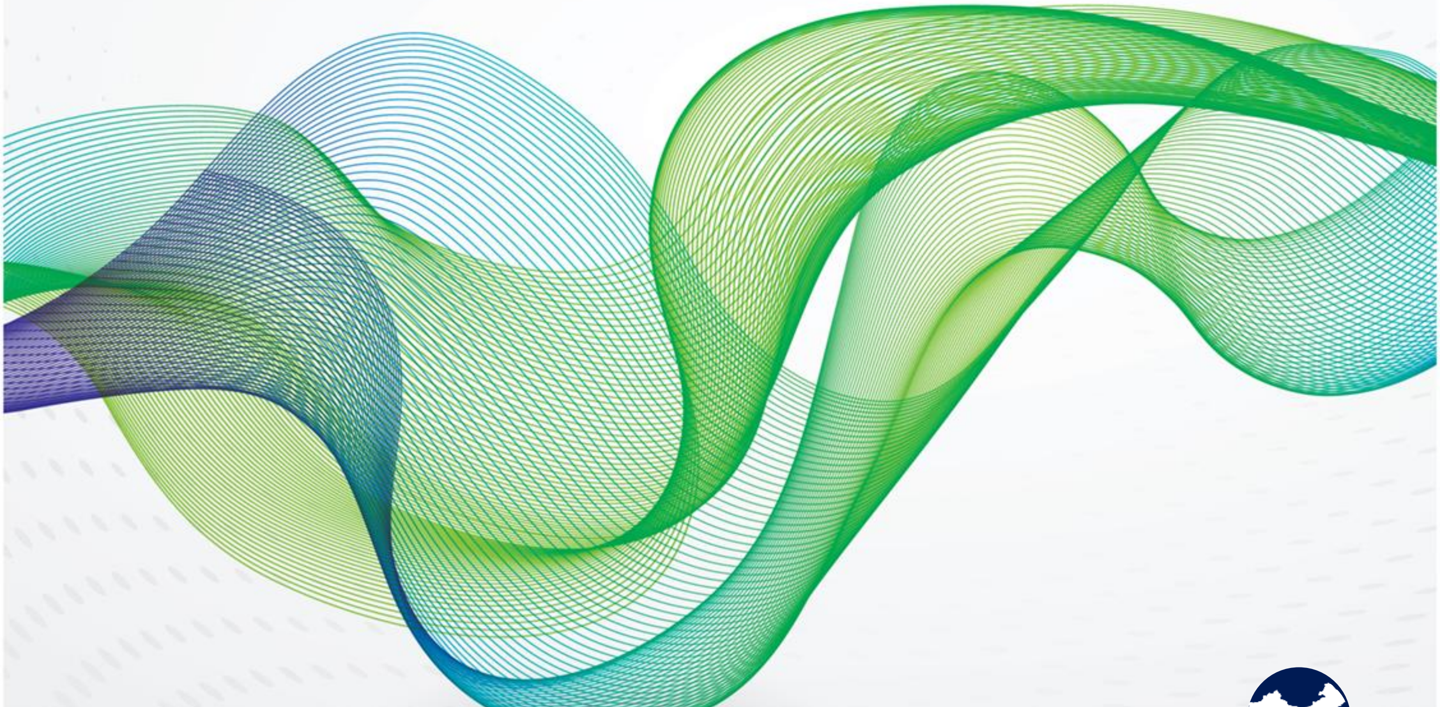
Synergies between China's Whole County PV program and rural heating electrification



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Executive Summary:

- Electrification of heating, particularly with highly efficient heat pumps, is increasingly viewed as essential for reaching the targets of the Paris Climate Agreement. In China, rural heating has long represented a major contributor to local air pollution, poor indoor air quality, and significant greenhouse gas emissions from coal burning.
- For years China has promoted replacement of dirty coal heating in rural areas, initially with natural gas, and more recently with clean coal stoves, both of which have significant emissions.
- More recently China has also begun promoting distributed solar PV as a rural development strategy, particularly with the launch of the Whole County PV pilots in 2021. The Whole County PV pilot program centres on having at least a minimum percentage of rooftops equipped with solar PV—20 per cent in the case of residential rooftops.
- Several analyses have shown that heat pumps are economical in China, including when paired with solar PV. However, the Whole County PV program has not been specifically studied.
- This study examines the economics of heat pumps in participating counties in the Whole County PV program. The analysis shows that pairing residential heat pumps with PV in counties in Shandong, Henan, and Jiangsu – the provinces with the most counties participating in the Whole County PV program – would result in short economic payback periods versus gas or resistance heat, while also increasing self-consumption of PV.
- The results suggest that expanding the Whole County PV program to incorporate energy efficiency and heating/cooling measures could represent an economically attractive way to accelerate the rural energy transition and improve rural livelihoods.
- Barriers to such an approach include involvement of different government ministries, the cost of upgrading building insulation, the design of building codes, and the structure of electricity tariffs. While these barriers are significant, they also represent some of the same barriers that previously hindered distributed PV adoption, suggesting that the design of the Whole County PV program might be applied to help address these barriers.
- From a wider perspective, residential heating and cooling represent a relatively straightforward way to abate carbon emissions, given that an economically attractive and technically viable technology already exists. Scaling up heat pump adoption in rural areas would also greatly expand manufacturing of heat pumps in China, with the potential to boost availability of low-cost heat pumps for adoption of this technology worldwide.

Introduction

China is undergoing a multi-decade clean energy transition, shifting away from its historic reliance on coal and other fossil fuels, with the goal of achieving carbon neutrality by 2060. In the first phase of China's transition, which preceded the country's carbon neutrality goal, China's policies focused on the supply side of the power sector, particularly improving the efficiency of the country's fossil fuel power plant fleet while scaling up renewable energy sources such as wind and solar. For several years, China has had more wind and solar capacity than any other country and continues to add more additional capacity at rates far exceeding other regions.[1] As a result of China's manufacturing scale-up in solar and batteries, these technologies have come down rapidly in price, and are now competitive in China and elsewhere.[2]

In recent years, policy makers have accelerated the deployment of distributed renewable energy, particularly solar photovoltaics (PV). Given the nature of China's dense urban environment, and the need to improve the living standards of rural areas, promotion of distributed energy has targeted rural and peri-urban parts of the country.

The next phase of the transition is likely to require greater attention to demand-side energy efficiency and electrification of energy consumption. To this end, heat pumps have an important role in decarbonizing the heating sector in China.[3] This is particularly true in rural areas, where heating historically has relied on fossil fuels, and where policy makers focus on air quality combined with rising incomes. Changing preferences for interior comfort and indoor air quality are leading to rapidly rising energy demand for clean space heating.[4] Energy use for summer cooling has also risen dramatically, due to rising incomes as well as the effects of global climate change.[5]

Because of their high efficiency and low emissions relative to fossil fuel alternatives, heat pumps have the potential to provide efficient heating solutions in much of rural China, including in regions with low winter temperatures. Also, studies have demonstrated the clear air quality and public health benefits from heat pump adoption in China.[6] Emissions from natural gas and clean coal stoves, though lower than conventional coal stoves, are still significant in terms of both indoor emissions and their impact on ambient air quality. Heat pumps have also been shown to have significant potential to contribute to China's carbon neutrality goals.[7]

Although heating demand peaks in the winter at night, while solar output peaks in summertime, China's dry winter climate makes the country relatively attractive for winter solar production. Pairing heat pumps

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[1] "Renewables 2022 Global Status Report," REN21, 2022, at https://www.ren21.net/wp-content/uploads/2019/05/GSR2022_Full_Report.pdf.

[2] Jonas Nahm and Edward S. Steinfeld, "Scale-up Nation: China's Specialization in Innovative Manufacturing," World Development 54, 2014, at https://doi.org/10.1016/j.worlddev.2013.09.003; Alan C. Goodrich et al., "Assessing the drivers of regional trends in solar photovoltaic manufacturing," Energy & Environmental Science, 2013, at https://doi.org/10.1039/c3ee40701b; Rainer Quitzow et al., "Development trajectories in China's wind and solar energy industries: How technology-related differences shape the dynamics of industry localization and catching up," Energy Policy 39, 2017, at http://dx.doi.org/10.1016/j.jclepro.2017.04.130; Jorrit Gosens and Yongling Lu, "From lagging to leading? Technological innovation systems in emerging economies and the case of Chinese wind power," Energy Policy 60, September 2013, at https://doi.org/10.1016/j.enpol.2013.05.027; Annegret Stephan et al., "How has external knowledge contributed to lithium-ion batteries for the energy transition?," iScience 24, January 22, 2021, at https://doi.org/10.1016/j.isci.2020.101995.

[3] Hongzhi Yan et al., "The Underestimated Role of the Heat Pump in Achieving China's Goal of Carbon Neutrality by 2060," Engineering, 2022, at https://doi.org/10.1016/j.eng.2022.08.015; Hongzhi Yan et al., "The role of heat pump in heating decarbonization for China carbon neutrality," Carbon Neutrality, 1(40), 2022, at https://doi.org/10.1007/s43979-022-00038-0.

[4] Baojun Tang, "Clean heating transition in the building sector: The case of Northern China," Journal of Cleaner Production, 307, 20 July 2021, https://doi.org/10.1016/j.jclepro.2021.127206.

[5] Xiao-Bing Zhang et al., "Cooler rooms on a hotter planet? Household coping strategies, climate change, and air conditioning usage in rural China," Energy Research & Social Science, 68, October 2020, at https://doi.org/10.1016/j.erss.2020.101605.

[6] Hongxun Liu and Denise L. Mauzerall, "Costs of clean heating in China: Evidence from rural households in the Beijing-Tianjin-Hebei region," Energy Economics, 90, 2020, at https://doi.org/10.1016/j.eneco.2020.104844; Mi Zhou et al., "Environmental benefits and household costs of clean heating options in northern China," Nature Sustainability, November 2021, at https://doi.org/10.1038/s41893-021-00837-w.

[7] Hanzhi Yan et al., "The role of heat pump in heating decarbonization for China carbon neutrality," Carbon Neutrality, 1(40), 2022, at https://doi.org/10.1007/s43979-022-00038-0.

with solar PV or energy storage has been studied both in China and internationally; studies show that heating paired with solar could be effective and economically feasible in much of China.[8] Pairing heat pumps with solar has the potential to reduce peak loads, contribute to system stability by providing ancillary services, and improve PV economics by increasing self-consumption.[9] Further, heat pumps can reduce winter electricity demand and related emissions, especially in northern China where coal power predominates. Also pairing heat pumps with distributed solar PV can help alleviate the problem of weak distribution grids, which often limits the amount of midday excess electricity production that distributed PV can feed back into the grid for other users.

Although the temporal mismatch between heating demand (which peaks in the winter and at night) and solar PV output could present a challenge, researchers have evaluated several potential solutions. For example, heat pumps have the potential to incorporate energy storage capability, such as with hot water,[10] a solution that has been evaluated for the cold areas of North China.[11] Well-insulated homes can also act as a store of thermal energy via pre-heating with a smart thermostat.[12] Combining smart control systems for preheating and energy storage can result in lower energy use, higher-efficiency heat pump operation during cold temperature periods, and lower capital cost due to reduced design capacity of heat pump systems with more consistent load factors, an especially important consideration for buildings with variable occupancy levels.[13]

China's Whole County PV pilot program, launched in 2021, has potential synergies with programs to encourage heat pump adoption in certain regions, particularly regions with substantial demand for both heating and cooling. Rural regions are especially attractive, given the barriers to installing solar and heat pumps in dense, urban districts, and given government policies to encourage rural development and clean heating.

This paper is organized as follows: the first section provides background on rural energy policy, particularly for solar PV, and analyses the solar potential of rural areas participating in the Whole County PV program. The second section analyses the building energy situation in rural areas and the potential for heat pumps. The third section analyses the potential for PV to improve self-consumption for homes with heat pumps across China, followed by an economic analysis. The concluding section offers suggestions and discusses policy barriers for incorporating heat pumps into the Whole County PV program.

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[8] Xiaoyang Hou et al., "A Critical Review on Decarbonizing Heating in China: Pathway Exploration for Technology with Multi-Sector Applications," Energies 15, 2022, at https://doi.org/10.3390/en15031183; Hongxun Liu and Denise L. Mauzerall, "Costs of clean heating in China: Evidence from rural households in the Beijing-Tianjin-Hebei region," Energy Economics, 90, 2020, at https://doi.org/10.1016/j.eneco.2020.104844; Chunling Wu et al., "Low-temperature air source heat pump system for heating in severely cold area: Long-term applicability evaluation," Building and Environment, 208, 15 January 2022, at https://doi.org/10.1016/j.buildenv.2021.108594; Maggie Mowrer and Qianqian Cui, "Research Shows Huge Heat Pump Potential in China," CLASP, 30 August 2022, at https://www.clasp.ngo/updates/research-shows-huge-heat-pump-potential-in-china/; Yaolin Lin et al., "A Review on the Research and Development of Solar-Assisted Heat Pump for Buildings in China," Buildings, 13 September 2022, at https://doi.org/10.3390/buildings12091435.

[9] International case studies include Elena Bee et al., "Air-source heat pump and photovoltaic systems for residential heating and cooling: Potential of self-consumption in different European climates," Building Simulation, June 2019, at https://doi.org/10.1007/s12273-018-0501-5; David Fischer et al., "Smart meter enabled control for variable speed heat pumps to increase PV self-consumption," Proceedings of the 24th IIR International Congress of Refrigeration, 16 August 2015, at http://dx.doi.org/10.18462/iir.icr.2015.0580; Maria Pinamonte et al., "Rule-Based Control Strategy to Increase Photovoltaic Self-Consumption of a Modulating Heat Pump Using Water Storages and Building Mass Activation," Energies, 13(23), 2020 at https://doi.org/10.3390/en13236282; David Fischer et al., "Model-based flexibility assessment of a residential heat pump pool," Energy, 188, 1 January 2017, at https://doi.org/10.1016/j.energy.2016.10.111; Dashamir Marini et al., "Sizing domestic air-source heat pump systems with thermal storage under varying electrical load shifting strategies," Applied Energy, 255, 2019, at https://doi.org/10.1016/j.apenergy.2019.113811.

[10] For an overview of thermal energy storage options, see Philip Eames et al., "The Future Role of Thermal Energy Storage in the UK Energy System: An Assessment of the Technical Feasibility and Factors Influencing Adoption," UK Energy Research Council, November 2014, at https://ukerc.ac.uk/publications/the-future-role-of-thermal-energy-storage-in-the-uk-energy-system/.

[11] Meng Yu et al., "Techno-economic analysis of air source heat pump combined with latent thermal energy storage applied for space heating in China," Applied Thermal Engineering, 185, 2021, at https://doi.org/10.1016/j.applthermaleng.2020.116434.

[12] Sihui Li et al., "Dynamic coupling method between air-source heat pumps and buildings in China's hot-summer/cold-winter zone," Applied Energy 254, 2019, at https://doi.org/10.1016/j.apenergy.2019.113664.

[13] Jiewen Deng et al., "Can heat pump heat storage system perform better for space heating in China's primary schools? A field test and simulation analysis," Energy & Buildings, 279, 2023, at https://doi.org/10.1016/j.enbuild.2022.112684.

1. Background: rural energy policy and the Whole County PV pilots

The rural population is a priority for development, including in energy and energy efficiency.

According to the National Bureau of Statistics, rural China had a population of 510 million in 2020, larger than most world regions.[14] Rural China faces profound development challenges. Rural incomes—around RMB 18,000 per capita in 2020—are just a fraction of urban incomes.[15] In the poorest areas, remittances account for a significant share of household income.[16] Rural areas lost 164 million in population in the decade between 2010 and 2020, a decline of 2.7 per cent annually, and is now just 36 per cent of the country's population.[17] (Rural population loss is roughly consistent across China's regions.[18]) Rural residents are also older: 24 per cent are over age 60, compared to 16 per cent in urban areas, and the gap is rising.[19]

In other respects, rural areas have seen improvements. Rural household incomes rose by a factor of 3x from 2010 to 2020.[20] The rural-urban income gap peaked at a ratio of over 3.0 in 2009 before gradually declining in subsequent years.[21] Many of these changes have been helped by policies targeted to improve rural livelihoods, both in agricultural and non-agricultural regions.

For years, energy policy has included programs aimed at rural areas, including both solar energy and clean heating. The goals of such programs include improving living conditions, reducing regional and local air pollution, and accelerating the energy transition.

Clean heating has been the most visible such program. While China had long promoted clean stoves and heaters, the effort accelerated as part of the Action Plan on Air Pollution Control and Prevention, from 2013-2017. The central government launched a campaign aimed at replacing the use of low-quality loose coal (*sanmei*, also called dispersed or bulk coal), and switching from coal to gas or coal to electricity for heating in northern regions, especially in the Beijing-Tianjin-Hebei region surrounding the capital city. The early phase of the program was beset by problems, most notably in the winter of 2017, when residents and schools in some areas were left without heating.[22] The policy's focus on gas and electric heat, which are often more expensive than coal—especially for poorly insulated buildings typical in rural areas—has led to increases in energy vulnerability in many poorer regions.[23] The program has

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[14] "Communiqué of the Seventh National Population Census (No. 7)－Urban and Rural Population and Floating Population," China National Bureau of Statistics, 11 May 2021, at http://www.stats.gov.cn/english/PressRelease/202105/t20210510_1817192.html.

[15] "Annual per capita disposable income of rural households in China from 1990 to 2021," Statista, January 2022, at https://www.statista.com/statistics/289182/china-per-capita-net-income-rural-households/.

[16] "Income of Rural Residents in Poor Areas in 2019," China National Bureau of Statistics, 3 February 2020, at http://www.stats.gov.cn/english/PressRelease/202002/t20200203_1724909.html.

[17] "Communiqué of the Seventh National Population Census (No. 7)－Urban and Rural Population and Floating Population," China National Bureau of Statistics, 11 May 2021, at http://www.stats.gov.cn/english/PressRelease/202105/t20210510_1817192.html.

[18] Hua Zhang et al., "Evolution and influencing factors of China's rural population distribution patterns since 1990," PLoS One, 15(5), May 2020, at https://doi.org/10.1371/journal.pone.0233637.

[19] "Health commission bulletin highlights aging population," China Development Brief, 10 November 2021, at https://chinadevelopmentbrief.org/reports/health-commission-bulletin-highlights-aging-population/. See also, He Huifeng, "Rural China ageing faster than urban areas as proportion of over-60s continues to grow," South China Morning Post, 16 October 2021, at https://www.scmp.com/news/china/article/3152604/rural-china-ageing-faster-urban-areas-proportion-over-60s-continues-grow.

[20] "Annual per capita disposable income of rural households in China from 1990 to 2021," Statista, January 2022, at https://www.statista.com/statistics/289182/china-per-capita-net-income-rural-households/.

[21] Zhang Junsen, "A Survey on Income Inequality in China," Journal of Economic Literature, 59 (4), 2021, at https://doi.org/10.1257/jel.20201495.

[22] Hu Zhanping, "De-Coalizing Rural China: A Critical Examination of the Coal to Clean Heating Project from a Policy Process Perspective," Frontiers in Energy Research, 6 July 2021, at https://doi.org/10.3389/fenrg.2021.707492.

[23] Lunyu Xie et al., "Who suffers from energy poverty in household energy transition? Evidence from clean heating program in rural China," Energy Economics, 106, 2022, at https://doi.org/10.1016/j.eneco.2021.105795; Shengyue Fan et al., "Using energy vulnerability to measure distributive injustice in rural heating energy reform: A case study of natural gas replacing bulk coal for heating in Gaocheng District, Hebei Province, China," Ecological Economics, 197, 2022, at https://doi.org/10.1016/j.ecolecon.2022.107456.

nevertheless continued, converting at least eight million households away from coal heating, while also providing various subsidies targeting poorer rural households.[24]

Solar energy is also a longstanding target for rural energy policy. Low-cost solar thermal collectors for water heating became popular in the 1990s and have shown strong growth in rural areas up to the present.[25] More recently, solar photovoltaics have become prominent. The Targeted Poverty Alleviation program, a 2010-2020 package of measures was designed to lift 70 million rural residents out of poverty, included subsidies and targets for rural PV and other ecological measures.[26] However, the program was not fully successful in bringing PV directly to rural residents. A survey of program implementation in Qinghai suggested that many PV programs were switched from distributed to centralized PV plants, and that administrators had difficulty targeting villages or poor residents.[27]

Local PV-related programs have also benefited rural areas. Efforts to develop agricultural PV on unused or degraded lands have provided supplementary income and employment opportunities for villages in Shanxi, Shandong, and other provinces.[28]

Solar accounted for just 3.9 per cent of electricity generated in 2021,[29] but is rising rapidly as new capacity comes online. China has an official 2030 target of 1,200 GW of wind and solar capacity, but with 50-90 GW of solar coming online annually, this is likely to be surpassed. In the National Development and Reform Commission (NDRC) Energy Research Institute's carbon-neutral scenario, solar PV would generate roughly 30 per cent of electricity by 2060, and account for nearly half China's total generating capacity.[30]

China's scale-up of PV has historically focused on large, centralized plants. The proportion of rooftop and distributed solar began to rise rapidly in 2019, as China phased out subsidized feed-in tariffs for central PV plants. Residential rooftop solar installations reached 21 GW in 2021, double the previous year, and roughly 40 per cent of annual installations.[31] The majority of PV installations in both 2021 and 2022 were classified as distributed PV, a substantial change from pre-2020, when virtually all PV was at large centralized plants.

The Whole County PV program is a relatively new policy launched in June 2021 by the National Energy Administration (NEA).[32] The requirements for the percentage of rooftops to be covered by PV under the program is:

- Government office buildings, 50 per cent
- Public buildings such as schools and hospitals, 40 per cent
- Industrial and commercial plants, 30 per cent

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[24] Hu Zhanping, "De-Coalizing Rural China: A Critical Examination of the Coal to Clean Heating Project from a Policy Process Perspective," Frontiers in Energy Research, 6 July 20221, at https://www.frontiersin.org/articles/10.3389/fenrg.2021.707492/full.

[25] Frauke Urban et al., "Solar PV and solar water heaters in China: Different pathways to low carbon energy," Renewable and Sustainable Energy Reviews 64, 2016, at http://dx.doi.org/10.1016/j.rser.2016.06.023;

[26] Jianjun Tang et al., "Narrowing urban–rural income gap in China: The role of the targeted poverty alleviation program," Economic Analysis and Policy, 75, September 2022, at https://doi.org/10.1016/j.eap.2022.05.004.

[27] Chuan Liao et al., "Targeted poverty alleviation through photovoltaic-based intervention: Rhetoric and reality in Qinghai, China," World Development, 137, January 2021, at https://doi.org/10.1016/j.worlddev.2020.105117.

[28] "122 village-level PV power stations start operation in China's Datong to boost households' income," Xinhua, 23 May 2019, at http://www.xinhuanet.com/english/2019-05/23/c_138083554.htm; "Across China, Clean energy fuels rural vitalization," Xinhua, 19 June 2019, at http://www.xinhuanet.com/english/2020-06/09/c_139125982.htm.

[29] "2021 年全国电力工业统计快报一览表 [2021 National Industrial Statistics Preliminary Report]," China Electricity Council, 26 January 2022, at https://www.cec.org.cn/detail/index.html?3-306014.

[30] "China Energy Transformation Outlook: Executive Summary," National Development and Reform Commission Energy Research Institute, 4 November 2022, at https://ens.dk/sites/ens.dk/files/Globalcooperation/2021-11-04_ceto21_summary_en-final_0.pdf.

[31] "户用光伏项目信息 [Household PV project information]," National Energy Administration, 19 January 2022, at http://www.nea.gov.cn/2022-01/19/c_1310431338.htm.

[32] "国家能源局综合司关于报送整县（市、区）屋顶分布式光伏开发试点方案的通知 [NEA Comprehensive Department Issues Whole County/City/District Rooftop Distributed PV Pilot Plan]," National Energy Administration, 20 June 2021, at http://www.chic.org.cn/home/index/detail?id=1100; "国家能源局综合司关于公布整县（市、区）屋顶分布式光伏开发试点名单的通知 [NEA Comprehensive Department Issues Whole County/City/District Rooftop Distributed PV Pilot List]," National Energy Administration, 8 September 2021, at http://www.gov.cn/zhengce/zhengceku/2021-09/15/content_5637323.htm.

- Rural residential buildings, 20 per cent

If the counties reach these targets by the end of 2023, they will be awarded with full status as demonstration counties—though the status does not come with any stated financial incentive for participation. The primary innovation of the program is reducing the costs of distributed solar—especially the soft costs of customer acquisition and contracting—via a tender or auction to select a single supplier and installer to cover all the rooftop installations included in each county pilot. The program has already been credited with a dramatic increase in distributed solar since its launch[33] and the NDRC has noted the program had over 66 GW of projects registered by the end of 2022.[34] However, it has not been without challenges, with Shandong and Hebei provinces facing criticism for flouting NEA directives by temporarily suspending all new rooftop installations or giving preferential treatment to certain state-owned enterprises.[35] Even so, Shandong anticipates the program could add 20 GW to the province's total solar capacity.[36]

Following the June 2021 issuance of the Whole County PV plan, in September 2021 NEA published a list of counties that applied to participate. The list contains 676 counties or districts, roughly two dozen of which are new development districts or zones instead of counties in the administrative sense. Thus, the localities in the program account for just under half of China's roughly 1300 county/city/district-level administrative areas. The counties in the 2021 list represent approximately 21 per cent of Mainland China's land area and 24 per cent of its population.[37] The eastern provinces of Shandong, Jiangsu, and Henan lead with over 50 counties each, while traditional western solar leader Gansu comes in fourth with 46 counties, and Qinghai has 32. Xinjiang, and Inner Mongolia have 5 and 11, respectively.

Table 1: Number of participating counties or administrative areas per province in the Whole County PV pilot

Province	amount	Province	amount	Province	amount	Province	amount
Beijing	6	Shanghai	8	Hubei	19	Yunnan	28
Tianjin	4	Jiangsu	59	Hunan	12	Tibet	9
Hebei	37	Zhejiang	30	Guangdong	32	Shaanxi	26
Shanxi	26	Anhui	17	Guangxi	22	Gansu	46
Inner Mongolia	11	Fujian	24	Hainan	10	Qinghai	32
Liaoning	15	Jiangxi	8	Chongqing	16	Ningxia	7
Jilin	1	Shandong	70	Sichuan	6	Xinjiang	5
Heilongjiang	11	Henan	66	Guizhou	13	/	/

Source: NEA 2021

The counties range widely in terms of characteristics and are certainly not entirely rural—and some are fully urbanized. In the case of Jiangsu province, the counties listed have a combined population of 46 million, or 54 per cent of the province's total, and cover 60 per cent of the province's land area. Similarly for Shandong, the whole county PV provinces account for 49 per cent of the land area and 51 per cent of the population. Several participating counties, such as the Gulou (drum tower) district of Nanjing, are

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[33] Chloé Farand, "China's ambitious rooftop solar pilot helps drive 'blistering' capacity growth," Climate Home News, 14 July 2022, at https://www.climatechangenews.com/2022/07/14/chinas-ambitious-rooftop-solar-pilot-helps-drive-blistering-capacity-growth/.

[34] "国家发改委：风、光大基地总规模 450GW，整县试点累计备案 66GW [NDRC: Wind and solar bases to reach 450 GW, Whole County PV plans 66 GW]," Solarzoom, 1 December 2022, at https://mp.weixin.qq.com/s/xnV3bVqWKveIwLJVE49HsA.

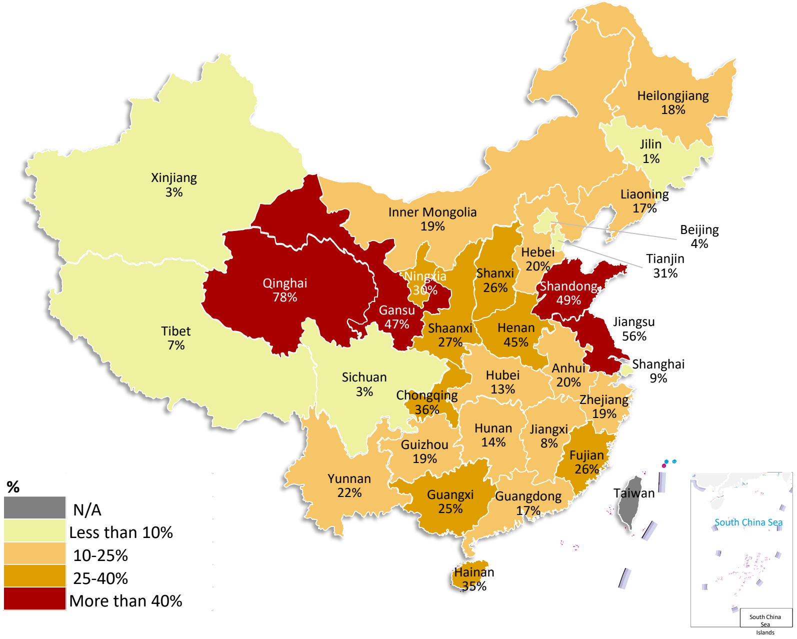
[35] "分布式光伏，山东为何"整县推'不'进"？[Why can't distributed PV get into Shandong's Whole County PV program?]," Huaxia Energy Net, 10 March 2022, at https://m.jiemian.com/article/7191779.html; "光伏"整县推进"为何陷入"四方尴尬"？[PV Counties facing embarrassing 'Why can't we get in' questions]," WeChat Energy Net, 12 April 2022, at https://mp.weixin.qq.com/s/5aeB7XsRgLEMYJpSCPeJlQ.

[36] "到"十四五"末，山东省整县分布式光伏规模化开发容量将达到 20GW 以上 [By the end of the 14th Five-Year Plan, Shandong's Whole County PV pilot could reach over 20 GW capacity]," Solarzoom, 4 March 2022, at https://mp.weixin.qq.com/s/XEMlxnt928BVNvCtJl6hIg.

[37] Author analysis, based on population and land area data searched by individual county and development zone from Wikipedia and Baidu.

at the heart of large cities, while other counties contain substantial cities, such as Gangcheng (Steel City) in Shandong province. Others are more rural, but typically still have at least some urbanized areas.[38] A typical participating county has a population between 500,000 to 1 million.

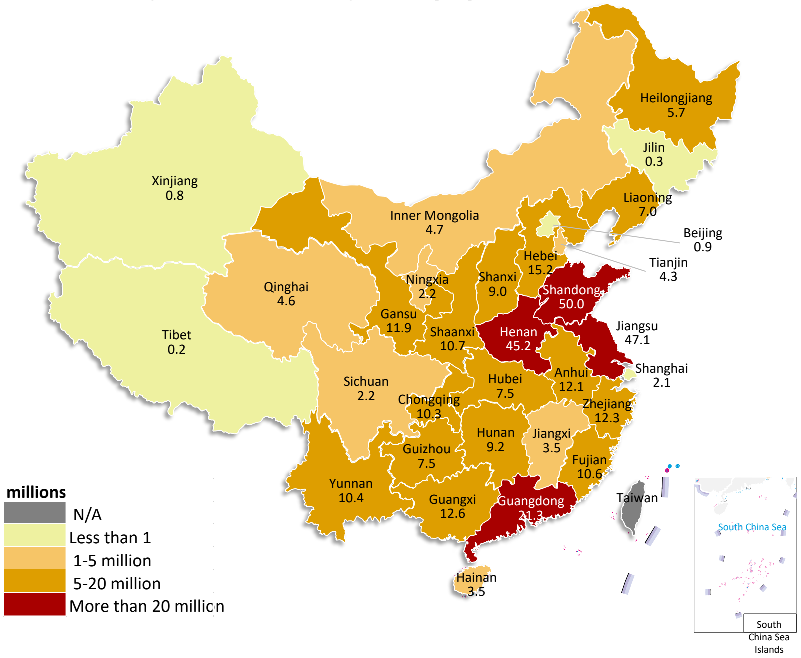
Figure 1: 2021 Whole County PV counties as percentage of the number of counties in province



Note: The maps in this report are for illustrative purposes and do not represent the expression of any opinion concerning the legal status or sovereignty of any country or territory, the delimitation of frontiers or boundaries or the names of any territory, city or region.

Source: Anders Hove, OIES, 2022

Figure 2: 2021 Whole County PV counties by total population covered



Source: Anders Hove, OIES, 2022

Considering the number of counties or share of population, participating provinces are heavily weighted towards those that already have significant solar PV capacity, and overlap with China's solar manufacturing hubs in eastern China's Jiangsu and Guangdong provinces. In contrast, Jilin and

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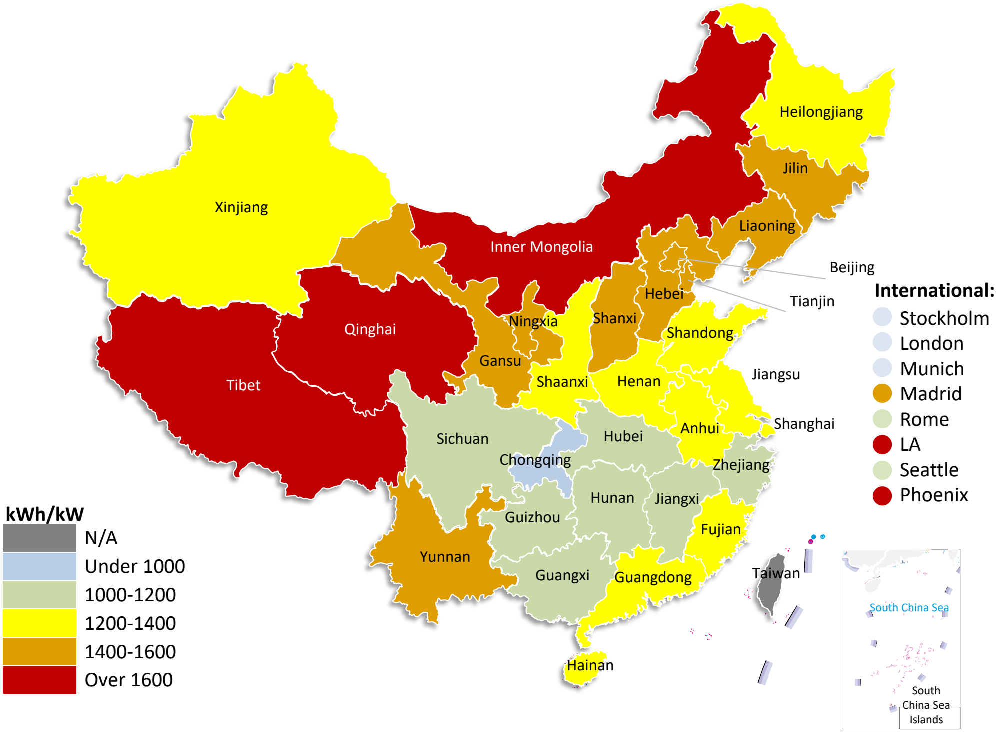
[38] Author calculation.

Heilongjiang—which have barely any participating counties—are vast provinces with high solar resources, but are a part of the country's rust belt of industrial cities.

While the best solar resources are in the sparsely inhabited north and west of China, coastal China is notable for having moderate to good solar resources. A typical county solar annual production for Jiangsu or Henan province is around 1200-1400 kWh per kW of PV capacity, substantially higher than most of Europe, though lower than Madrid or Los Angeles.[39] In China, heating load is more significant than cooling load in most regions, whereas PV output peaks in the summer. Nevertheless, China's solar resources are more seasonally balanced than in other prominent regions of Europe and North America, making heating electrification with solar more attractive. A typical PV system in coastal China would see winter (December-February) output only 35-40 per cent lower than summer (June-August) output, compared to 55-75 per cent lower winter output in much of Europe.[40]

Figure 3: Annual solar PV production (kWh per kW of PV capacity) for counties in the Whole Solar PV pilot, and international comparison



Source: OIES 2023, data from NREL PVWatts, 2022

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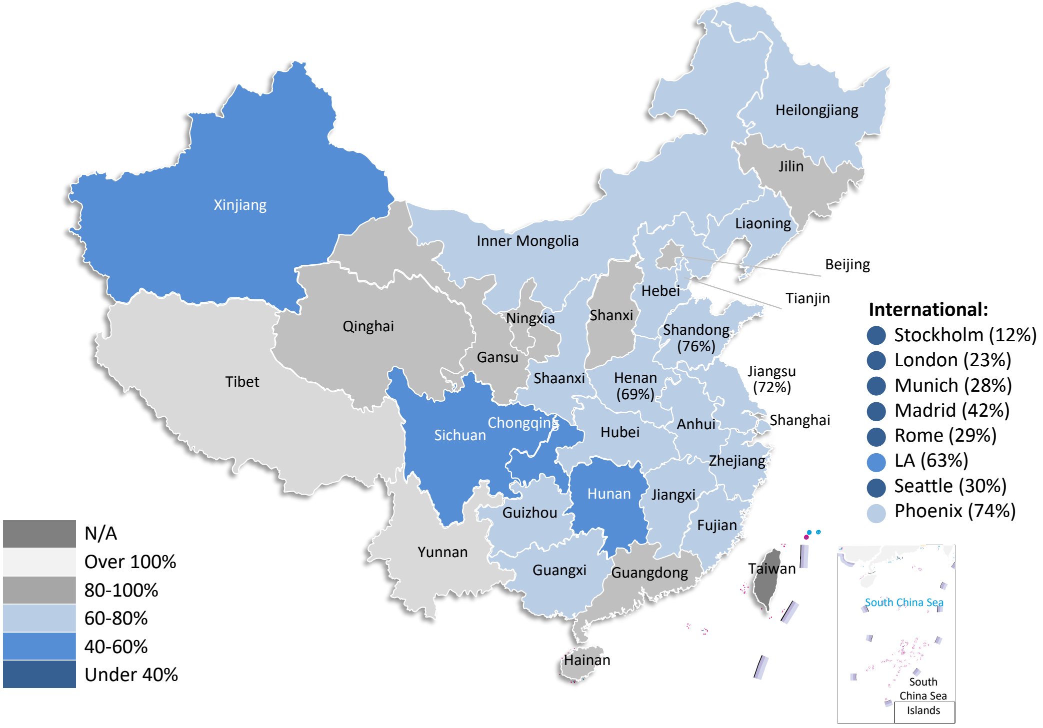
[39] Unless otherwise noted, all solar and temperature data based on author analysis and data from NREL PVWatts.

[40] Author calculations, NREL PVWatts data.

Figure 4: Winter solar PV output as a percentage of summer solar PV output, and international comparison



Source: OIES 2023; data from NREL PVWatts, 2022

2. Background: rural energy use and the potential for heat pumps

The rural energy use situation is dire. Rural residents consume more energy due to poor construction quality.[41] Typical building materials include concrete blocks, sintered clay bricks, and ceramic bricks. [42] Residents often construct or renovate on their own with locally available materials, leading to poor air tightness and high degrees of moisture infiltration. In some areas, less than 20 per cent of new buildings meet government efficiency standards.[43] In most urban areas, central heating in apartment buildings is not separately metered and charged on a floor-area basis, discouraging energy saving measures by residents and building owners.[44]

To cope with poor building performance, in South China the majority of rural residents rely on electric appliances such as electric blankets, hand-warmers, and resistance space heaters. The energy consumption of these devices can be substantial, and there is also some risk of fire given their number.[45] For those with air conditioning, such devices are used in resistance heating mode in winter for space heating.

In North China, coal is the leading fuel for heating. While many rural counties have district heating for their more urbanized areas, rural residents may use basic coal stoves and heat caves with loose coal (sanmei) or clean coal heaters. Gas heating is available in some areas, and electric heating has also been promoted as a part of the coal-to-gas/coal-to-electricity fuel switching effort in many regions.

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[41] He Bao-jie et al., “Overview of rural building energy efficiency in China,” Energy Policy, 69, 2014, at https://doi.org/10.1016/j.enpol.2014.03.018.

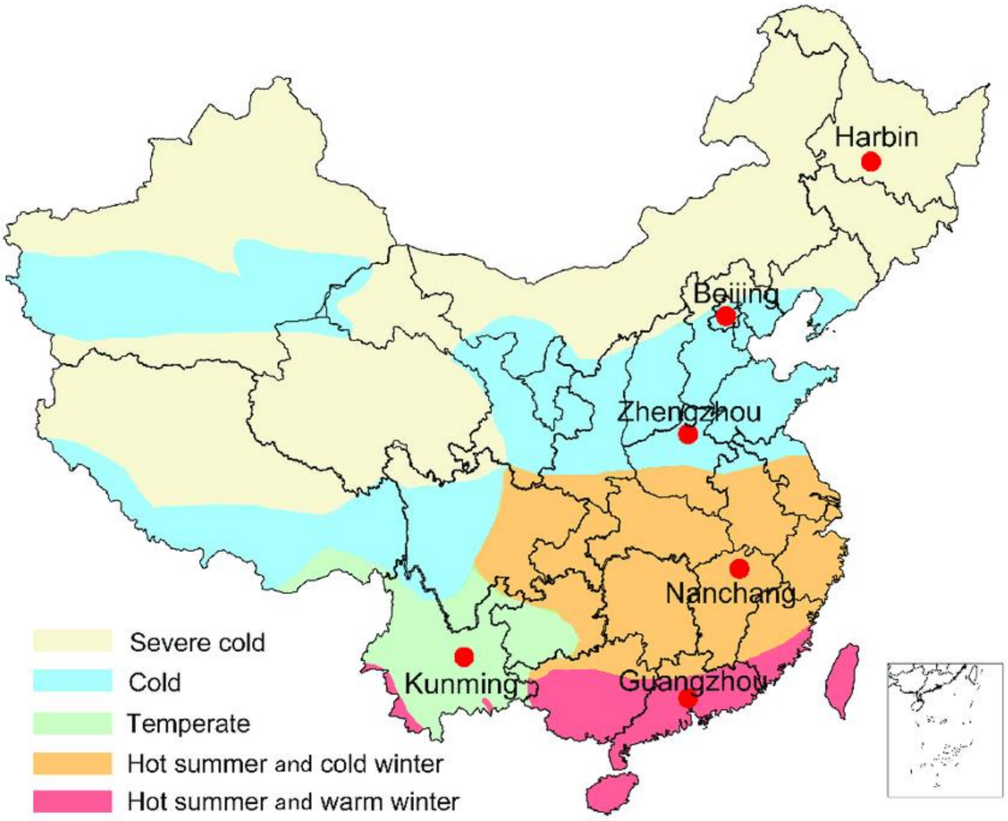
[42] Baiyi Li et al., “Energy consumption pattern and indoor thermal environment of residential building in rural China,” Energy and Built Environment 1(3), July 2020, at https://doi.org/10.1016/j.enbenv.2020.04.004; Rongdan Diao et al., “Thermal performance of building wall materials in villages and towns in hot summer and cold winter zone in China,” Applied Thermal Engineering, 128, 5 January 2018, at https://doi.org/10.1016/j.applthermaleng.2017.08.159.

[43] Rongdan Diao et al., “Thermal performance of building wall materials in villages and towns in hot summer and cold winter zone in China,” Applied Thermal Engineering, 128, 5 January 2018, at https://doi.org/10.1016/j.applthermaleng.2017.08.159.

[44] Xinye Zheng et al., “Characteristics of residential energy consumption in China: Findings from a household survey,” Energy Policy, 75, 2014, at http://dx.doi.org/10.1016/j.enpol.2014.07.016.

[45] Baiyi Li et al., “Energy consumption pattern and indoor thermal environment of residential building in rural China,” Energy and Built Environment 1(3), July 2020, at https://doi.org/10.1016/j.enbenv.2020.04.004.

Figure 5: Map of China climate zones



Source: Fan Xinying et al., Energies, 2020 (CC)

While most focus is on heating, cooling is increasingly important. Cooling demand is growing due to urbanization and higher incomes. China's cooling demand has grown 13 per cent annually since 2000, rising from 7 TWh in 1990 to 45 TWh in 2000 and 450 TWh in 2016.[46] According to the International Energy Agency, cooling demand could reach 700 TWh by 2030.[47] Cooling demand in China is also rising due to climate change, particularly in areas outside South China.[48] China's average temperatures are rising faster than the global average,[49] and more regions of China are experiencing heat waves that last longer and occur in more seasons of the year.[50]

To respond to the issue of cooling, and meet the requirements of the Kigali Amendment, in 2019 China introduced the Green Cooling Action Plan, which raised performance standards for air conditioners and heat pump, among other measures.[51]

Only a small proportion of rural residents have air conditioning for cooling,[52] but rural air conditioning ownership and usage is rising dramatically, especially in provinces with higher incomes and summer

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[46] Xiao-Bing Zhang et al., "Cooler rooms on a hotter planet? Household coping strategies, climate change, and air conditioning usage in rural China," Energy Research & Social Science, 68, October 2020, at https://doi.org/10.1016/j.erss.2020.101605.

[47] "The Future of Cooling in China," International Energy Agency, June 2019, at https://www.iea.org/reports/the-future-of-cooling-in-china.

[48] Xiao-Bing Zhang et al., "Cooler rooms on a hotter planet? Household coping strategies, climate change, and air conditioning usage in rural China," Energy Research & Social Science, 68, October 2020, at https://doi.org/10.1016/j.erss.2020.101605.

[49] "China warns that its temperatures are rising faster than global average," Reuters, 4 August 2022, at https://www.reuters.com/world/china/china-warns-that-its-temperatures-are-rising-faster-than-global-average-2022-08-04/.

[50] Liu Zhao, "Summer (and Spring, and Fall) Heat Waves Are the New Normal," Sixth Tone, 20 July 2022, at https://www.sixthtone.com/news/1010811/summer-%28and-spring%2C-and-fall%29-heat-waves-are-the-new-normal.

[51] Yi Jiang, "Chilling Prospects 2022: China's progress towards sustainable cooling," Sustainable Energy for All, 22 June 2022, at https://www.seforall.org/data-stories/chinas-progress-towards-sustainable-cooling.

[52] Rongdan Diao et al., "Thermal performance of building wall materials in villages and towns in hot summer and cold winter zone in China," Applied Thermal Engineering, 128, 5 January 2018, at https://doi.org/10.1016/j.applthermaleng.2017.08.159.

temperatures. Shandong, Jiangsu and Zhejiang are among the provinces with above average air conditioner ownership, in both urban and rural areas.[53]

Cooling demand is a major factor in rising peak loads in much of China, not just the South. Cooling demand is driving power outages in certain regions due to extreme heat waves. The severe 2022 power outages in Sichuan and Chongqing were directly related to heat waves that led to poor hydropower output coinciding with peak loads over 25 per cent above the previous year's record, with 60-70 per cent of peak load attributed to air conditioning use.[54] Residential electricity load nationally in August 2022 was 33 per cent higher than the previous year.[55] Rising peak loads is a primary reason for building more coal plants, with coal power shifting towards a peak-shaving role in the power system.

3. Analysis: pairing heat pumps with PV in the Whole County PV program

Pairing electric heat pumps with distributed PV has the potential to help address the rising importance of residential cooling to peak loads, while potentially replacing coal heating with cleaner sources, at least in certain regions where climate and solar resources are suitable. In some regions, energy storage may improve both self-consumption and economics, while further helping reduce the impact on distribution grids of distributed solar. (Some Shandong counties have already mandated Whole County PV projects over a certain size must include two hours of energy storage for this reason.[56]) This section analyses the key variables and discusses the results.

While PV is typically associated with worsening peak power demand due to the duck curve, distributed energy paired with storage is a potential solution. Provinces such as Shandong and Hebei have explicitly encouraged rooftop PV, including households, to participate in peak shaving markets to encourage greater responsiveness to system needs.[57]

Although China's heat pump market is growing, it lags far behind developments in solar PV. China sales of air source heat pumps rose from 1.5 million annually in 2017 to 2.5 million in 2021. This is dwarfed by the 150 million annual air conditioner unit sales to residential households in 2021,[58] which includes wall-mounted units that might cover a single room.[59]

Heat pumps have gradually come down in price and improved in performance.[60] Heat pumps in China cost less than those in Europe or the U.S., as low as RMB 18,000, but also have a wide cost range.[61] Heat pumps can be combined with thermal energy storage for improving overall performance and efficiency, preventing frosting, increasing self-consumption, load shifting, and participating in

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[53] Maximilian Auffhammer, "Cooling China: The Weather Dependence of Air Conditioner Adoption," Frontiers of Economics in China, 9(1), 2014, at https://iar.sufe.edu.cn/_upload/article/files/c6/e8/27ab705644cea0600cda3c9de3a8/2378bc06-0308-43e9-be6d-39faac3bfd25.pdf.

[54] Jiahai Yuan et al., "四川高温限电痛点在何处，如何防止重演？[How to resolve power shortages due to high temperatures in Sichuan, and keep them from getting worse?" Caixin, 6 September 2022, at http://zhishifenzi.blog.caixin.com/archives/260319.

[55] "中电联发布《2023 年度全国电力供需形势分析预测报告》，预计 2023 年全社会用电量同比增长 6%左右," China Energy Council, 19 January 2023, at https://mp.weixin.qq.com/s/sGKUTn7WDGGNwbkWlyaxKA.

[56] "山东某县整县光伏需配建或租赁≥15%*2h 储能 [Some Shandong counties require Whole County PV come with at least 2 hours of storage]," WeChat Energy Net, 11 August 2022, at https://mp.weixin.qq.com/s/sbbRUFhP-V4s_79CwD-xiw.

[57] Yan Qi, "分布式光伏掀“巨变”!," Beijixing, 27 June 2022, at https://guangfu.bjx.com.cn/news/20220627/1236296.shtml.

[58] "Monthly China's Household AC Production" and "FY China's ASHP Sales," from China Industry Online, accessed 10 January 2023, at http://data.chinaiol.com/ecdata/index.

[59] Note that the Chinese system for classifying heat pump and residential air conditioning sales differs from other countries. Conventional air conditioners include those that provide heating via a resistance heating element.

[60] "Cumulative capacity and capital cost learning curve for vapour compression applications in the Sustainable Development Scenario, 2019-2070," International Energy Agency, October 2022, at https://www.iea.org/data-and-statistics/charts/cumulative-capacity-and-capital-cost-learning-curve-for-vapour-compression-applications-in-the-sustainable-development-scenario-2019-2070; Atse Louwen et al., "Technological Learning in Energy Modelling: Experience Curves," Reflex, 2018, at https://reflex-project.eu/wp-content/uploads/2018/12/REFLEX_policy_brief_Experience_curves_12_2018.pdf; Renaldi Renaldi et al, "Experience rates of low-carbon domestic heating technologies in the United Kingdom," Copenhagen School of Energy Infrastructure, Working Paper 14-2020, 2020, at https://doi.org/10.1016/j.enpol.2021.112387; "Air Source Heat Pumps," U.S. Department of Energy, accessed 20 January 2023 at https://www.energy.gov/energysaver/air-source-heat-pumps.

[61] Mi Zhou et al., "Environmental benefits and household costs of clean heating options in northern China," Nature Sustainability, November 2021, at https://doi.org/10.1038/s41893-021-00837-w.

demand response programs.[62] Well-insulated buildings themselves can act as a thermal battery depending on thermal inertia, which could combine with heat pumps to reduce electricity costs and increase self-consumption.[63]

A 2022 study by Hou et al. of different clean heating technology options found that different options were suited for different regions, with North and Northeast China more suited to biomass and heat pumps combined with solar.[64] A 2020 study by Liu and Mazerall found, on the other hand, that clean coal briquettes offered the cheapest option in most regions without subsidies, with air source heat pumps and gas heating competitive where subsidies are available.[65] A 2021 study by Zhou et al. of heat pump economics in China found that air source heat pumps offered the best synergy between economics and air quality benefits in the long-term, and given their low operating costs found they are competitive economically in China.[66] However, for now, heat pumps are generally unsuited to China's severe cold regions due to poor efficiency at low temperatures, poor building insulation, and high humidity leading to issues of frosting.[67]

In terms of fuel cost, China city gas prices are approximately RMB 3/m^3 (US$ 0.43/ m^3). However, residential gas prices have historically had a wide range, from RBM 2-3.5/m^3 (US$ 0.29-0.50/ m^3) in eastern provinces.[68] Similar to electricity, the government uses tiered pricing to discourage high household gas consumption—with the exception of gas heating. Though local policies vary, a typical level would charge a 20-50 per cent premium to gas beyond the two thresholds representing above-average consumption, but typically the tiers either do not apply to homes with separate gas heating, or do not apply to residential heating in certain months or for certain fixed volumes.[69]

For electricity, China's residential electricity prices are among the lowest in the world at RMB 0.53/kWh (US$ 0.076/kWh).[70] China has a long-term policy of maintaining residential electricity prices at a stable level. In late 2021, when the government raised the allowed price range for wholesale and retail prices for industrial and commercial customers, residential and agricultural prices remained unchanged versus the catalogue price—though provinces may adjust time-of-use pricing to encourage peak load reduction.[71] Despite relatively low prices, household electricity usage remains below that of the U.S. or

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[62] Qinglong Meng et al., "Reduction in on-off operations of an air source heat pump with active thermal storage and demand response: An experimental case study," Journal of Energy Storage, 26, June 2021, at https://doi.org/10.1016/j.est.2021.102401; Ying Lin et al., "Performance investigation on an air source heat pump system with latent heat thermal energy storage," Energy, 239, Part A, 15 January 2022, at https://doi.org/10.1016/j.energy.2021.121898; Conrado Ermel et al., "Thermal storage integrated into air-source heat pumps to leverage building electrification: A systematic literature review," Applied Thermal Engineering, 215, October 2022, at https://doi.org/10.1016/j.applthermaleng.2022.118975; Wangsik Jung et al., "Investigation of Heat Pump Operation Strategies with Thermal Storage in Heating Conditions," Energies 10(12), December 2017, at https://doi.org/10.3390/en10122020.

[63] David Fischer et al., "Smart meter enabled control for variable speed heat pumps to increase PV self-consumption," Proceedings of the 24th IIR International Congress of Refrigeration, 16 August 2015, at http://dx.doi.org/10.18462/iir.icr.2015.0580; Maria Pinamonte et al., "Rule-Based Control Strategy to Increase Photovoltaic Self-Consumption of a Modulating Heat Pump Using Water Storages and Building Mass Activation," Energies, 13(23), 2020 at https://doi.org/10.3390/en13236282.

[64] Xiaoyang Hou et al., "A Critical Review on Decarbonizing Heating in China: Pathway Exploration for Technology with Multi-Sector Applications," Energies 15, 2022, at https://doi.org/10.3390/en15031183.

[65] Hongxun Liu and Denise L. Mauzerall, "Costs of clean heating in China: Evidence from rural households in the Beijing-Tianjin-Hebei region," Energy Economics, 90, 2020, at https://doi.org/10.1016/j.eneco.2020.104844.

[66] Mi Zhou et al., "Environmental benefits and household costs of clean heating options in northern China," Nature Sustainability, November 2021, at https://doi.org/10.1038/s41893-021-00837-w.

[67] Xiaoyang Hou et al., "A Critical Review on Decarbonizing Heating in China: Pathway Exploration for Technology with Multi-Sector Applications," Energies 15, 2022, at https://doi.org/10.3390/en15031183.

[68] Jia-Man Li et al., "Urban natural gas demand and factors analysis in China: Perspectives of price and income elasticities," Petroleum Science, 19(1), February 2022, at https://doi.org/10.1016/j.petsci.2021.12.028.

[69] "家用天然气阶梯气价是怎么划分的？最全的回复来啦 [How is residential gas ladder pricing calculated? Here's the best answer]," The Paper, 1 January 2020, at https://m.thepaper.cn/baijiahao_5401877.

[70] "我国电价的国际比较分析 [International Comparison of China Electricity Prices," Stage Grid Corporation of China, 23 March 2021, at http://www.sasac.gov.cn/n16582853/n16582883/c17715327/content.html.

[71] "Notice on Further Deepening the Market Reform of On-grid Electricity Price for Coal-fired Power Generation," National Development and Reform Commission, 12 October 2021, at https://www.ndrc.gov.cn/xwdt/ztzl/jgjzgg/zcjd/202110/t20211027_1301157.html.

Europe—though it has risen strongly over the past two decades—and rural households use less electricity than urban households.[72]

As of 2021, at least 14 of China's provinces had adopted peak-to-valley time-of-use (TOU) pricing, though this likely omits some cities or localities with TOU.[73] Some provinces—often those that rely more on hydropower—lack TOU pricing on an hourly basis, but do have seasonal peak prices. The central government has steadily encouraged localities to adopt TOU pricing and to increase the range between the peak and valley prices to encourage greater load shifting to off-peak periods. As a result, peak rates have trended higher and valley rates lower, with peak rates currently around 70 per cent above shoulder rates, valley rates 58 per cent below shoulder rates, and in some provinces a super-peak rate in the early evening and sometimes mid-morning 20 per cent above the peak rate.[74]

Most recently, in the NDRC/NEA power pricing work plan for 2023, the central government urges provinces, localities, and grid companies to increase the granularity of retail TOU electricity prices from three to five daily price segments to more than five, and to adapt them to reflect both peak demand and wind and solar output conditions.[75] For this reason, future TOU pricing schedules are likely to differ from present levels in terms of timing of peak periods or price levels. Eventually, increasing solar penetration and residential air conditioning use could push policy makers to further reduce midday power prices and increase evening rates—adding to the incentive for self-consumption of PV output and adoption of energy storage.

China also has policies to discourage high residential electricity consumption, known as tiered pricing. Under tiered pricing, households with electricity consumption in the highest quintile (the highest 20 per cent) pay higher power prices, and the highest 5 per cent consuming households pay the highest rate—though many provinces simply set fixed thresholds above which higher rates apply.[76] Such policies may discourage adoption of EVs and heat pumps, but could encourage self-production of PV-produced electricity, depending on implementation. In most northern provinces, heat pump owners benefit from either discounted winter pricing or an alternative peak-valley pricing, and the tiered pricing policy does not apply.[77] Shanxi province, for example, offers participants in the coal-to-electricity heating policy the choice of either using the residential TOU price without tiered pricing or any upper limit, or a flat price of RMB 0.28/kWh (US$ 0.04/kWh) for the first 2,600 kWh per month of heating electricity consumption.[78] The policy only applies during the heating season, so heat pump cooling use would be unaffected. Many consumers have a separate meter for heating electricity use to facilitate separate pricing for power and heating.

For solar energy, for many years rooftop solar benefited from a flat per-kWh subsidy for all power output, on top of the local on-grid coal tariff, but this was cancelled in 2021.[79] Currently, distributed PV energy

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[72] Dong Wu et al., "Features and drivers of China's urban-rural household electricity consumption: Evidence from residential survey," Journal of Cleaner Production, 365, 10 September 2022, at https://doi.org/10.1016/j.jclepro.2022.132837.

[73] "国家发展改革委有关负责同志就 《关于进一步完善分时电价机制的通知》答记者问 [NDRC officials reply to journalist questions regarding notice on further improving time-of-use electricity pricing]," National Development and Reform Commission, August 2021, at https://www.ndrc.gov.cn/xxgk/jd/jd/202108/t20210802_1292769.html; "全国各地最新销售电价表一览 [National listing of latest retail electricity prices]," Beijixing, 31 May 2021, at https://news.bjx.com.cn/html/20210531/1155249.shtml.

[74] "全国23个省市完善分时电价机制政策汇总 [Comprehensive summary of 23 provincial policies to improve time-of-use pricing mechanisms]," In-en.com, 9 December 2021, at https://m.in-en.com/article/html/energy-2310448.shtml.

[75] "发改委、能源局发布关于做好2023年电力中长期合同签订履约工作的通知 [NDRC, NEA publish 2023 mid-to-long-term contract coverage work notice]," National Development and Reform Commission, 2 December 2022, at https://zfxxgk.ndrc.gov.cn/web/iteminfo.jsp?id=19042.

[76] "关于居民生活用电试行阶梯电价的指导意见 [Guiding opinions on residential household electricity use ladder pricing]," National Development and Reform Commission, 2011, at https://www.ndrc.gov.cn/xxgk/zcfb/tz/201111/t20111130_964836.html.

[77] "各地电采暖电费补贴情况一览 [List of every province's electric heating subsidies]," Beijixing, 3 December 2020, at https://news.bjx.com.cn/html/20201203/1119638.shtml.

[78] "今冬明春采暖期"煤改电"用电价格定了 [This winter's coal-to-electricity heating price policy set]," Suxiang Daily, 29 October 2022, at https://baijiahao.baidu.com/s?id=1747994000161827098.

[79] "国家发展改革委关于2021年新能源上网电价政策有关事项的通知 [NDRC notice on new energy 2021 on-grid electricity tariff policy]," National Development and Reform Commission, 11 June 2021, at https://www.ndrc.gov.cn/xxgk/zcfb/tz/202106/t20210611_1283088.html.

sent to the grid benefits only from the local on-grid coal tariff, and some regions may stop accepting power from distributed solar at periods of lower electricity demand, such as Spring Festival.[80] It is likely that surplus midday PV output will no longer receive the full on-grid coal feed-in tariff, which would further encourage self-consumption of PV output.

Adding heat pumps to existing solar is economically attractive in many provinces.

For households already participating in the Whole County PV program, would it make sense to invest in a costly heat pump instead of other clean heating options, such as a clean-coal improved stove, gas heating, or resistance heating? To answer this question, this analysis employed hourly solar and ambient temperature data for 137 counties across China participating in the Whole County PV program. These counties are from every province of China, and, where possible, cover a range of geographies within each province. The model bases hourly heating load on an individual 100-square-metre house that follows the basic Chinese rural residential building standard—a conservative assumption given that a less efficient building would offer greater benefits to heat pump adoption due to their higher efficiency, at least up to a point. For comparability, the analysis uses a consistent national electricity tariff based on five time-of-use price periods and a stable electricity, gas, and coal price over the 15-year life of each heating system. For cooling, all households without heat pumps are assumed to already have electric air conditioning installed. The analysis considers a 5-kW solar system assumed to already exist as part of the Whole County PV program, hence the PV capital costs are excluded. As a further step in the analysis, the model examines pairing the solar PV with an 8-kWh battery system operated in a fashion designed to maximize self-consumption of PV output.

Table 2: Heating, cooling, storage, and fuel scenarios evaluated in this paper

	Air-source heat pump (ASHP)	*ASHP with energy storage*	*Gas*	*Coal*
PV	5 kW existing	5 kW existing	5 kW existing	5 kW existing
Heating	ASHP	ASHP	Gas boiler	Clean coal improved stove
Cooling	ASHP	ASHP	Existing air conditioning	Existing air conditioning
Storage	-	8 kWh	-	-

Source: OIES 2023

Further assumptions are listed in the methodology appendix.

The results of the analysis suggest that a 5-kW PV system can cover a significant portion, but generally less than half, of total household electricity load over a full year when combined with an air-source heat pump (ASHP) for both heating and cooling. Given that heating accounts for the major share of total electricity load under this scenario, PV coverage of load generally increases in warmer climate zones. For the two climate zones with the highest overall electricity load—the *Cold* climate zone and the *Hot Summer Cold Winter* climate zone—PV met 25 per cent and 32 per cent of total household electricity load over the year. This is higher than the overall solar capacity factor of solar, reflecting greater daytime electricity consumption for cooling and household loads. With storage added, PV can meet 42 per cent and 56 per cent of the household load in these regions.

Holding the size of the PV system constant, self-consumption of PV electricity output is below 10 per cent in the absence of electric heating, for all climate regions. Combining PV with an ASHP boosts self-consumption substantially in all regions, to between 20 per cent and 35 per cent in regions with cold winters. Adding 8-kWh of energy storage greatly increases self-consumption in all regions. Again, considering only the *Cold,* and *Hot Summer Cold Winter* climate zones, self-consumption rises from 27 per cent to 48 per cent and from 22 per cent to 40 per cent, respectively. Self-consumption is generally higher in colder provinces, reflecting longer heating seasons and greater overall heating demand versus cooling demand in much of China.

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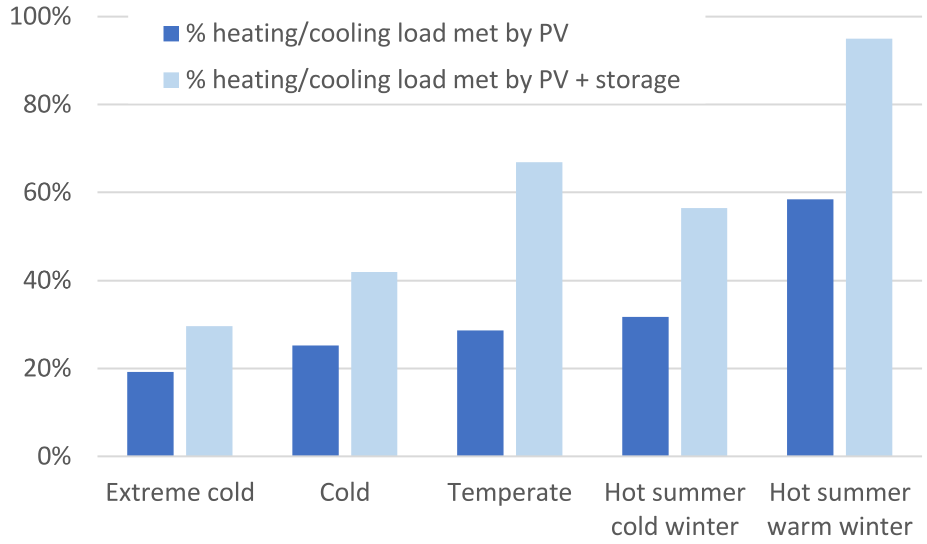
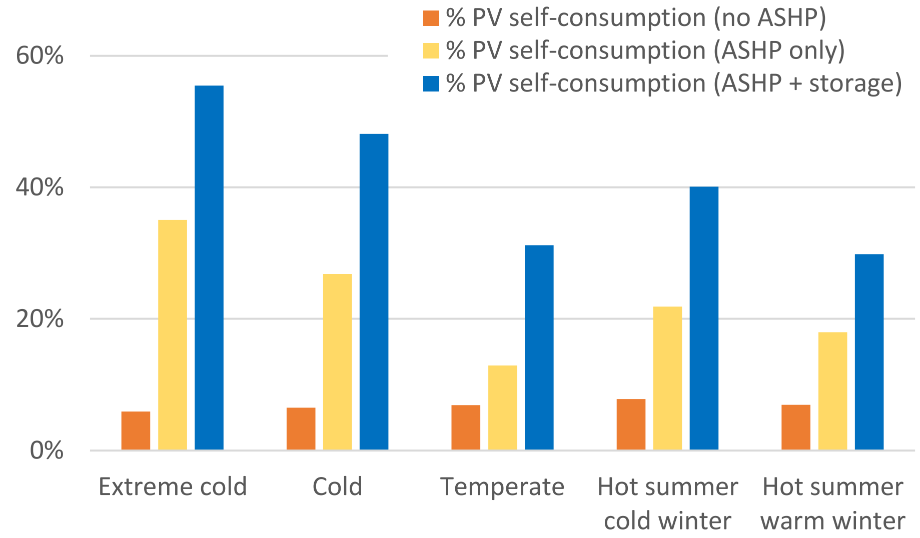
[80] "春节期间山东分布式光伏停发 9 天！ [Over Spring Festival Shandong distributed PV will stop producing for 9 days]," Sohu, 16 January 2023, at https://www.sohu.com/a/630981395_121123886.

Figure 6: Percentage of ASHP and household load met by PV and PV plus storage, by climate zone



Source: OIES, 2023

Figure 7: Percentage of PV self-consumption in three cases: (1) PV only, (2) PV and ASHP, and (3) PV, ASHP, storage



Source: OIES, 2023

Considering provinces by their main climate zone, by population 43 per cent of the Whole County PV population is in *Cold* regions, 34 per cent in *Hot Summer Cold Winter*, 11 per cent in *Hot Summer Warm Winter*, 7 per cent in *Temperate*, and the remainder in *Severe Cold*.[81]

The analysis considers the payback period of adopting ASHP with and without storage compared to a resistance heating, a new gas stove or a clean-coal briquette stove. In rural China, resistance heating and cooling from an air conditioning unit is the base case for southern China outside the traditional heating zone marked by the Huai River, whereas clean coal briquettes and gas are likely to represent the base case in the north. For consistency, the analysis here presents the resulting payback periods in all provinces for the ASHP cases versus the three alternative clean heating cases.

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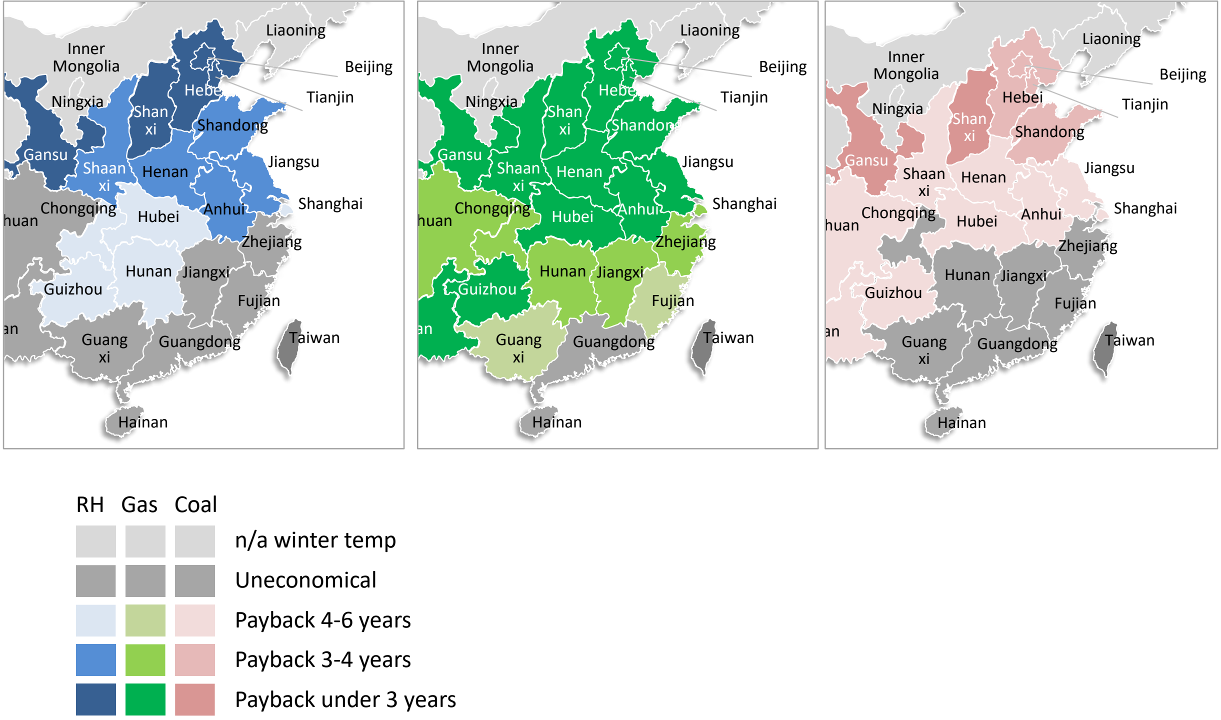
[81] Author calculation. See note above.

Figure 8: Payback period for ASHP versus resistance heating, gas heating, and coal heating by province



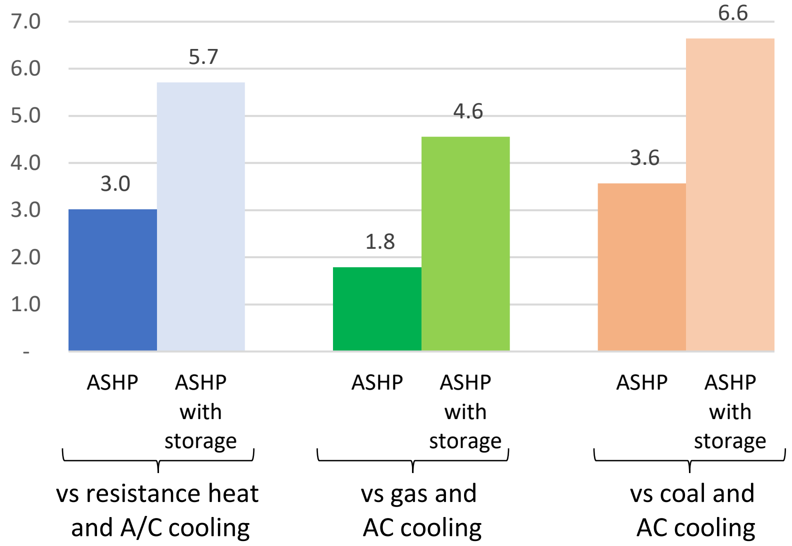
Source: OIES, 2023

The results of the analysis show that heat pumps provide the greatest benefit to PV households in the northern provinces, with good overlap with those that are prominent in the Whole County PV program. For households with PV already installed, adding ASHP results in a payback period of under three years versus resistance heating in Hebei, Beijing, Tianjin, and Shanxi provinces, and a payback of 3-4 years versus resistance heating in Shandong, Henan, Jiangsu, and Anhui. Even shorter payback periods are available across a broad region when comparing ASHP to gas boilers, with most provinces having less than three-year payback periods. For payback periods versus clean coal stoves, payback periods are under six years in most East-Central provinces, and under four years in Shandong, Hebei, and Shanxi provinces.

Northern provinces offer the greatest economic benefit because they have good solar resources and experience both heating and cooling loads. In particular, high heating loads are beneficial for the economics of ASHP, given the greater efficiency gains. For colder provinces, the 5-kW PV system is unable to meet a large fraction of heating demand, necessitating higher midday electricity usage. In warmer provinces such as Hainan and Guangdong, the efficiency benefit of heat pump adoption is lower, reducing or eliminating the economic savings.

Adding storage generally results in a substantially longer payback period, given the capital cost of storage is almost equal to that of the heat pump cost premium over other clean heating options. Adding battery energy storage would also not be economical for gas or clean coal heating options, given that the annual electricity cost savings from increasing self-consumption of PV output are less than the electricity cost savings of the heat pump in almost all regions.

Figure 9: Payback period of PV and ASHP versus gas and coal, with and without energy storage in Shandong



Source: OIES, 2023

Heat pump adoption also substantially reduces the carbon and air emissions from household heating, whether considering coal or gas alternatives. Based on the 2020 electricity generation mix in the North China, East China, and Central China electricity regions, heat pumps would reduce a household's winter heating carbon dioxide emissions by 90 per cent versus clean coal stoves, and this would improve to 94 per cent when considering the 2030 electricity generation mix in these regions under a carbon peaking scenario developed by the Tsinghua School of Environment. Compared with gas boilers, a grid-only ASHP would reduce annual household heating carbon emissions by 72 per cent based on the 2020 generation mix, and by 82 per cent based on the 2030 generation mix. Considering heating emissions in isolation, household PV would reduce heat pump electricity consumption for winter heating by a further 15-20 per cent in the provinces in these regions.[82]

4. Analysis: policy barriers to heat pump adoption need further attention

Although heat pump adoption could bring economic and environmental benefits, it remains low across China, even nearly a decade after the clean heating transformation began. Several barriers to heat pump adoption in rural areas exist.

The most straightforward barrier is public awareness. In urban China, the building of heating systems is largely a matter for building owners and local heating enterprises, while rural residents tend to view building energy efficiency and clean heating as a government responsibility. In rural China there is little awareness of the potential cost savings from adopting clean heating. Rather, there is widespread acceptance of fossil fuel heating as a historic practice in rural areas.[83] The overall lack of consumer knowledge is exacerbated by poor efficiency labelling for heat pumps and other energy-saving appliances.[84] Energy and energy-equipment companies have little incentive to educate consumers about clean heating, and building trades in rural areas are often performed by temporary workers with low skills and awareness of energy efficiency or clean energy.[85] Rural residents also have low

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[82] Author calculations, based on clean coal and gas boiler emissions from Xiaoyang Hou et al., "A Critical Review on Decarbonizing Heating in China: Pathway Exploration for Technology with Multi-Sector Applications," Energies 15, 2022, at https://doi.org/10.3390/en15031183; 2020 and 2030 regional electricity emissions from Fang Wang et al., "The drivers of decarbonizing battery electric vehicles (BEVs) in China: the recent progress and future perspectives," Tsinghua School of the Environment, unpublished manuscript, 2022.

[83] Yurong Zhang and Yuanfeng Wang, "Barriers' and policies' analysis of China's building energy efficiency," Energy Policy, 62, 2013, at http://dx.doi.org/10.1016/j.enpol.2013.06.128.

[84] Maggie Mowrer and Qianqian Cui, "Research Shows Huge Heat Pump Potential in China," CLASP, 30 August 2022, at https://www.clasp.ngo/updates/research-shows-huge-heat-pump-potential-in-china/.

[85] Guo Liu et al., "Building green retrofit in China: Policies, barriers and recommendations," Energy Policy, 139, 2020, at https://doi.org/10.1016/j.enpol.2020.111356.

awareness of the health effects of indoor air pollution.[86] However, several factors may increase acceptance of clean heating and raise local awareness, including education of village leaders,[87] frequency of public education campaigns,[88] and emphasis on the factors shown to be the most salient to rural residents—especially heating quality, indoor air quality, and the availability of subsidies.[89]

Capital costs are a second barrier, given the well-known consumer resistance to spending more upfront on efficient devices that save money over time. As in other countries, Chinese consumers' willingness to upgrade building energy systems relates to a lack of understanding of the factors driving home energy costs, inaccurate estimates of potential savings, and a tendency to base energy decisions on perceptions rather than actual savings.[90] To alleviate capital cost concerns, long-term leases that pair PV with heat pumps are one potential option, though anecdotal reports suggest the Whole County PV program has seen better results when residents own their own PV systems.[91] Capital cost subsidies are also important, but face limitations due to availability of funds for clean heating. The Whole County PV program could help alleviate this concern by pooling program capital costs with commercial and industrial customers, which may be better able to finance such investments through energy services companies or commercial loans.

Administrative capacity and coordination represent a third barrier. Historically, administrative coordination has posed a barrier to building energy efficiency policy: energy efficiency and clean energy policies in rural areas suffer from unclear responsibilities,[92] fragmentation among different government bodies,[93] as well as contradictory incentives that lead to poor enforcement and lack of motivation at the local level.[94] Often policies apply mainly to new buildings, and long-term enforcement and monitoring is lacking.[95] Coordination problems bedevilled the original clean heating program, with responsibility for the transformation divided between State Grid (for electrification), state-owned and privately-held gas companies, local officials, and oversight by the National Development and Reform Commission (NDRC), the National Energy Administration (NEA) within the NDRC, the Ministry of Ecological Environment (MEE), and the Ministry of Housing and Urban Rural Development (MOHURD).[96] Given the NEA and NDRC focus on energy and MOHURD's focus on buildings, the fact that each tend to pursue separately-administered programs is apparent.

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[86] Ren Wang and Zhujun Jiang, "Energy consumption in China's rural areas: A study based on the village energy survey," Journal of Cleaner Production, 143, 1 February 2017, at https://doi.org/10.1016/j.jclepro.2016.12.090.

[87] Lin Zhang et al., "SWOT Analysis for the Promotion of Energy Efficiency in Rural Buildings: A Case Study of China," Energies, 11, 2018, at https://doi.org/10.3390/en11040851.

[88] Na Li et al., "Exploring the formation conditions and dynamic trends of rural residents' clean heating behaviour in northern China based on reinforcement learning," Journal of Cleaner Production, 344, 2022, at https://doi.org/10.1016/j.jclepro.2022.131142.

[89] Na Li et al., "Exploring the influencing factors of Chinese rural households' clean heating choice considering the attitude–behavior gap based on two-level classification methods," Energy & Buildings, 273, 2022, at https://doi.org/10.1016/j.enbuild.2022.112357; Yuanchao Gong et al., "Perceived fiscal subsidy predicts rural residential acceptance of clean heating: Evidence from an indoor-survey in a pilot city in China," Energy Policy, 144, 2020, at https://doi.org/10.1016/j.enpol.2020.111687.

[90] Yuanchao Gong et al., "Perceived fiscal subsidy predicts rural residential acceptance of clean heating: Evidence from an indoor-survey in a pilot city in China," Energy Policy, 144, 2020, at https://doi.org/10.1016/j.enpol.2020.111687.

[91] David Fishman, Twitter, 13 July 2022, at https://twitter.com/pretentiouswhat/status/1547096592582586369.

[92] Yanna Wu et al., "Barriers identification, analysis and solutions to rural clean energy infrastructures development in China: Government perspective," Sustainable Cities & Society, 86, 2022, at https://doi.org/10.1016/j.scs.2022.104106.

[93] Bei Zhu et al., "Urban residential heating policy in China: A review," Energy & Buildings, 253, 2021, at https://doi.org/10.1016/j.enbuild.2021.111547; Guo Liu et al., "Building green retrofit in China: Policies, barriers and recommendations," Energy Policy, 139, 2020, at https://doi.org/10.1016/j.enpol.2020.111356.

[94] Genia Kostka and Jonas Nahm, Central–Local Relations: Recentralization and Environmental Governance in China, The China Quarterly, 231, September 2017, at https://doi.org/10.1017/S0305741017001011; Ran Ran, "Perverse Incentive Structure and Policy Implementation Gap in China's Local Environmental Politics," Journal of Environmental Policy & Planning, 15, 2013, https://doi.org/10.1080/1523908X.2012.752186.

[95] Yurong Zhang and Yuanfeng Wang, "Barriers' and policies' analysis of China's building energy efficiency," Energy Policy, 62, 2013, at http://dx.doi.org/10.1016/j.enpol.2013.06.128.

[96] Anders Hove and Lauri Myllyvirta, "Analysis: How to fix China's botched heating policy," China Dialogue, 22 December 2017, at https://chinadialogue.net/en/energy/10308-analysis-how-to-fix-china-s-botched-heating-policy/; Hu Zhanping, "De-Coalizing Rural China: A Critical Examination of the Coal to Clean Heating Project from a Policy Process Perspective," Frontiers in Energy Research, 6 July 20221, at https://www.frontiersin.org/articles/10.3389/fenrg.2021.707492/full.

Similarly, the separate processes for setting building energy codes, appliance efficiency codes, and electricity sector regulations and pricing could inhibit the potential for heat pumps, energy storage, and building energy efficiency upgrades to work together in such a way as to bolster the stability of the electricity system. For example, by reducing net loads or participating in nascent markets for ancillary services. Building codes and appliance standards rarely reference flexibility or responsiveness to price signals in energy markets, nor do building efficiency standards reference distributed renewable energy. The separation between these policy bodies and regulatory domains could complicate any proposed linking of the Whole County PV program and clean heating.

The fourth barrier concerns the overall framing of the energy transition in China as one favouring centralized generation and long-distance transmission over distributed energy solutions. Most media coverage and central government announcements have focused on achieving carbon neutrality through the construction of large clean energy bases. The 14th Five-Year Plan calls for self-sufficiency in eastern provinces, while also promoting clean energy bases and long-distance power lines as the main solution for integrating clean energy.[97] Grid companies have also tended to downplay the benefits of building electrification, especially in rural areas with insufficient local distribution capacity—in some cases supported by analysis that suggests heat pumps or EVs could worsen peak loads.[98] Increasing self-consumption by integrating heat pumps with distributed PV could lessen the weight of this argument, though even with storage heat pumps would still draw significant power from the grid in most regions.

Conclusion

China's Whole County PV program represents a major effort to bring rooftop solar to rural areas, and could be responsible for adding as much as 60 GW by the program's conclusion in 2025. Given that many villages will have solar PV rooftops, this program could become a natural platform for experimenting with integrating heat pumps and energy storage to increase self-consumption of PV output and reduce peak electricity loads in summer. This analysis shows such an approach is most beneficial in North Central China, including in those provinces where the Whole County PV program is most active: Henan, Jiangsu, and Shandong.

However, significant policy barriers may have to be overcome to deliver such a program in practice. Even in advanced economies with high penetration of solar and heat pumps, low consumer awareness and high capital costs have hindered their adoption. In rural China, these barriers loom especially large given the income gap with urban areas. Lack of effective building codes and standards in rural areas and divided government responsibilities and priorities have also slowed the rural energy transition, including the clean heating campaign, despite its high policy priority and central coordination.

While these barriers may appear prohibitive, the Whole County PV program offers a potential solution. By bundling residential solar installations with a single tender covering the entire county, including larger and more profitable solar installations in commercial, industrial, and public buildings, solar installation companies have been able to offer economically compelling packages to rural residential customers. Such bundling can also help overcome institutional and regulatory barriers by raising the priority attached to residential efficiency projects that are otherwise too small to matter individually. In short, the same design elements that have enabled the Whole County PV program to expand solar to thousands of villages could also prove effective for heat pump adoption.

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[97] "'十四五'现代能源体系规划 [14th Five-Year Plan for a Modern Energy System]," National Energy Administration, 2021, at http://www.nea.gov.cn/1310524241_16479412513081n.pdf. See also, "国家能源局有关负责同志就《"十四五"现代能源体系规划》答记者问 [NEA officials respond to journalist questions on 14th Five-Year Plan for a Modern Energy System]," National Development and Reform Commission, 22 March 2022, at https://www.ndrc.gov.cn/xxgk/jd/jd/202203/t20220322_1320031.html.

[98] Cong Wu et al., "Exploring the challenges of residential space heating electrification in China: A case study in Jinan and Qingdao," Case Studies in Thermal Engineering, 30, 2022, at https://doi.org/10.1016/j.csite.2022.102283.

Appendix 1: Data and Methodology

Capital costs

The calculation derives capital costs for scenarios from previously published research from Zhou et al. and Hou et al. Coal and gas stoves and boilers, as well as resistance heating and air conditioning systems, are considerably cheaper than heat pumps:

- clean coal stoves: RMB 1,400,[99]
- gas heating systems RMB 8,000,[100]
- resistance heating systems 1,400,[101]
- air-source heat pump (ASHP) RMB 18,000.[102]

For energy storage systems, the capital cost of RMB 17,920 is based on a recent (January 2023) price for a 5.3-kWh lithium-iron-phosphate home battery system from Huaniu,[103] adjusted proportionally to reflect the cost of an 8-kWh system.

Fuel costs and efficiency

The model employs consistent fuel prices and time-of-use electricity rates in all provinces and regions. These assumptions are:

- Natural gas: RMB 2.6/m^3.
- Coal: RMB 1,200/tonne, with a heating value of 26.3 MJ/kg.[104]
- Electricity: base rate of RMB 0.3/kWh, with five time-of-use intervals as follows: RMB 0.234/kWh for 22:00-8:00, RMB 0.90/kWh for 8:00-11:00 and 20:00-22:00, RMB 0.53/kWh for 11:00-18:00, and RMB 1.08/kWh from 18:00-20:00.

In all cases, the calculation excludes inflation or price increases, reflecting the general approach of the central government to protect residential users from energy price changes.

For air-source heat pumps, the winter coefficient of performance (COP) is based on a 2019 analysis of real-world performance of various heat pumps in cold temperatures in Europe.[105] For both ASHP and air conditioning, the model employs a COP of 3.5, based on the performance of a 5-kW, non-ducted, 48,000 Btu/hr Mitsubishi h2i MXZ.[106]

For natural gas and clean coal briquette stoves, the efficiencies are taken from Zhou et al.[107]

Building efficiency

The model estimates the building heat-loss coefficient for a single, detached residence of 100 m^2 floor area that meets the overall national standard for residential units in the *Hot Summer Cold Winter* climate zone. The estimate is based on the following U-values: walls 1.8; roof 0.6; floor 1; and windows and

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[99] Mi Zhou et al., “Environmental benefits and household costs of clean heating options in northern China: Supplementary Information,” Nature Sustainability, November 2021, at https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-021-00837-w/MediaObjects/41893_2021_837_MOESM1_ESM.pdf. See table 7.

[100] Xiaoyang Hou et al., “A Critical Review on Decarbonizing Heating in China: Pathway Exploration for Technology with Multi-Sector Applications,” Energies 15, 2022, at https://doi.org/10.3390/en15031183.

[101] Mi Zhou et al., “Environmental benefits and household costs of clean heating options in northern China: Supplementary Information,” Nature Sustainability, November 2021, at https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-021-00837-w/MediaObjects/41893_2021_837_MOESM1_ESM.pdf. See table 7.

[102] Xiaoyang Hou et al., “A Critical Review on Decarbonizing Heating in China: Pathway Exploration for Technology with Multi-Sector Applications,” Energies 15, 2022, at https://doi.org/10.3390/en15031183.

[103] “5 kWh 储能蓄电池价格多少钱 [How much does a 5 kWh energy storage battery cost?],” Huaniu Energy, 13 January 2023, at http://www.chinahuaniu.cn/answer/10909.html.

[104] Mi Zhou et al., “Environmental benefits and household costs of clean heating options in northern China: Supplementary Information,” Nature Sustainability, November 2021, at https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-021-00837-w/MediaObjects/41893_2021_837_MOESM1_ESM.pdf. See tables 6 and 11.

[105] Oliver Ruhnau et al., “Time series of heat demand and heat pump efficiency for energy system modeling,” Scientific Data, 6(189) 2019, at https://doi.org/10.1038/s41597-019-0199-y.

[106] See product specifications at https://leesheatingandcoolingservice.com/wp-content/uploads/2019/04/MXZ-Catalog.pdf.

[107] Mi Zhou et al., “Environmental benefits and household costs of clean heating options in northern China: Supplementary Information,” Nature Sustainability, November 2021, at https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-021-00837-w/MediaObjects/41893_2021_837_MOESM1_ESM.pdf. See table 6.

doors 3; with air changes per hour of 0.8.[108] Rural village areas may have wall and window thermal properties substantially below the national standard, with U-values for roof and walls as high as 6W/k*m^2 and single-pane windows with U-values over 4W/k*m^2.[109] Residential standards for rural areas are mainly voluntary, and emphasize the importance of affordability and use of locally-available materials.[110] While a less efficient building would result in larger economic gains for adopting efficient heating systems, this must be weighed against the greater capital cost of using a larger heat pump, as well as potential efficiency losses if the interior temperature cannot be maintained at a sufficient level for optimal performance. Similar to other recent analyses,[111] the model does not incorporate occupancy, changes in temperature set points (such as turning down the heat at night), internal gains, solar gains, and other characteristics that affect building energy performance. Aside from considerations of simplicity and data availability, these building efficiency assumptions result in consistency across buildings and climate zones, as well as comparability to prior research on combining heat pumps with PV in China.

Heating and cooling loads

The model calculates hourly heating and cooling loads based on ambient temperature (hourly values obtained for each location via PVWatts,[112] with no adjustments for future climate change), with cooling degrees calculated as the number of temperature degrees above 26 degrees C, while heating degrees are calculated as the number of temperature degrees below 16 degrees C. (Note: 18 degrees C is the warmth standard set by MOHURD.)[113] The model ignores building thermal inertia or the potential for pre-heating or pre-cooling to maximize PV self-consumption or minimize time-of-use electricity prices, and uses the building total heat-loss coefficient to evaluate the hourly heating load based on cooling- or heating-degree hours.

PV output and pricing

PV output is based on system AC output for a 5-kW system with a 20-degree south-facing tilt. The calculation employs hourly PV data for a sample year for each county location derived from PVWatts.[114] The price paid for surplus PV output sent to the grid after accounting for self-consumption or battery charging is assumed to remain at a price near the on-grid coal power tariff of RMB 0.35/kWh, except for peak solar hours from 11:00-15:00, when this is reduced by 50 per cent.

Appendix 2: Sensitivity analysis

The results of this analysis are most sensitive to three main assumptions: the household heating load, the heat pump efficiency at low temperatures, and capital cost assumptions.

The household heating load is a critical assumption. Heating load depends on factors such as the building insulation properties, occupancy, temperature set preferences, and internal and external gains. This analysis assumes residential property meeting China's standards for rural residential buildings, which results in substantially lower heating load versus a more typical Chinese rural home, and hence lower efficiency benefit from heat pump adoption. All other things being equal, reducing the thermal efficiency to reflect that of a more typical rural building would increase the total heating load by 2-3x, with a corresponding benefit for the heat pump payback period. The building heating loads calculated in this analysis for each province correspond roughly to those reported in Zhou et al., which employed a seasonal temperature average instead of an hourly temperature used here.[115] However, the annual coal consumption calculated in this analysis is substantially higher than that reported for typical northern

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[108] "Design standard for energy efficiency of residential buildings in hot summer and cold winter zone, JGJ 134-2010," China Architecture and Building Press, 2010.

[109] Baiyi Li et al., "Energy consumption pattern and indoor thermal environment of residential building in rural China," Energy and Built Environment 1(3), July 2020, at https://doi.org/10.1016/j.enbenv.2020.04.004.

[110] He Bao-jie et al., "Overview of rural building energy efficiency in China," Energy Policy, 69, 2014, at https://doi.org/10.1016/j.enpol.2014.03.018.

[111] Hongxun Liu and Denise L. Mauzerall, "Costs of clean heating in China: Evidence from rural households in the Beijing-Tianjin-Hebei region," Energy Economics, 90, 2020, at https://doi.org/10.1016/j.eneco.2020.104844.

[112] PVWatts, U.S. National Renewable Energy Laboratory, at https://pvwatts.nrel.gov/pvwatts.php.

[113] "Design standard for energy efficiency of residential buildings in hot summer and cold winter zone, JGJ 134-2010," China Architecture and Building Press, 2010.

[114] PVWatts, U.S. National Renewable Energy Laboratory, at https://pvwatts.nrel.gov/pvwatts.php.

[115] Mi Zhou et al., "Environmental benefits and household costs of clean heating options in northern China: Supplementary Information," Nature Sustainability, November 2021, at https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-021-00837-w/MediaObjects/41893_2021_837_MOESM1_ESM.pdf. See table 9.

China households[116]—even though such households would not occupy housing up to the China national efficiency standard. The difference likely relates to the lower temperature households in poorly insulated rural households, where an interior temperature of 10 degrees C is not uncommon.[117] In the calculation of household heating load used here, setting a 10 degree C temperature set point for the cold county of Shanhaiguan in northeast Hebei reduces the annual heating load by half. To account for internal and solar gains by setting an 8 degree C temperature saves 60 per cent versus the base case.

Setting a low temperature obviously saves money, but does it reflect personal preferences—that is, what people are used to and prepared to accept, even as incomes rise and building efficiency improves? If so, the economic analysis of clean heating should take lower set temperatures as a base assumption, rather than the 18 degrees set as the government standard, or the 16 degrees C used here. However, if rising incomes and lower energy costs (due to higher efficiency or subsidies) result in higher interior temperature practices, this comparison would not be reasonable. In their 2020 study of rural Sichuan building energy efficiency and occupant satisfaction, Li et al., found household interiors averaging as low as 6.5 degrees C in occupied rooms—and that over 50 per cent of residents considered the interior temperature of their buildings as uncomfortably cold.[118] In my own experience visiting the poor mountain village of Tielucun that had undergone heating retrofit with heat pumps as part of a government-subsidized program connected to the 2022 Winter Olympics, I observed residents keeping room temperatures at comfortable levels, not freezing themselves to save money. Improved interior temperatures were one of the elements of greatest satisfaction in a survey of rural Hebei residents that had undergone heating retrofit.[119]

The efficiency benefit of heat pumps relates to the heat pump coefficient of performance, which declines in colder temperatures. There are various methods for adjusting COP, but there is only moderate sensitivity to different calculation methods. For example, using the method of Yang (2018),[120] which is in turn employed in the heat pump analysis of Liu and Mauzerall (2020),[121] changes the payback period of ASHP versus resistance heating in Shanhaiguan from 2.5 years to 2.7 years, compared to our base case, despite the ASHP heating season COP falling from 3.15 to 2.58 under the two different calculation methods.

Gas and electricity prices

Heat pumps offer the greatest economic benefit compared to gas heating, which is influenced by both the price of gas as well as the capital cost of gas heating, which is considerably above that of the other options of resistance heating or clean coal stoves. This analysis employs a single national gas price, whereas currently gas prices can be quite low for inland provinces. Both factors have a significant impact on payback periods, as shown below:

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[116] https://www.mdpi.com/2071-1050/13/1/169

[117] Baiyi Li et al., "Energy consumption pattern and indoor thermal environment of residential building in rural China," Energy and Built Environment 1(3), July 2020, at https://doi.org/10.1016/j.enbenv.2020.04.004.

[118] Baiyi Li et al., "Energy consumption pattern and indoor thermal environment of residential building in rural China," Energy and Built Environment 1(3), July 2020, at https://doi.org/10.1016/j.enbenv.2020.04.004.

[119] Shuo Xu and Jianping Ge, "Sustainable shifting from coal to gas in North China: An analysis of resident satisfaction," Energy Policy, 138, March 2020, at https://doi.org/10.1016/j.enpol.2020.111296.

[120] Yang Xudong, "Current situations and technical routes of rural clean heating," 14th session of Building Energy Efficiency Academic Week in Tsinghua University. Clean Heating Forum, Beijing, China, 2018, at https://www.ne01.com/news/8001.html.

[121] Hongxun Liu and Denise L. Mauzerall, "Costs of clean heating in China: Evidence from rural households in the Beijing-Tianjin-Hebei region," Energy Economics, 90, 2020, at https://doi.org/10.1016/j.eneco.2020.104844.

Table 3: Sensitivity of payback periods (cell values, in years) to gas prices and gas furnace cost (Zouping, Shandong case)

		Gas price (RMB/m3)				
		1.5	2.0	2.5	3.0	3.5
Gas furnace cost	4000	5.0	3.5	2.7	2.2	1.8
	6000	4.3	3.0	2.3	1.9	1.6
	8000	3.6	2.5	1.9	1.5	1.3
	10000	2.9	2.0	1.5	1.2	1.0

Source: OIES, 2023

Since the analysis considers both electricity prices and time-of-use prices, with the assumption that both will remain static, it is worth evaluating the impact of each on payback periods versus alternatives, with and without energy storage. Again, considering the case of Zouping in Shandong province, we see that the overall base electricity price is more important than the peak and super-peak rates.

Table 4: Sensitivity of payback periods (cell values, in years) to base electricity price and peak premium (Zouping, Shandong case), comparing ASHP to resistance heating with and without storage

		PV+ASHP (no storage)					PV+ASHP (with storage)			
		Peak premium (%)					Peak premium (%)			
		60%	70%	80%	90%		60%	70%	80%	90%
Base	0.50	3.3	3.2	3.1	3.0	0.50	6.3	6.1	5.9	5.7
Electricity	0.55	3.0	2.9	2.8	2.8	0.55	5.7	5.5	5.4	5.2
(RMB/	0.60	2.8	2.7	2.6	2.5	0.60	5.3	5.1	4.9	4.8
kWh)	0.65	2.6	2.5	2.4	2.4	0.65	4.8	4.7	4.5	4.4

Source: OIES, 2023

If the battery were used in load-shifting mode, charging at night from grid power, and dispatched to minimize peak load rather than maximizing self-consumption of PV, the results would likely be more favourable to the ASHP with storage option.