Costs of clean heating in China:
Evidence from rural households in the Beijing-Tianjin-Hebei region

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ABSTRACT

To address severe air pollution, the Chinese government plans to replace most residential coal stoves in northern China with clean heating devices by 2021. Coal stove replacement started in the "Beijing-Tianjin-Hebei (BTH)" region and is expanding throughout northern China. Removing coal stoves reduces air pollutant emissions and hence is beneficial for both air quality and public health, as well as offering greenhouse gas mitigation co-benefits. However, there is little discussion of the economic costs of various clean heating technologies. In this study, we estimate total annual costs (TAC, annualized capital costs plus annual operating costs) for rural households, across cities/counties in the BTH region, to replace their coal stoves with several prevalent clean options—air-source heat pumps with fan coils (ASHPwF), electric resistance heaters with thermal storage (RHwTS), natural gas heaters (NGH), and clean coal briquettes with improved stoves (CCIS). We find: 1) Without subsidies, CCIS have the lowest TAC of all clean options. TAC of unsubsidized CCIS approximately doubles TAC of raw coal with improved stoves (RCIS), while unsubsidized electric/gas heaters cost 3–5 times more than RCIS. Thus, it is important for governments to financially support households' replacement of their coal stoves with clean heaters to facilitate widespread adoption. 2) With subsidies, CCIS have the lowest TAC in all regions except Beijing. In Beijing, generous subsides make ASHPwF—the most energy-efficient option—have the lowest TAC. In Tianjin, TAC of subsidized ASHPwF are slightly higher than CCIS and NGH. Throughout Hebei, except for a few severely cold northern counties where gas prices are high, subsidized NGH have lower TAC than ASHPwF and RHwTS. 3) Cost competitiveness of ASHPwF increases as heat demand increases, (e.g., higher desired indoor temperatures, larger home sizes, etc.) indicating that ASHP are good options for households with larger home sizes and commercial buildings. 4) Substantial potential exists to reduce heating expenses by improving building energy efficiency particularly in severely cold regions. 5) Cost advantages of NGH vary sharply with gas prices.

1. Introduction

At the end of 2016, coal was still used to meet more than 80% of total heating demand in northern China[1] (NDRC et al., 2017). Approximately 400 million tons of coal per year were used for space heating, 50% of which were combusted in small-scale residential heating stoves in rural areas without district heating (NDRC et al., 2017). Such extensive and inefficient use of coal without emission controls has had a major impact on ambient air pollution and public health, and contributes disproportionately to greenhouse gas emissions (Zhang et al., 2000; Almond et al., 2009; Huang et al., 2014; WHO (World Health Organization), 2014a, 2014b; Zheng et al., 2010; Yang et al., 2018). As end-of-pipe controls for residential coal stoves are infeasible, the Chinese government aims to replace residential coal stoves with clean heating options. Coal stove replacement started in the Beijing-Tianjin-Hebei (BTH) region and is gradually expanding throughout northern China.

Removing residential coal stoves substantially reduces ambient PM$_{2.5}$ concentrations and associated premature mortalities (Liu et al., 2016; Zhao et al., 2018a, 2018b). Among the clean heating options, heat pumps, electric resistance heaters with thermal storage and wall-mounted natural gas heaters are being widely promoted by the Chinese government (NDRC et al., 2017; BMG (Beijing Municipal Government), 2018a; TMG, 2017a, 2017b; HPG, 2018). The use of clean coal with improved stoves is also being considered for remote mountainous regions where it is currently difficult and costly to provide the infrastructure necessary to replace coal stoves with gas or electric heaters (NEA, 2019).

Previous scientific studies found that the replacement of residential coal stoves in China not only lead to significant air quality improvement and associated health benefits, but also contributed to carbon dioxide emission reductions (He et al., 2010; Liu et al., 2016; Meng et al., 2019; Zhang et al., 2019). For example, Liu et al. (2016) found that elimination of residential emission-sources (i.e., coal and other solid fuels) in Beijing and in the entire BTH region reduced the primary PM$_{2.5}$ concentrations in Beijing by $14 \pm 7\ \mu g^{-3}$ ($22 \pm 6\%$) and in the BTH region by $28 \pm 19\ \mu g \cdot m^{-3}$ ($40 \pm 9\%$). Zhang et al. (2019) found that more than 721,000 morbidity cases and 34,000 mortality cases couldbe avoided by improving ambient and indoor air quality by implementing a "coal-to-electricity" policy in the BTH region between 2016 and 2020. Zhao et al. (2018a, 2018b) found that heat pumps were better choices than resistance heaters to replace fossil-fueled heaters from the perspective of CO$_2$ emission reduction.

However, there is a cost to replace coal stoves with clean heating technologies. Furthermore, most of the replacement projectswere targeted at relatively low-income rural areas without district heating, where the willingness to pay for clean technologies is low (Mobarak et al., 2012; Wang et al., 2019). Barrington-Leigh et al. (2019) found negative impacts on residents' well-being in some low-income districts of Beijing, due to the high capital and operating costs of clean heaters. Thus, similar to Hanna et al. (2016), an important question is how to best facilitate uptake of clean household heating systems over time, given that in poor rural regions, concern about the costs of clean heaters may be larger than an appreciation of the benefits of clean heating.

To answer this question, we first need to know the costs for households to adopt clean heating technologies. Such information is valuable in order to determine the level of subsidies necessary to facilitate a willing and widespread uptake of clean heaters. Although both the national and local governments have provided various policies to financially support the capital and operating costs of replacements, as well as the infrastructure necessary to operate the clean heaters, analysis is still needed to determine the cost of each heating option for households, whether

they are affordable in specific locations, and whether further subsidies or other government assistance are necessary to facilitate uptake.

Thus, in this study, we evaluate the capital and operating costs for rural households in the BTH region of China to replace their coal stoves with four possible clean heating technologies: air-source heat pumps (ASHP) (air-to-water type), resistance heaters with/without thermal storage (RHwTS and RHwoTS), wall-mounted natural gas heaters (NGH), and clean coal briquettes with improved stoves (CCIS). We only consider air-to-water heat pumps rather than air-to-air heat pumps here as many households in the BTH region have already installed water-based heating systems.

We study the four heating technologies mentioned above because they are highly recommended by the Chinese government in the "Clean Winter Heating Plan", and have already received the widest application in the BTH region to achieve clean heating targets. A variety of factors make them attractive, including their high efficiency (e.g., ASHP vs. resistance heaters), using off-peak electricity (e.g., RHwTS vs. RHwoTS), easy installation (e.g., ASHP vs. Geothermal heat pumps), accessibility of energy resources (e.g., electric/gas heaters vs. biomass heaters), affordability (e.g., NGH and CCIS). Other alternative technologies (like geothermal heat pumps, biomass heaters, etc.) are also worth studying but are left for future work.

We choose the BTH region for two reasons: First, it is one of the most severely polluted regions in China and is also the most economically developed and densely populated. Among all air pollution sources, coal combustion in households for space heating contributes the most to PM$_{2.5}$ pollution during winter in this region (Liu et al., 2016). Despite successful efforts to improve air quality in recent years, the annual average ambient PM$_{2.5}$ concentration in the region (annual mean of 53 μg/m³ in 2018 from He et al., 2019) remains far above both the Chinese ambient air quality standard for residential and commercial areas (annual mean of 35 μg/m³ from Zhao et al. (2016)), as well as the air quality standard of the World Health Organization's Air Quality Guideline (annual mean of 10 μg/m³) for avoiding adverse health effects (WHO, 2005). Thus, improvements in air quality resulting from coal stove replacement in the BTH region will lead to substantial health benefits.

Second, starting in 2013, the BTH region pioneered the replacement of residential coal stoves with clean heaters. The replacement project has been accelerated since 2016 as the governments increased their financial supports. For example, in Beijing, ~230,000 households, ~370,000 households and ~160,000 households replaced coal with clean energy in 2016, 2017 and 2018, respectively. But during 2013–2015, only 40,000–100,000 households in Beijing were involved in the replacement project annually. By the end of 2018, more than 6 million rural households in the BTH region had replaced their coal stoves with electric or gas heaters (NCERB-NEA and CPMGCL, 2019). Policies and subsidies in the BTH region implemented to support the replacement provide remaining regions in northern China with a template for facilitating clean heating. Thus, our analysis for the BTH region is also of value for much of northern China.

The remainder of this paper is organized as follows: Section 2 reviews previous literature and highlights the contributions of this paper. Section 3 presents the methods we adopt and the data sources in our analysis. It also includes the policies implemented in the BTH region to support the adoption of clean heating by rural households. Section 4 compares total annual costs with and without subsidies of various heating options across the BTH region, including annualized capital costs and annual operating costs. Section 5 conducts sensitivity analyses examining the cost impacts of various desired indoor temperatures, home sizes, building energy efficiencies and natural gas prices. Section 6 summarizes our main findings and concludes with some policy implications.

2. Literature review

Previous studies regarding coal replacement in the residential sector of China can be classified into three categories. The first category

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[1] Northern China includes 15 provinces/municipalities/ autonomous regions: Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Heilongjiang, Shandong, Shaanxi, Gansu, Ningxia, Xinjiang, Qinghai, and Henan (partly).

evaluates the air quality and health benefits of replacing coal with clean energy for heating and/or cooking. For example, Liu et al. (2016) described the benefits for ambient air quality of eliminating coal and other solid fuels from the residential sector in the BTH region. Chen et al. (2018) evaluated the contribution to indoor air quality and associated health impacts of space heating in rural China. Zhang et al. (2019) and Fan et al. (2020) further included health-related economic benefits from ambient and indoor air quality improvement in their analyses, and indicated that replacing coal for heating in the residential sector of the BTH region would result in net social benefits.

The second category explores factors driving the adoption of clean heating options. Among various factors, such as household size (Cai and Jiang, 2008), location (Pachauri and Jiang, 2008), education (Liu et al., 2013), income (Duan et al., 2014), the cost of using clean heaters has gained attention (Wang et al., 2019) and is highly related to the well-being of households' (Barrington-Leigh et al., 2019).

The third category examines the cost of clean heating options. From the macro perspective, Computable General Equilibrium (CGE) models are widely used to estimate the impacts of the replacement on the economy, such as Zhang et al. (2019), Lin and Jia (2020). However, the macro-economic cost analyses provide little reference for households' or local governments' decision making. Thus, some recent studies are trying to analyze the cost of using various heating options from the techno-economic perspective (Zhang et al., 2017a, 2017b), as well as to conduct surveys in households to collect data on costs, such as Wang et al. (2019), Barrington-Leigh et al. (2019). However, these studies are often limited to a specific area and have limited applicability to other locations.

Building on previous work, we make the following additional contributions. First, we provide a framework for evaluating the capital and operating costs of using various heating options in the residential sector from the household perspective. Our framework includes not only geographical factors (e.g., ambient temperatures and heating days during the heating season, etc.), but also human behaviors (e.g. desirable indoor temperatures, heating hours per day, etc.) as well as policies (e.g. building codes, heating subsidies, etc.). Our approach is applicable for assessing heating costs in other situations and other parts of China and the world. Second, we estimate the heat loss of rural residential buildings in various regions and compare heating expenses for a representative rural household across the BTH region. Third, we consider both subsidized and unsubsidized costs of various heating options which helps clarify where additional subsidies are necessary in order to make the clean heating options competitive. Our findings provide valuable implications for government subsidy policies necessary to support clean heating.

3. Methods and data

In this paper, we evaluate households' clean heating costs by comparing their total annual costs (TAC) of using various heating technologies, (TAC = annualized capital costs (ACC) + annual operating costs (AOC)). Power capacities of the heaters and fuel consumption with resulting capital and operating costs are estimated based on various parameters across cities/counties in the BTH region, including residential building energy efficiencies, home sizes, average outdoor temperatures, desired indoor temperatures, heating days, prices of devices and fuels, subsidies, etc. We divide the BTH region into 18 sub-regions: Beijing municipality, Tianjin municipality and 16 cities/counties that belong to Hebei province, as shown in Fig. 1.

Data are collected from government documents, literature, and conversations with rural residents, heating device suppliers, gas/electricity distribution companies, etc. The methods and data we use provide a map of rural residential clean heating costs in the BTH region, and can be applied to calculate heating costs for households elsewhere in northern China.

3.1. Alternative heating technologies

We summarize the attributes of clean heating technologies evaluated in this paper below.

3.1.1. Air-source heat pumps (ASHP)

Unlike traditional electric resistance heaters which directly covert electricity to heat, ASHP only use electricity to operate a motor and are thus two to three times as energy-efficient as resistance heaters. Heat pumps utilize a compressor and a condenser to absorb heat in one place and release it in another, allowing a building to be heated in winter or cooled in summer (Hewitt et al., 2011). When ASHP operate in the heating mode, they extract heat from the outdoor air at a low temperature and put it into a fluid. The fluid passes through a compressor where its temperature is increased and the heat is released indoors into hot water circuits, such as water-filled underfloor pipes (ASHPwP), wall-mounted radiators (ASHPwR) or fan coils (ASHPwF).

3.1.2. Resistance heaters with/without thermal storage (RHwTS/RHwoTS)

RHwTS are electric resistance heaters which can store thermal energy at night when electricity rates are lower due to time-based electricity pricing (NDRC, 2013), and release the heat during the day as needed. In contrast, RHwoTS release all heat immediately.

3.1.3. Wall-mounted natural gas heaters (NGH)

NGH provide heat by burning gas and transfering the heat indoors directly or via hot water circuits. As most households in the BTH region have already installed indoor wall-mounted radiators, we do not consider the cost of installing indoor heating circuits when calculating the replacement costs of NGH. However, most of the radiators in rural households are made of iron, which require water to be heated to a higher temperature than ASHP can normally provide. Therefore, unlike NGH, costs of updating/replacing indoor heating circuits are included in the capital costs of ASHP.

3.1.4. Clean coal briquettes with improved stoves (CCIS)

Compared to burning unprocessed raw coal in traditional stoves (RCTS), CCIS can significantly reduce $PM_{2.5}$ and CO_2 emissions (Liu et al., 2018a, 2018b; Tian et al., 2018). "Clean coal briquettes" usually refer to processed semi-coke or anthracite briquettes which have lower volumns of volatile than unprocessed raw coal and thus contribute less to fine particulate matter emissions (Li et al., 2016). In 2014, Hebei issued a standard for "clean coal briquettes", requiring that the volatile compounds be ≤10% and thermal value ≥5740 kcals/kg (or 24 MJ/kg) (HQTSB, 2014). However, a national uniform definition/standard for "clean coal briquettes" has not yet been issued.

Table 1 presents details of the capital and operating costs of various clean heating technologies. Fig. S1 in the SI shows images of these clean heating technologies.

We do not consider the large-scale infrastructure improvements and construction costs for gas pipelines or electricity generation and transmission in this paper. They are undertaken by the national and local governments and utility companies and do not directly affect household costs. Previous studies estimated that the incremental infrastructure construction costs for power grids are ~20,000 RMB per household while the incremental infrastructure construction costs for gas pipelines are ~6000–16,000 RMB per household in the BTH region (NCERB-NEAC and CPMGCL, 2019). By 2015, China had already achieved 100% electricity access (Karplus and Von Hirschhausen, 2019). However, the distribution networks (including the substations, transformers, lines, etc.) in most rural areas will need upgrades as replacing coal stoves with electric heaters will increase electricity demand. However, upgrades to ASHPwF will require less additional electricity than RH. For example, to support the "coal-to-electricity" projects in the BTH region and its surrounding cities, the State Grid Corporation of China issued a technical guideline in 2016, indicating that the power distribution capacity in
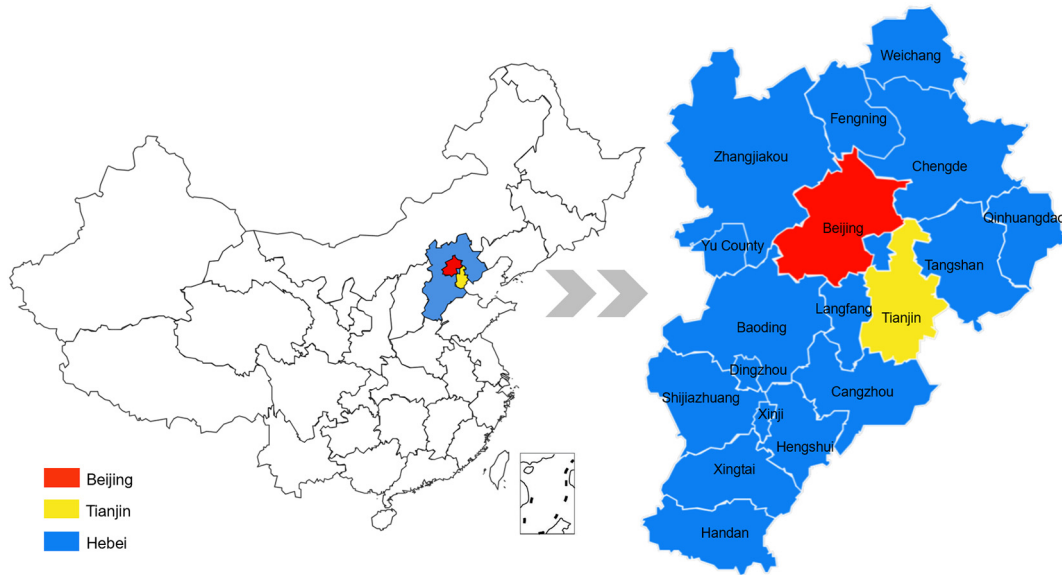
Fig. 1. Divisions of the BTH region. The BTH region contains two municipalities (Beijing and Tianjin) and one province (Hebei). Considering the geographic, climatic and policy varieties, we further divide Hebei into 16 cities/counties: Handan, Xingtai, Shijiazhuang, Hengshui, Xinji, Dingzhou, Cangzhou, Baoding, Langfang, Tangshan, Qinhuangdao, Zhangjiakou, Chengde, Yu County, Fengning, and Weichang.

Table 1
Capital and operating costs of residential clean heating technologies.

Heating options	Capital costs	Operating costs
Air-source heat pumps (ASHP)	Purchase and installation of: 1) ASHP; 2) Accessories, e.g., water tank, pipes, etc.; 3) Heating radiators, such as underfloor pipes, wall-mounted radiators, or fan coils.	Electricity
Electric resistance heaters with/without thermal storage (RHwTS/ RHwoTS)	Purchase and installation of RHwTS or RHwoTS.	Electricity
Wall-mounted natural gas heaters (NGH)	Purchase and installation of NGH and accessories.	Gas and electricity*
Clean coal briquettes with improved coal stoves (CCIS)	Purchase and installation of improved coal stoves.	Clean coal briquettes

Note: *Although NGH generate heat by burning gas, they also consume electricity to operate the controlling/computer system so that less gas is needed when the water temperature reaches a pre-set value.

rural areas should be increased to 5–7 kW per household (SGCC, 2016). Pipeline natural gas has been available in many urban areas of China, providing an advantage of "coal-to-gas" projects in urban areas. But only LPG cylinders are available in most rural areas and are used mainly for cooking (Chen et al., 2016). Hence, widespread uptake of NGH in rural areas will require additional natural gas pipeline construction.

3.2. Methods of estimating capital and operating costs

3.2.1. Capital costs

Considering that these heating devices are durable goods which provide service over their lifespans, we adopt the equivalent annual cost (EAC) method to measure the annualized capital costs of each heating option, as shown in Eq. (1). The EAC method was proposed in the early 1920s and has been widely used to determine whether it makes economic sense to invest, by comparing investment costs of alternative projects of unequal lifespans by utilizing discount rates (Jones and Smith, 1982; Kauffmann et al., 2012; Brealey et al., 2012). We adopt this method so that we can compare the estimated annual capital plus

operating costs between heating technologies. We recognize that upfront capital cost is also important especially for poor households, and thus provide upfront capital cost of each heating option in Table S1 of supplementary information (SI).

$$ACC_{ik} = NPV_{ik} / \left(1 + \frac{1}{1+r} + \dots + \frac{1}{(1+r)^{n_i-1}} \right) \quad (1)$$

where ACC_{ik} is the annualized capital cost of purchasing and installing a heating device (i) for each household in each region (k). r is the discount rate, referring to the time value of money, i.e., 8% in this paper (Zhang et al., 2017a, 2017b). NPV_{ik} is the net present value of device i in region k. n_i is lifespan of each device (i), as shown in Table S2 in SI. NPV equals the upfront capital costs that each household pays for the devices. We do not consider salvage values of residential heating devices here due to their low present values which will not influence decision-making criteria (Rout et al., 2018). NPV_{ik} depends on device i's required power capacity PC_{ik} (kW) in each region, which is calculated in Eq. (2):

$$PC_{ik} = \frac{60\% \times HL_k \times HS \times HH}{1000 \times HE_{ik} \times RH_i} \quad (2)$$

where HL_k is the heat loss of buildings (W/m^2) in rural areas of each region as defined in MHURD (2010), which refers to the power that heating devices need to provide to maintain a certain indoor temperature, which we assume is 18 °C in accordance with MHURD (2010). We use the methods in MHURD (2010) and parameters for rural buildings in MHURD (2009) to calculate the values of HL_k. The estimates are shown in Table S6 in SI, which are close to the estimates in BERC, 2011 and Yang (2018). See SI for more details on the methods and data of calculating HL_k. HS is home size per household, which we assume is 100m^2. The heating area is ~60% of the home size (BERC, 2011). HH are heat demand hours per day, which we assume are 24 h/day. HE_{ik} is heating efficiency of each device. For ASHP, HE_{ik} equals the coefficient of performance (COP) in each region, which is determined by the local ambient temperatures and the indoor heating circuits (Pospíšil et al., 2018; Hu et al., 2019). RH_i is each device's running hours per day. See Table S2 in SI for details on COP of ASHP and RH_i.

With the power capacities of the heaters and associated prices and installation fees we collected from device suppliers (see Table S1 in

SI), we obtain the values of NPV_{ik} and thus the annualized capital costs ACC_{ik}.

3.2.2. Annual operating costs

We calculate the annual operating costs (AOC_{ik}) of each type of device in each region for each household in Eq. (3):

$$AOC_{ik} = \sum_j P_{jk} \times Q_{ijk} = \sum_j P_{jk} \times \frac{60\% \times HL_k \times HS \times HH \times HD_k}{\tau_j} \quad (3)$$

where j is fuel (electricity, natural gas, clean coal briquettes, and raw coal). P_{jk} is each fuel's price in each region (see Table S7 in SI). Q_{ijk} is the quantity of each fuel consumed by each device in each region per year in each household. HD_k are heating days per year in each region (See Table S2 in SI). α is the energy conversion coefficient from kilowatt hour (kWh) to megajoule (MJ), which equals 3.6 MJ/kWh (Xu et al., 2017). τ_j are thermal values of natural gas, clean coal briquettes and raw coal (See Table S1 in SI).

3.3. Policies in the BTH region to support clean heating in rural areas

National clean heating project policies in China can be traced back to 2013. After the severe haze airpocalypse period in many cities in early 2013, the State Council of China issued an action plan and initiated replacement efforts for coal use in the residential sector to reduce ambient air pollution levels (SCC, 2013). In 2014, Beijing, Tianjin, Hebei, and 5 additional provinces were selected by the Chinese central government to start the "coal-to-gas/electricity" project in the residential sector (NDRC, 2014). In December 2016, following the publication of Liu et al. (2016), which demonstrated the large effect residential coal heating had on ambient air quality in the BTH region, Chinese President Xi stated in the 14th meeting of the central leading group for financial and economic affairs, that China needed to facilitate a transition to clean winter heating in northern regions. Soon after the statement, in 2017, the Chinese central government, together with 4 provincial governments, jointly issued the Work Program on Prevention and Control of Air Pollution for the Beijing-Tianjin-Hebei Region and surrounding regions, in which Beijing, Tianjin, and another 26 cities were required to implement clean heating (MEE et al., 2017). At the end of 2017, ten departments of the central government jointly issued the Clean Winter Heating Plan for Northern China (2017–2021), expanding the clean heating project from the "2 + 26" cities to all of northern China (NDRC et al., 2017).

Governments in the BTH region have implemented a series of policies to financially support households (especially in the rural areas) to replace their coal stoves. These policies mainly include: 1) Subsidies for purchasing clean heating devices and fuels; 2) Adjustments to residential electricity and gas pricing mechanisms; 3) Imposition of price ceilings on clean heaters, improved coal stoves and clean coal briquettes through public bidding. We collect and present the main policies over 2015–2018 at the provincial, municipal, district, city and county levels in Table S8 in the SI.

To make sure that households use clean heaters rather than coal stoves, in many areas, coal stoves were removed from households and taken away once the electric or gas heaters were installed using government subsidies. In addition, the sale of raw coal in markets for residential use was banned.

3.3.1. Subsidies for device purchase and fuel costs

Table S9 in SI lists the subsidies for upfront capital costs of clean heating devices and fuel costs in rural areas of the BTH region which were in effect in 2018 and 2019 (TMG, 2015; BMG, 2016; TMG, 2017a, 2017b; BMG, 2018a; HPG, 2018; CMG, 2018; SMG, 2018; XMG, 2018). Households in Beijing and Tianjin received greater subsidies for upfront capital costs of clean heating devices than households in Hebei, especially for ASHP users. In Beijing, subsidies for ASHP purchase were

based on home size (200 RMB/m^2) while subsidies for purchasing RHwTS/NGH/improved coal stoves were price-determined. In Tianjin, subsidies for upfront capital costs of clean heating devices were all price-determined without rate limits but with ceilings (≤25,000 RMB per household). In Hebei, subsidies for purchasing ASHP, RHwTS and NGH were all price-determined with rate and ceilings as well. Meanwhile, only a few parts of Hebei province have implemented subsidies for purchasing improved coal stoves.

For subsidies for fuel costs, the Beijing and Tianjin governments provided comparatively greater support for electricity users than Hebei. The Tianjin government provided greater subsidies for natural gas users compared to Beijing and Hebei. In Beijing and Tianjin, households replacing coal with electricity were only subsidized for electricity costs at night, while in Hebei, electricity costs during day time were also subsidized but at a lower rate (0.12 RMB/kWh) compared to Beijing (0.2 RMB/kWh) and Tianjin (0.2 RMB/kWh).

The subsidies are provided by both the central and local governments. For example, in 2015, the Ministry of Finance of China and the Ministry of Ecology and Environment of China jointly set up a special fund for energy conservation and emission reductions (MFC and MEE, 2015). In 2018, the Ministry of Finance of China set up additional funding for air pollution prevention and control (MFC, 2018). Provincial governments are encouraged to apply for the funds if they have relevant projects including clean heating for the residential sector. In addition to the funding from the central government, local governments often also need to allocate financing for this. For example, the Tianjin Municipal Government clearly stated in their policies that 40% of subsidies for "coal-to-gas/electricity" will come from the municipal government while the remaining 60% must come from the district governments (TMG, 2017a, 2017b).

3.3.2. Adjustments on residential electricity and gas pricing

Electricity and gas prices are regulated by the governments in China. In the BTH region, residential electricity and gas pricing were both adjusted for clean heating by the municipal/provincial governments. For ASHP and RHwTS users, the quantity-based residential tiered pricing for electricity was replaced in 2017 by time-based peak-valley pricing[2] during the heating season in the BTH region (BMG, 2017). The pricing adjustment partly addressed users' concerns of higher costs resulting from increased electricity demand due to heating. Particularly in Beijing and Tianjin, the municipal governments not only extended the valley hours from 9 pm-6 am (9 h) to 8 pm-8 am (12 h), but also reduced the electricity price during valley hours from 0.4433 (Beijing) and 0.49 (Tianjin) to 0.3 RMB/kWh (BMG, 2018a; TMG, 2018). Like electricity, the residential pipeline natural gas price is also tiered in the BTH region, which means that gas consumption is billed at different rates depending on the amount of gas each household consumes. To reduce households' operating costs of using NGH, the Beijing municipal government increased gas quantities allowed in the 1st tier[3] from 0–1500 m^3 to 0–2500 m^3 for heating in rural areas; and thus rural households which replace their coal stoves with NGH pay at the lowest gas rate (2.63 RMB/m^3) if annual gas use does not exceed 2500m^3 (BMG, 2018a). The Tianjin municipal government and the Hebei provincial government even suspended the tiered pricing policy for residential gas use during the heating season, which means that gas prices were fixed at the lowest baseline levels of the 1st tier (TMG, 2017a, 2017b; HDRC, 2017a). See Table S10 and Table S11 in SI for more details on the

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[2] Currently, there are two main electricity pricing mechanisms for the residential sector in China: tiered pricing and peak-valley pricing. For tiered pricing, the price is fixed for a range of electricity consumed and increases to a higher level as the electricity consumption exceeds that threshold. For peak-valley pricing, the 24 h per day are divided into periods of peaks and valleys and the electricity price varies depending on the time of the day. Prices are higher during peak hours than they are in valley hours (Zheng and Wei, 2019).

[3] For tiered gas pricing, the price is fixed for a range of gas consumed and increases to a higher level as the gas consumption exceeds specific thresholds.
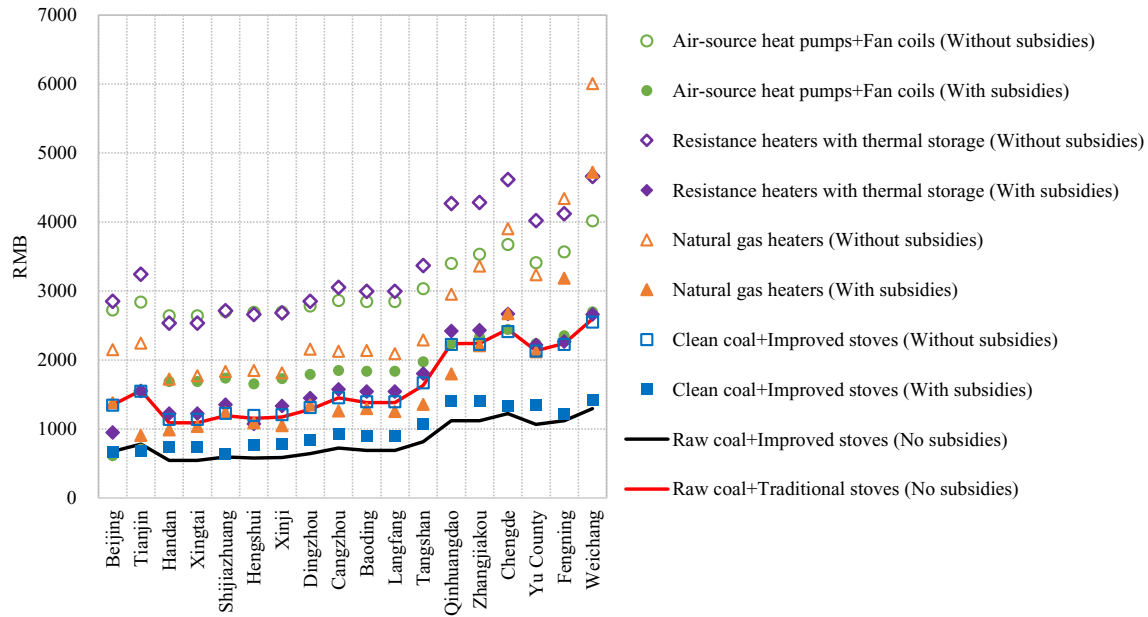
Fig. 2. Subsidized and unsubsidized total annual costs (capital + operating costs) of various heating options for each household across the BTH region. In the figure, open symbols indicate heating costs without subsidies and closed symbols indicate heating costs with subsidies. For households using raw coal with either traditional or improved stoves, the capital costs are not included in the figure as we assume most households already own them and thus they are sunk costs.

residential electricity and gas prices in the BTH region before and after adjustments.

3.3.3. Imposing ceilings on the prices of clean heaters, improved coal stoves and clean coal briquettes through public bidding

Unlike regulated electricity and gas prices, prices of clean heaters, improved coal stoves and clean coal briquettes are market-driven. Thus, the governments are unable to directly determine prices of devices/briquettes in the markets. Instead, the governments set public bidding to determine which suppliers will be permitted to to sell clean heating devices and clean coal briquettes with subsidies. Commonly, the governments release public bidding notifications to look for qualified suppliers of certain goods i.e., ASHP, RHwTS, NGH, improved coal stoves and clean coal briquettes, etc. The bidders need to meet the requirement in the notifications (e.g., price ceilings, installation and warranty services, etc.) and submit bidding documents regarding their products and services by type and price to the governments (TMG, 2018). The governments then choose the winning bids and release a list of the chosen suppliers (HDRC, 2017b; BMG, 2018b). Only if households purchase from the chosen suppliers will they receive subsidies on the devices or briquettes (YDGB, 2019).

4. Results and discussion

4.1. Total annual costs for households using clean heating options in the BTH region

In Fig.2 and Table 2, we present the TAC (ACC + AOC) of using various heating options with and without subsidies (see Fig. S4 in SI for details of separated ACC and AOC in each city/county). To observe the incremental TAC for households to replace raw coal with clean energy, we also present the TAC of using raw coal with traditional stoves (RCTS) and raw coal with improved stoves (RCIS). Therefore, Fig. 2 includes six heating options: ASHPwF, RHwTS, NGH, CCIS, RCIS, and RCTS. TAC of ASHPwP or ASHPwR are higher than ASHPwF no matter with or without subsidies (see Fig. S5 in SI). TAC of RHwoTS are higher (lower) than RHwTS with (without) subsidies (see Fig. S6 in SI). To

save space, TAC of ASHPwP, ASHPwR and RHwoTS are not included in our analyses below but are presented in the SI.

We find that RCTS costs more than RCIS due to the low efficiencies of traditional stoves. This is consistent with the fact that more than half of rural households in the BTH region had already switched from traditional coal stoves to improved stoves for heating even before policy interventions and subsidies for clean heating started in 2013 (Peng et al., 2019). Even without subsidies for CCIS, switching from RCTS to CCIS results in little increase in costs for households in all the cities/counties. With subsidies for devices and fuels, at least one clean heating option (i.e., ASHPwF, RHwTS, NGH or CCIS) has lower TAC than RCTS for households across the BTH region. However, some low-income rural households continued to use RCTS for heating until the coal replacement policy intervention. To reduce heating costs, they would often just heat a small room in their homes and spend most of their time in that room around the stove. In that case, the AOC of RCTS may be lower than our estimates here.

In addition, the differences in TAC of various heating options are larger in Fenning and Weichang counties than other cities/counties in the BTH region. These two counties are extremely cold compared with the other cities/counties in our study. First, the average ambient temperatures during the heating period (generally, Novemeber to March) in these two counties are lower: Fengning (−5 °C), Weichang (−7.6 °C), the remainder (−3.4 to 3.8 °C). Second, the heating periods in these two counties are longer: Fengning (161 days/a), Weichang (172 days/a), the remainder (93–151 days/a) (MHURD, 2009; MHURD, 2010). The differences in heating demand between these two counties and the rest cities/counties lead to the differences in both ACC and AOC. However, subsidies do not increase proportionately with demand. Therefore, the differences in TAC of various heating options in Fengning and Weichang are larger than the other areas.

TAC with and without subsidies are discussed separately below.

4.1.1. Costs without subsidies

Without subsidies, CCIS have the lowest TAC of all substitutes across the BTH region. RHwTS have the highest TAC of all substitutes in most cities/counties except Fenging and Weichang (in northern Hebei, where NGH have the highest TAC of all substitutes due to high gas prices

Table 2
Costs of using various heating technologies in the BTH region (Units: RMB per household).

Heating options	Upfront capital costs		Annualized capital costs		Annual operating costs		Total annual costs	
	With subsidies	Without subsidies	With subsidies	Without subsidies	With subsidies	Without subsidies	With subsidies	Without subsidies
ASHPwP	~17,000–29,000	~35,000–36,000	~1400-2700	~3300-3500	~400–1500	~600–2100	~1900-4200	~4000-5600
ASHPwR	~7000–20,000	~25,000–27,000	~700–2000	~2600-2800	~500–1600	~700–2300	~1300-3600	~3300-5100
ASHPwF	~1500-13,000	~19,000–20,000	~200–1400	~2100-2200	~300–1300	~500–1800	~600–2700	~2600-4000
RHwTS	~3900-8800	~12,000-16,000	~200–1400	~1300-1800	~300–1300	~1300-3000	~1000-2700	~2500-4700
RHwoTS	~600–2100	~1500-2100	~90–350	~250–350	~1000-3100	~1800-4300	~1200-3400	~2000-4600
NGH	~0–2000	~3000	~0–300	~500	~900–4600	~1200-5500	~900–4700	~1700-6000
CCIS	~0–1350	~1350	~0–200	~200	~600–1400	~1000-2400	~600–1400	~1100-2600
RCIS	Not included	Not included	Not included	Not included	~500–1300 (No subsidies)		~500–1300 (No subsidies)	
RCTS	Not included	Not included	Not included	Not included	~1100–2600 (No subsidies)		~1100–2600 (No subsidies)	

there), Handan and Dingzhou (in southern Hebei, where ASHPwF have the highest TAC of all substitutes).

Without subsidies, switching from coal stoves to clean heaters will substantially increase housholds' heating expenses. Considering average annual disposable incomes in rural areas of the BTH region (10,000–26,000 RMB per capita in 2018, see Fig. S7 in SI for more details), replacing coal stoves with clean heaters in rural areas is financially challenging for households without financial support from the governments.

Regarding the most energy-efficient and environmentally friendly option (ASHPwF here in our analysis), the unsubsidized TAC of ASHPwF in the BTH region is ~80%–100%, ~70%–150%, ~1.5–2.3 times, ~3–5 times, and ~1.5–2.4 times of RHwTS, NGH, CCIS, RCIS, and RCTS, respectively. Although ASHPwF are much more energy-efficient and thus have the lowest operating costs (see Fig. S4 in SI), their capital costs are much higher than the other options (see Fig. S4 in SI), making them costly to adopt without subsidies.

4.1.2. Costs with subsidies

When subsidies are included, we find that in Beijing, ASHPwF have the lowest TAC of all substitutes due to the generous subsides for electricity and ASHP devices from the Beijing municipal and district governments. The subsidized TAC of CCIS are just slightly more than ASHPwF. NGH have the highest TAC of all subsidized options. For households in Beijing using ASHPwF, RHwTS, NGH and CCIS, the subsidies reduced ~77%, ~70%, ~40% and ~50% of their unsubsidized TAC, respectively.

In Tianjin, CCIS have the lowest TAC of all subsidized substitutes, but that's just slightly less than the TAC of subsidized ASHPwF/NGH due to the Tianjin government's generous subsides for ASHP, NGH and CCIS users. The subsidized RHwTS cost much higher than the other clean options as the subsides for RHwTS devices in Tianjin can only cover a small part of the upfront capital costs. For households in Tianjin using ASHPwF, RHwTS, NGH and CCIS, the subsidies reduce ~75%, ~50%, ~60% and ~60% of their unsubsidized TAC, respectively.

In Hebei, CCIS have the lowest TAC of all subsidized substitutes across the province. ASHPwF have the highest TAC of all subsidized substitutes in most cities/counties of Hebei except some northern parts (i.e., Chengde, Fengning and Weichang), where NGH have the highest TAC of all subsidized substitutes because of high gas prices there. For households in Hebei using ASHPwF, RHwTS, NGH and CCIS, the subsidies reduce ~30%–40%, ~40%–60%, ~20%–40% and 35%–50% of their unsubsidized TAC, respectively.

4.2. Technical limitations

Although ASHP are energy-efficient, they often operate with frost formation on the outdoor heat exchanger at low ambient temperatures in winter. The frost insulates the finned surface and reduces the heat transfer rate, leading to performance degradation and can even shutdown the ASHP system (Wang et al., 2015). The Chinese quality standard for ASHP requires that ASHP must be able to work at an ambient

temperature as low as −20 °C (GB/T25127–2010, 2010; GB37480–2019, 2019). Only a few northern mountainous parts of Hebei occasionally drop below −20 °C, resulting in only rare interference with ASHP operation. Households in those areas should either adopt ASHP with better performance that can adequately operate in the low ambient temperatures there, or supplement with another clean heating option, e.g., CCIS.

Although CCIS have lower TAC than ASHP, RHwTS or NGH in most regions, they emit more fine particulates compared with them (especially with electric heaters owing to end-of-pipe controls for coal-fired electricity generation and increasing use of clean energy for electricity generation (see SI for more details of the end-of-pipe controls for coal-fired power, and emissions reduction of using clean heating options). Thus, CCIS are currently promoted only in remote mountain areas by the governments just as temporary substitutes before infrastructure and electricity/gas resources for electric/gas heaters are available and become less costly (NEA, 2019).

4.3. Policy implications

Our results indicate that more subsidies are needed in Hebei province (especially in the severely cold northern parts) to make clean heating affordable for rural households. However, Hebei has a less developed economy and a much larger population than Beijing or Tianjin, thus it is challenging for the Hebei governments to provide the same level of subsidies as the governments of Beijing and Tianjin. Therefore, regional financial collaborations on clean heating subsidies would be valuable for improving air quality throughout the BTH region. Our previous work has shown that air quality in Beijing benefits substantially from reductions in emissions from the residential sector in Tianjin and Hebei (Liu et al., 2016).

Although our analysis identifies the least costly heating options after subsidies, it is typically necessary for an individual household to purchase a heating substitute (i.e., gas, electricity, or clean coal) that the local governments have decided to make available with the subsidies. Not all heating devices are available with subsidies in all locations. In most cases, the local governments plan and determine the heating substitutes for a given region (e.g., a village) that will receive subsidies. For example, in Beijing, ~80% (20%) of the villages without district heating switched from coal to electricity (gas) for heating by the end of 2018 as the Beijing government had planned (People's Daily, 2019). But the Tianjin and Hebei governments have the reverse preference on gas. In Tianjin, ~18%, ~30%, and ~42% of the households without district heating had replaced coal with electricity, gas, and clean coal briquettes for heating by the end of 2018 (Tianjin Daily, 2019). In Hebei, ~17% (~80%) of the households were projected to replace coal with electricity (gas) according to the Hebei provincial government's plan in 2018 (HPG, 2018).

After the subsidized subsitutes are planned, the local governments will set up public bidding to identify suppliers. Subsidies will then either be provided to the suppliers or to households for the chosen heater type.
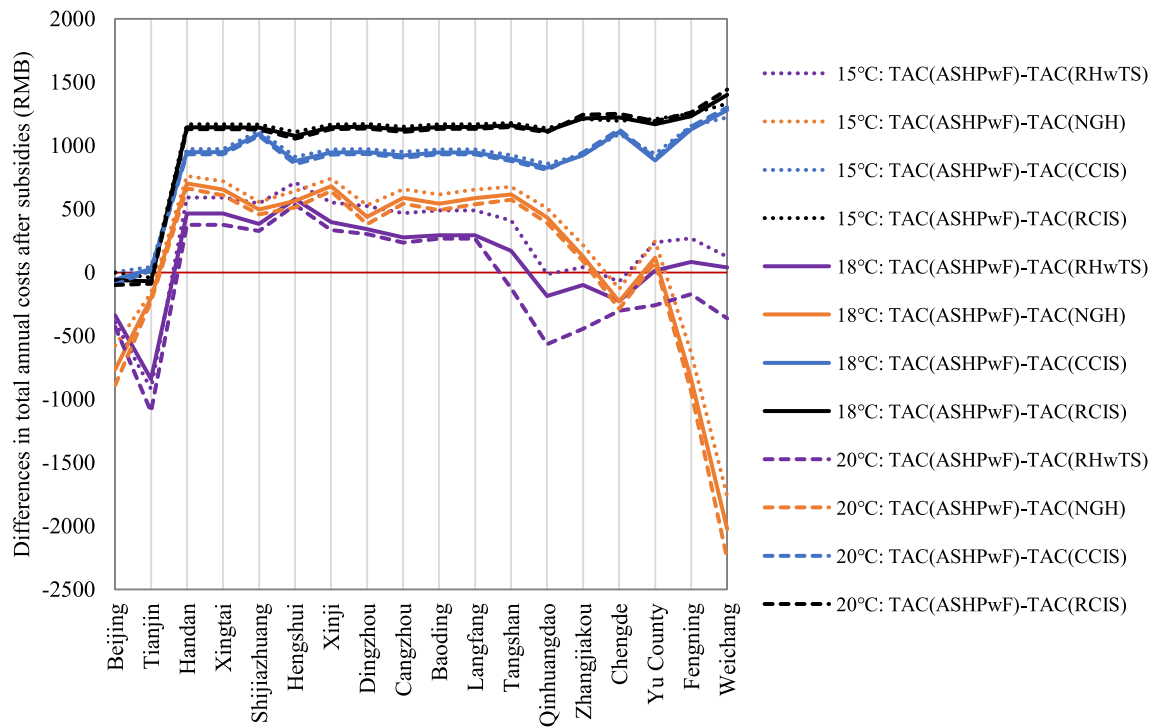
Fig. 3. Differences in total annual costs (capital + operating costs) with subsidies between air-source heat pumps with fan coils and other heating options for various indoor temperatures. TAC refers to total annual cost. Heater abbreviations are: air-source heat pumps with fan coils (ASHP*w*F), resistance heaters with thermal storage (RH*w*TS), natural gas heaters (NGH), clean coal with improved stoves (CCIS), and raw coal with improved stoves (RCIS). Positive (negative) values indicate ASHP*w*F cost more (less) than other heating options. The dotted, solid and dashed lines indicate cost differences when indoor temperatures are 15 °C, 18 °C and 20 °C, respectively.

The criteria used to determine the clean heating substitute that a certain region will adopt largely depends on local infrastructure availability (e.g., natural gas pipelines, power grid capacities, etc.), financial ability of local governments for subsidies, etc. Thus, before substitution policies are determined, it is very important for both the public and the governments, to determine the long-term efficacy of the heating substitutes for air quality improvement, greenhouse gas mitigation, in addition to their costs.

5. Sensitivity analyses

Considering that the values of the parameters we use in our analyses above vary in reality, which may change the heating substitutes' cost competitiveness, here we conduct sensitivity analyses to explore the impacts of desired indoor temperature, home size, building energy efficiency, and natural gas price on TAC of clean heating substitutes.

5.1. Sensitivity to desired indoor temperature

Here we examine the cost implications of three possible indoor temperature choices: 15 °C (energy and cost-saving), 18 °C (frequently used for analysis of energy use in urban homes), and 20 °C (for households with elderly and children). Fig. 3 compares the differences between TAC with subsidies of ASHP*w*F and other heating options for each desired temperature. We present the differences between ASHP*w*F and other heating options because ASHP*w*F are more energy-efficient and have lower associated air pollutant emissions than the other heating options.

We find in Fig. 3 that the cost competitiveness of ASHP*w*F increases with higher desired indoor temperatures, but the differences of TAC with subsidies between ASHP*w*F and NGH/CCIS/RCIS do not substantially change in any region as the desired indoor temperature changes by ±5 °C. In Beijing and Tianjin, the subsidized ASHP*w*F remains

competitive over 15–20 °C desired indoor temperature due to generous subsidies. In most cities of Hebei, regardless of desired indoor temperatures, the subsidized ASHP*w*F have higher TAC than the other heating options because subsidies for ASHP*w*F are small in Hebei. However, in the severely cold northern parts of Hebei, as the desired indoor temperature decreases to 15 °C, RH*w*TS become more competitive than ASHP*w*F.

5.2. Sensitivity to home size

In Fig. 4, we compare the differences in TAC with subsidies between ASHP*w*F and other heating options for three different home sizes: 50m², 100m², 200m². 50-200 m² is the typical household size range in rural areas of China. We find that the cost competitiveness of ASHP*w*F increases with larger home size. When the home size increases to 200m², ASHP*w*F become much less costly than RH*w*TS across the BTH region.

For households in Beijing, the subsidized ASHP*w*F have lower TAC than the other options except for small home size (i.e., 50m² case in our analysis). This is because subsidies for capital costs in Beijing depend on the home size (200 RMB/m²) while the cost of purchasing ASHP does not increase linearly with capacity of the device. For small households in Beijing (e.g., 50m²), the subsidized ASHP*w*F have higher TAC than CCIS or RH*w*TS.

For households in Tianjin, CCIS have lower TAC with subsidies than the other options for households with home size 50 or 100m² but ASHP*w*F are just slightly more costly than CCIS for 50-100 m² home size. When the home size increases to 200m², ASHP*w*F become the least costly option with subsidies.

For households in Hebei, CCIS have the lowest TAC with subsidies among all clean options for all home size (50-200 m²). ASHP*w*F have the highest TAC with subsidies for most southern parts of Hebei for home size 50-100 m².When home size approximates 200m², ASHP*w*F
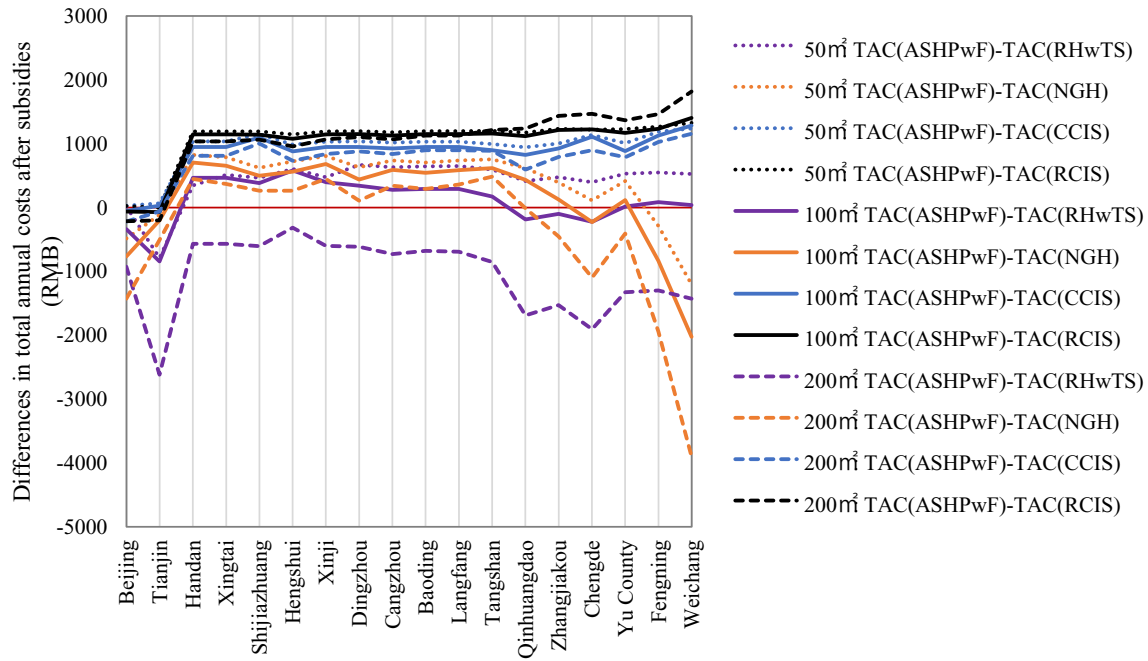
Fig. 4. Differences in total annual costs (capital + operating costs) with subsidies between air-source heat pumps with fan coils and other heating options for various home size. TAC refers to total annual cost. Heater abbreviations are the same as Fig. 3. The dotted, solid and dashed lines indicate cost differences when home size is 50m^2, 100m^2 and 200m^2, respectively.

have less TAC with subsidies than RHwTS. For the severely cold northern parts of Hebei (i.e., Fengning and Weichang), NGH have higher TAC with subsidies than the other options for all home sizes (50-200 m^2).

5.3. Sensitivity to building energy efficiency

Here we examine how households' TAC with subsidies of using clean heating technologies change with building energy efficiency (BEE). Taking the inverse of heat loss of buildings (W/m^2), used in this paper, as an indicator of building energy efficiency (m^2/W), we find that our estimates of rural residential building energy efficiency is ~50% of urban residential BEE reported by MHURD (2010). However, the efficiency of individual buildings varies. Thus here we consider three situations. Situation 1 (S1): The rural residential BEE is 30% of the urban residential BEE. Situation 2 (S2): The rural residential BEE is 50% of the urban residential BEE. Situation 3 (S3): The rural residential BEE is 100% of the urban residential BEE.

Fig. 5 shows that energy efficiency is a critical factor in the cost a household must spend on heating with heating expenses declining dramatically, regardless of heating device chosen, as BEE improves. In addition, BEE is of greatest importance, providing the largest cost savings, in extremely cold regions. We find: 1) Cost savings for heating due to BEE improvement increase sharply in the severely cold northern parts of Hebei. 2) Cost competitiveness of ASHPwF increases as BEE decreases. If rural residential BEE is only 30% of the urban residential BEE, ASHPwF have less TAC with subsidies than RHwTS across the BTH region. 3) Cost differences between clean heating options decrease as the BEE increases. If rural residential BEE reaches the urban level, TAC with subsidies of RHwTS, NGH and CCIS are similar in most cities/counties of the BTH region. In addition to the cost savings from BEE improvements indicated here, previous studies also found that improving BEE would increase residents' well-being and life satisfaction (Shove, 2018).

Our findings in Fig. 5 indicate that building energy efficiency is important for residential heating expenses and selection of heating technologies. Improvements in rural residential building energy efficiency is extremely valuable to obtain energy and cost savings as well as greenhouse gas and air pollution mitigation. For households with low

building energy efficiency, using more energy-efficient heating devices such as heat pumps can be a cost-effective decision.

Previous literature has suggested that the average cost of a major building energy efficiency retrofit is above 200 RMB/m^2 (MHURD, 2012; Liu et al., 2016). Thus, for the typical 100m^2 home size, as in our case, the total cost is above 20,000 RMB. If the lifetime of a retrofit is 30 years and the discount rate is 8% (Zhang et al., 2017a, 2017b), then the annualized cost is more than 1600 RMB. In 2018, the annual disposable income of rural residents in the BTH region was ~11,000–26,000 RMB per capita while the median national income was ~15,000 RMB per capita (NBS, 2019). As Tong (2019) indicated, the cost of major building energy efficiency retrofits is approximately 10% of their income and, without government assistance and access to loans, is likely to be more than the rural residents' are willing to pay.

In practice, improving energy efficiency has been regarded as a key point for energy conservation and emission reduction in China since the "11th Five-year Plan" (Shao et al., 2019a, 2019b). For the building sector, more than 150 million households with ~1 billion m^2 are4a improved their energy efficiency between 2011 and 2015 (MHURD, 2017). The national government has implemented a residential building energy efficiency retrofit project. The project has primarily focused on urban areas and will cover another 0.5 billion m^2 building area between 2016 and 2020 (MHURD, 2017). The cost of building energy efficiency retrofits is also subsidized in many provinces. For example, households in Beijing are subsidized with 100 RMB/m^2 for building energy efficiency retrofits (BMG, 2011). However, most of the retrofit projects have been undertaken in urban areas. Building energy efficiency retrofits in rural areas need more attention and support to achieve clean winter heating goals.

5.4. Sensitivity to natural gas price

The price of natural gas fluctuates regionally as a function of availability and policies as it's regulated by both the central and provincial governments in China (Qin et al., 2018a). In Fig. 6, we examine how the cost competitiveness of NGH compare with electric air source heat pumps, resistance heaters and coal stoves as natural gas prices vary.
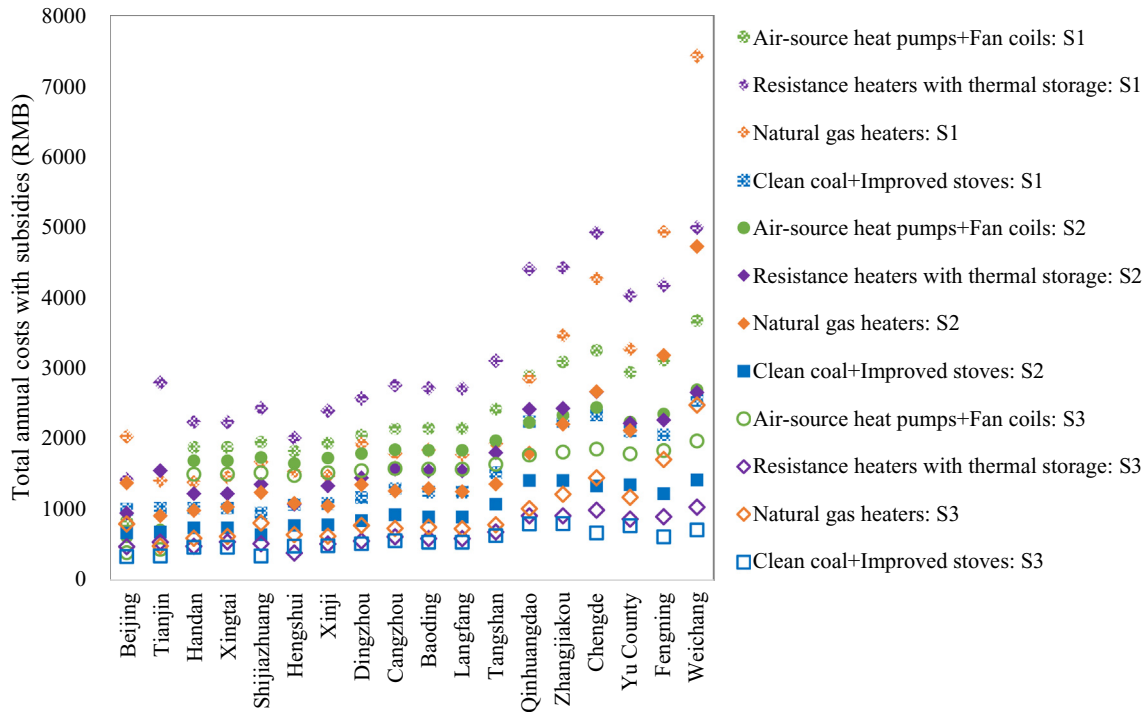
Fig. 5. Comparisons of total annual costs (capital + operating costs) with subsidies of using clean heating technologies in the BTH region under various building energy efficiency situations. S1 (stippled symbols) refers to Situation 1, in which the rural residential building energy efficiency is 30% of the urban residential BEE. S2 (closed symbols) refers to Situation 2, in which the rural residential building energy efficiency is 50% of the urban residential BEE. S3 (open symbols) refers to Situation 3, in which the rural residential building energy efficiency is 100% of the urban residential BEE.
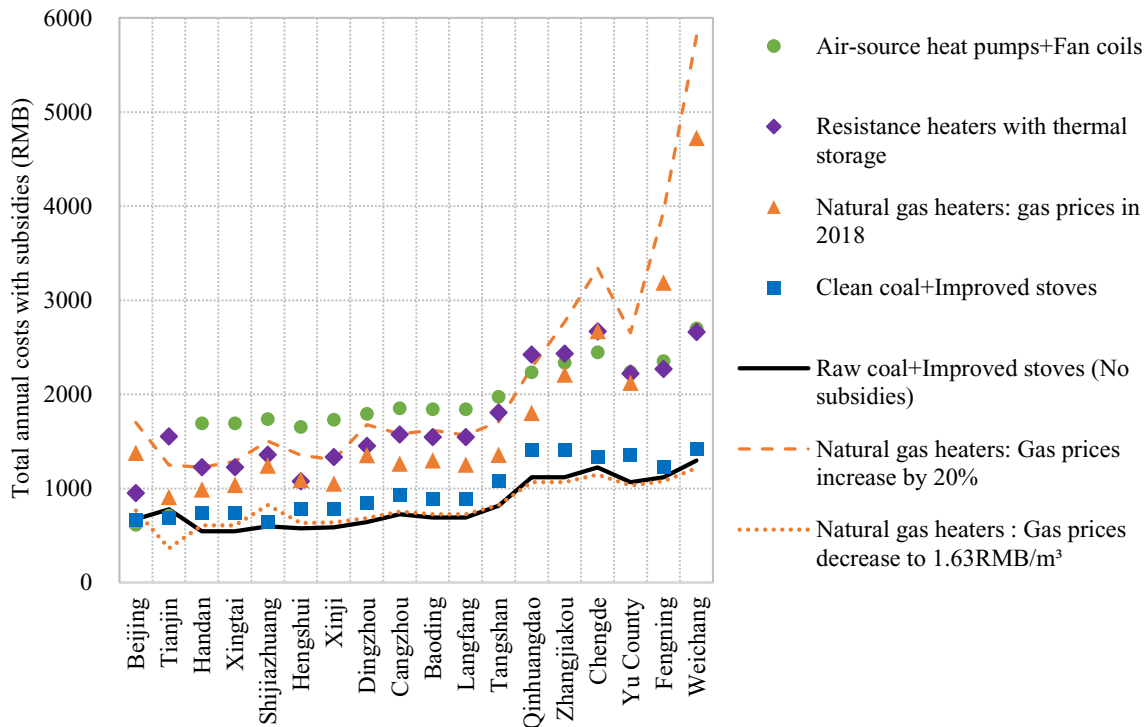

Fig. 6. Total annual costs (capital + operating costs) with subsidies for each household in the BTH region using ASHPwF, RHwTS, CCIS, RCIS and NGH under various gas prices. The dotted line refers to TAC with subsidies of NGH if residential gas prices in all the cities/counties fall to the lowest national average level over 2000–2019, which is 1.63 RMB/m³ in Feb., 2003 (CEIC, 2019). The dashed line refers to TAC with subsidies of NGH if residential gas prices in all the cities/counties increase by 20% from the level in the middle of 2018 (NDRC, 2018).

5.4.1. Gas price increases

On the one hand, gas price may increase due to rapidly increasing domestic demand combined with a limited supply. In 2018, China's natural gas import dependency rose to 45% and severe gas shortages took place in the BTH region in the winter of 2017–2018. Increasing demand due to increases in clean heating as well as increasing demands in the power and industrial sectors can be expected. Although synthetic natural gas (SNG) has been explored, the use of SNG would dramatically increase carbon emissions (Qin et al., 2017; Qin et al., 2018a) and the extraction of shale gas has not been as successful as hoped. Thus gas shortages may lead to price increases.

5.4.2. Gas price decreases

On the other hand, gas prices may decrease due to increased import of natural gas from other countries (e.g., Russia) and more successful domestic extraction of shale gas in the future. China is estimated to have large exploitable shale gas reserves. However, due to technological constraints, production rates have been low (Farah and Tremolada, 2016). Thus, technological breakthroughs may increase domestic shale gas supply and thus decrease gas prices. In addition, increased energy cooperation between China and foreign countries with gas resources may increase supply and hence decrease gas price. For example, three major gas pipeline projects from Russia to China are expected to reduce China's gas shortage. One of them (the eastern line, also named as "Power of Siberia") already came into service at the end of 2019 while the other two projects are under discussion. According to the contract, Russia will export 5–38 billion m^3/year natural gas for 30 years through the eastern line (Miyamoto and Ishiguro, 2018). Thus, due to potential technological breakthroughs and international energy co-operation, natural gas prices in China may decrease in the future.

Fig. 6 presents TAC with subsidies of NGH under various possible gas prices as in comparison with other heating technologies. In the middle of 2018, the NDRC released a document to reform the wholesale pricing mechanism of residential natural gas use. It states that city gate gas prices[4] are allowed to rise by no more than 20% and drop to whatever level to which suppliers and purchasers have agreed. In addition to the local prices in 2018, we therefore consider two other possible gas price scenarios based on the new NDRC policies (NDRC, 2018): (i) Residential natural gas prices in the BTH region increase by 20% from the level in the middle of 2018; (ii) Residential natural gas prices decrease to the lowest national average level over the past decade (2000–2019), which was 1.63 RMB/m^3 in February of 2003 (CEIC, 2019).

We find if gas prices decrease to 1.63 RMB/m^3, NGH become the lowest TAC among all the subsidized clean options across the BTH region except in Beijing and Shijiazhuang, where ASHP*w*F and CCIS still have the lowest TAC with subsidies, respectively. Besides, TAC of subsidied NGH is almost the same as AOC of RCIS in most cities/counties. In contrast, if gas prices increase by 20% from the level in the middle of 2018, TAC of subsidized NGH remain to be higher than TAC of subsidized ASHP*w*F and CCIS in Beijing, Tianjin and northern Hebei, while lower than TAC of subsidized ASHP*w*F but close to TAC of subsidized RH*w*TS in southern Hebei.

In particular, the competitiveness of subsidized ASHP*w*F to NGH changes sharply with gas prices in northern parts of Hebei. With gas prices in the middle of 2018, TAC with subsidies of ASHP*w*F is less than NGH in 3 cities/counties: Chengde, Fengning and Weichang. However, if gas prices increase by 20% from the level in middle 2018, TAC with subsidies of ASHP*w*F become less than NGH in 6 cities/counties: Yu County, Zhangjiakou and Qinhuangdao, in addition to Chengde,

Fengning and Weichang. In contrast, if gas prices decrease to 1.63 RMB/m^3, TAC with subsidies of ASHP*w*F are higher than NGH across the entire BTH region except in Beijing.

5.5. Summary of sensitivity analyses

We conduct sensitivity analyses on households' TAC with subsidies regarding desired indoor temperature, home size, building energy efficiency and natural gas price. We find: 1) The cost-competitiveness of ASHP increases with a higher desired indoor temperature and larger home size, implying that ASHP are likely the best clean heating options for wealthier families with larger home sizes as well as for commercial buildings. 2) Building energy efficiency improvements can result in large reductions in savings on heating costs, especially in severely cold regions. 3) The cost-competitiveness of NGH varies sharply with gas price and substantial uncertainty exists regarding future gas price volatility. 4) Heating expenses in severely cold northern parts of Hebei are more sensitive to changes in indoor temperature, home size, building energy efficiency and gas price than the other parts of BTH region as households in severely cold regions require more powerful heaters and more fuel.

6. Conclusions and policy implications

Replacing raw coal with electricity/natural gas/clean coal briquettes for residential heating in northern China is underway to address severe air pollution. Whether households, especially in the poorer rural regions are willing to purchase and use alternative heaters largely depends on the costs of such replacements. In this study, we calculate the annualized capital and operating costs for rural households across cities/counties in the BTH region to use clean heating technologies. The findings provide implications not only for the BTH region but also for the rest of northern China.

Our results demonstrate that, without subsidies, clean coal with improved stoves (CCIS) have the lowest total annual costs (TAC, annualized capital costs plus annual operating costs). Without subsidies, households have much higher heating expenses if they switch from coal stoves to air-source heat pumps with fan coils (ASHP*w*F), resistance heaters with thermal storage (RH*w*TS), or natural gas heaters (NGH). Considering the low incomes of rural residents and thus their cost constraints, financial support from governments, particularly for upfront capital costs, are needed to facilitate the transition to clean heating, especially for less developed and extremely cold areas, e.g., northwest and northeast China.

Thus, we go on to explore the role of subsidy policies in terms of ASHP*w*F, RH*w*TS, NGH and CCIS. Current subsidies in Beijing and Tianjin can largely cover the incremental capital and operating costs of replacing coal with alternative heaters including the environmentally friendly ASHP. However, more subsides are needed in Hebei, especially in its severely cold northern areas to facilitate a transition away from coal stoves.

We find that in Beijing and Tianjin, with subsidies, households' expenses on ASHP*w*F and CCIS are nearly the same as the costs of using raw coal with improved stoves (RCIS). As Hebei is large, there are large heterogeneities in heating demand between the cold southern areas and the severely cold northern areas. ASHP*w*F have lower TAC with current subsidies in Hebei than RH*w*TS and NGH in the severely cold northern parts of Hebei where natural gas prices are high. However, current subsidies in Hebei are insufficient for households to switch to clean heaters without a large financial burden. Thus without additional subsidies, households may choose to use CCIS rather than incur the additional cost of switching to ASHP*w*F, RH*w*TS or NGH.

As our previous work indicated, Beijing is strongly influenced by coal stove use in surrounding Tianjin and Hebei and air quality would substantially improve if coal stove use in Tianjin and Hebei were greatly reduced (Liu et al., 2016). Given the large number of households in need of

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[4] City gate prices are the prices that provincial gas distribution companies pay to oil companies that produce (or import), process, and transport gas from gas fields to end-use provinces. Generally, City gate prices are equal to wellhead prices plus transmission prices. Summing the city gate prices and distribution prices gives the retail prices either for residents or non-residents (Qin et al., 2018a).

coal stove replacement in less developed Hebei, financial support for Hebei, from either the central government or financial collaboration with Beijing/Tianjin government, would facilitate coal replacement and improve air quality throughout the BTH region. In addition to current policies, it would also be helpful to reduce households' upfront capital costs by establishing a credit mechanism with low interest rates. In addition, imposing an environmental tax (e.g., carbon tax) on fossil fuel use, particularly coal, could also be an efficient way to reduce coal consumption in the residential sector. The tax revenue could further be used to subsidize environmental protection projects such as subsidizing clean heaters (Jiang and Shao, 2014).

ASHP are the most energy efficient option which have the lowest operating costs among all the clean options even without subsidies on electricity. However, capital costs of ASHP are much higher than other clean heaters, posing challenges to poor rural households and reducing their competitiveness. Considering the likelihood of power grid decarbonization (Peng et al., 2018) and the rebound effect of energy use (Shao et al., 2019a, 2019b), we suggest more subsides for the capital costs of ASHP would be advantageous in the long term. Simultaneous decreases in the subsidies on both electricity and gas would lead to increased energy conservation and could avoid a rebound effect. However, for severely cold regions, a backup heating option such as CCIS is needed for periods when ambient temperatures drop below the point at which heat pumps work (~−25 °C).

We also find that substantial potential exists to reduce heating expenses by improving building energy efficiency. Benefits of building energy efficiency improvements are larger in northern areas of Hebei due to severely cold weather and associated larger heating demand there. Accordingly, in addition to the current efforts to reduce household expenses on heating devices and fuels, it is also important to support building energy efficiency improvements, especially for severely cold rural regions.

We note that policies need to be particularly cautious when encouraging the switch to fossil fuel-based technologies, i.e., CCIS and NGH. Because of the relatively low capital cost of CCIS, it can be used either for poor households living in remote mountainous regions, or as a transitional choice to highly-efficient electric heat pumps. Even though NGH can be more environmentally friendly than coal stoves, additional infrastructure (such as pipeline networks) as well as attention to minimize gas leakage from upstream natural gas processes are needed (Qin et al., 2018b). NGH commit additional future use of fossil fuels and emissions of CO_2 and CH_4 (Qin et al., 2017). Once fossil fuel infrastructure is built, it will likely be locked-in for decades and thus lead to further GHG emissions. Instead, if policies are directed to efficient electric heaters and the electricity system transitions from primarily coal to primarily non-fossil fuels, it will facilitate both a decrease in air pollutants and GHG emissions.

Facilitating interprovincial electricity transmission in China can also facilitate the use of renewable energy for electric clean heating. Renewable electricity transmitted from wider regions, such as wind power from Inner-Mongolia and utility scale photovoltaic panels from western China could reduce curtailment of renewable energy while providing an air pollution and greenhouse gas free source of electricity for clean electric heating devices throughout China.

Author contributions

Hongxun Liu and Denise L. Mauzerall designed research; Hongxun Liu collected data; Hongxun Liu and Denise L. Mauzerall analyzed data and wrote the paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2020.104844.

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