Natural gas and electricity: Two perspective technologies of substituting coal-burning stoves for rural heating and cooking in Hebei Province of China

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Abstract
Coal not only powers the household, social and global economy development but also emits large pollutants. Natural gas and electricity can be promising solutions to the energy supply and environmental pollution dilemma in Hebei Province of China. Currently, this coal-dependent province has launched the Hebei Air Pollution Prevention and Control Program to curb air pollution by replacing residential coal consumption with natural gas and electricity for space heating in winter. Approximately 2.53 million households have completed the switch from coal-burning stoves to natural gas or electricity stoves in rural areas surrounding Beijing and Tianjin since 2017. However, the contribution of this clean heating replacement on provincial emission reduction remains unclear. This study aimed to determine emission factors, energy efficiency, and economic profits of traditional coal-burning stoves, as well as cleaner natural gas and electricity stoves by laboratory simulation and field tests. The results indicated a significant reduction after clean replacement for PM2.5, CO, CO2, NOX, SO2, CH4, and 16 types of U.S. EPA priority polycyclic aromatic hydrocarbons (PAHs). The emission of PM2.5 can be reduced by 99% and 95% for natural gas and electricity switch. Toxic equivalent quantity value of PAHs was also decreased from 4.89 (coal) to 0.03 (natural gas) and 0.07 μg/MJnet (electricity). When comprehensively considering the upstream pollutants emissions from power plant, natural gas switching performed better than coal-fired electricity. Moreover, the government supported the clean heating replacement project with extensive financial subsidy for purchasing clean stoves and using clean energy within 3 years in rural areas. A relatively cheaper price on an energy basic of natural gas and electricity use can be obtained after this subsidy compared to coal.

KEYWORDS
clean heating, coal substitute, domestic stoves, polycyclic aromatic hydrocarbons, residential combustion
1 | INTRODUCTION

Solid fuels have powered human life and social development for many years.1-3 Coal is the dominant solid fuel with the fastest-growing production over the past 25 years, making up 28% of the world’s primary energy only lower than petroleum oil.4 The global coal consumption increased by about 66% from 2246 million tons of oil equivalent in 1990 to 3732 million tons in 2016.5 China is one of the leading countries of coal consumption in the developing world, accounting for over half of the world’s total coal consumption.6 Although the Chinese government has done much to develop alternative energies, coal will still play a key role in supporting population and maintaining a fast gross domestic production growth in the near-to-medium terms.7

Space heating and cooking accounted for the largest share of residential energy consumption. In rural areas of Northern China, raw coal burning in stoves is the major source of energy supply with an annual consumption of 2 million tons standard coal.8,9 As reported by China Heating Stove Report 2016 from China Association of Rural Energy Industry (http://www.carei.org.cn/), 66 million households in rural areas use coal burning as the main heating method with 120 million heating stoves but only 23% clean stoves. The coal-burning heating area accounts for about 83% of the total heating area, releasing large amount of pollutants including carbon monoxide (CO), carbon dioxide (CO₂), methane (CH₄), sulfur oxides (SOₓ), nitrogen oxides (NOₓ), particulate matter (PM), black carbon (BC), and polycyclic aromatic hydrocarbons (PAHs) in both indoor and outdoor environment.10,11 The main pollutants are produced due to the incomplete combustion of coal in inferior stoves (only 10-30% combustion efficiency), which have been considered as the major contributors to air pollution and human health risks.12 Excessive gaseous pollutants emitted from coal combustion would contaminate water resources, enter the food chain, and even lead to global warming.13,14 The haze caused by high PM₂.₅ and PM₁₀ emissions has caused public concerns due to its threat to visibility and human health.15 More than 90% of the victim of haze presents a respiratory symptom as well as elderly individuals suffer serious deteriorations of overall function.16 Another type of ecological hazardous emission is PAHs, which are a group of organic compounds with multiple aromatic rings, usually depositing in the nearby agricultural fields and residential communities.17 It has been estimated that many premature deaths, due to cardiopulmonary disease and lung cancer, are caused by the inhalation of PAHs into human body.

As a coal-dependent province, coal is over 80% of the energy production and consumption structure in Hebei Province with 4 × 10⁹ tons in rural consumption (76% for raw coal and 2% for honeycomb briquettes) for meeting daily energy needs.11,18 Simultaneously like other coal-based provinces in Northern China, this province also suffers from severe air pollution, especially in winter. Data showed that pollutants created from coal burning increased by 30% during winter according to the Ministry of Ecology and Environment of China (MEE, the formed name is Ministry of Environmental Protection http://www.zhb.gov.cn/). Haze is believed to be related with the high concentration of pollutants from frequent residential coal consumption, which contributes 40% of the monthly average PM₂.₅ emissions.19 Research has exhibited that the frequent outbreaks of heavy haze closely coincides with the intensive coal-burning heating season.20 Residential coal consumption for cooking and heating has been recognized as one of the major sources of air pollutant emissions. Given the low emission height, high pollution intensity, and insufficient law control of raw coal combustion, the current energy reforming program should be proposed for rural areas both nationally and locally. Promoting the clean heating in Northern China in winter is related to warming the people and reducing the haze days, being an important part of the revolution of rural energy, highly raised by central government of China.21 China has stepped up thorough efforts to fight air pollution by reducing reliance on coal and introducing more stringent emission standards for coal burning.

Natural gas and electricity are two perspective technologies chosen by Hebei government to replace coal-burning stoves in rural areas since 2016. Considering the low-cost supplies and great potential of exploitation, natural gas will be increasingly in demand to solve a short-term air quality problem with a predicted consumption of 350 billion m³ by 2020 in China.22 Electricity is a cleaner energy source for heating and cooking compared to fossil energy, especially for electricity generated from renewable energy which has no additional emission during production.23 Since 2017, this province has completed the switch from coal to natural gas in 1.96 million households as well as 8488 tons reduction in raw coal by using electricity.24 However, the emission reduction levels of different pollutants are not quantified with an unknown contribution of the clean heating replacement in rural areas, which will be a major obstacle to the future progress of energy reform and environmental protection.

In this study, we report the current air quality and related control polices in Hebei Province, exploring the clean heating replacement project and its progress. This study also evaluated the energy efficiency, emission performance (CO, CO₂, NOₓ, SOₓ, CH₄, PM₂.₅, and PAHs), and economic profits of natural gas and electricity compared to coal stoves to determine the contribution of replacing coal with clean energy on air pollution control.

2 | METHODS AND MATERIALS

2.1 | Air quality analysis and policy review

Current air quality in Hebei Province was analyzed by comparing air quality in each city and determining primary pollutants
according to atmospheric data obtained from MEE and China National Environmental Monitoring Center (NEMC, http://www.cnemc.cn/). Policies, such as emission control, financial subsidy, and especially clean heating replacement, were reviewed both national and locally from National Energy Administration (NEA, http://www.nea.gov.cn/), National Development and Reform Commission (NDRC, http://www.ndrc.gov.cn/), Hebei Development and Reform Commission (http://www.hbdrc.gov.cn/web/web/index.htm), Hebei Province Environment Monitoring Center (http://www.hebemc.net/), and Hebei Province Department of Finance (http://www.hebcz.gov.cn/). The contents of clean heating replacement, including targets, progresses during 2017 to early 2018, and limiting factors were also summarized.

2.2 | Experiment

The experiment of coal combustion was performed in a Stove Performance Testing System at the Bioenergy and Environmental Science & Technology Laboratory of China Agricultural University (Figure S1). A Hebei baseline stove (Figure S2) was used with a 6-hour testing sequence, including 45 minutes cold ignition, 4 hours low-power heating, 45 minutes high-power heating, and 45 minutes high-power cooking. Shenmu raw coal produced from Shaanxi Province was selected in this study and proximate analysis was performed in Northern China Electric Power University according to Chinese standard (GB/T 28731-2012).25 The higher heating value, lower heating value, moisture content, and ash content were 28.02 MJ/kg, 26.95 MJ/kg, 4.81%, and 5.67%, respectively. Emission performance of coal stove was determined by using current stove standards with a slight modification (detailed testing method shown in Supporting Information) (NY/T 2370-2013, NB/T 34021-2015).26,27 The main parameters of three stoves were shown in Table S1.

The experiments of natural gas and electricity stoves were performed in two pilot villages of Shijiazhuang city (one for coal-to-gas switching and one for coal-to-electricity switching) by a testing system (Figure 1). The exhaust gas was emitted from a natural gas stove and diluted by an air dilution system with a 250 CFM fan and a tunnel. Gases including O2, CO, CO2, NOx, SO2, and CH4 were measured by a gas analyzer (MGA5/Vario Plus; MRU Co., Ltd., Fuchshalde, Germany) from undiluted gas. PM emissions were determined by a DustTrak (DRX8533; TSI Co., Ltd., Shoreview, MN, USA) from diluted gas. PM concentrations were collected by a quartz fiber in DustTrak and analyzed according to a Chinese standard (HJ 645-2013).28 The indoor temperature was measured by an infrared thermometer (OS423-LS; OMEGA Engineering Inc., Norwalk, CT, USA). A meter was used to record the actual consumption values of natural gas during test. Emission factors of electricity stoves were determined by considering upstream emissions from power plant and transmission losses. Efficiency of natural gas or electricity stove could be read from the brand stuck in stove surface.

2.3 | Calculations

Emission factors on a useful energy basis of PM, CO, CO2, NOx, SO2, and CH4 of natural gas stoves (Figure S3) were calculated from testing data by following equations.29

$$\rho_{ng} = \frac{\rho_{nmg} \times v_a \times t \times H \times Q \times \eta}{H \times Q \times \eta}$$  \hspace{1cm} (1)

$$\rho_{nPM} = \frac{(\rho_{nmPM} - \rho_{nbPM}) \times v_d \times t}{H \times Q \times \eta}$$  \hspace{1cm} (2)

$$\rho_{nPAH} = \frac{\rho_{nmPAH} \times v_c \times DF}{H \times Q \times \eta}$$  \hspace{1cm} (3)

where $\rho_{ng}$ is actual value of gas emission (mg/MJ net); $\rho_{nmg}$ is the measured value of gas emission (mg/m3); $v_a$ is air velocity in chimney (2 m3/min); $t$ is operation time of stoves; $H$ is the heating value of fuel (MJ/m3); $Q$ is the gas consumption (m3); $\eta$ is the energy efficiency of stoves; $\rho_{nPM}$ is the actual value of PM concentration (mg/MJ net); $\rho_{nmPM}$ is the measured value of PM concentration (mg/m3); $\rho_{nbPM}$ is the background value of local PM concentration (mg/m3); $v_d$ is the diluted air velocity (7 m3/min); $\rho_{nPAH}$ is actual value of PAHs concentration (µg/MJ net) of natural gas; $\rho_{nmPAH}$ is measured value of PM concentration (µg/mL); $v_c$ is the concentrated volume of PAHs extractive solution (1 ml); and DF is dilution factor (10).

Emission factors on a useful energy basis of electricity stoves (Figure S4) were determined by Equation (4), according to emission limit from Chinese power standards (GB/T 16157-1996,
It was worth noting that the excess air coefficient should be considered in the following equation due to the application of theoretical air consumption value.

\[
\rho_e = \sum B_i \times A_i \times \frac{\rho_{el} \times V_{el}}{H \times \eta \times n} \tag{4}
\]

\[
\rho_{ePAH} = \frac{A \times \rho_{emPAH} \times V_e \times A}{H \times \eta \times n} \tag{5}
\]

\[
A = \frac{21}{1.7 \times (21 - G_o)} \tag{6}
\]

where \(i\) represents the individual fuel type for electricity generation; \(\rho_e\) is the emission value of electricity stove (gas and PM); \(B\) is the proportion of different fuel power in Hebei Province; \(\rho_{el}\) is the emission limit value (Table 1); \(V_o\) is the theoretical air consumption for complete combustion of unit fuel (m\(^3\)); \(n\) is the power transmission efficiency (95.53%); \(A\) is the excess air coefficient; \(\rho_{emPAH}\) is actual value of PAHs concentration (μg/m\(^3\)); and \(\rho_{emPAH}\) is cited value of PAHs concentration (μg/m\(^3\)).

The carcinogenic potency of PAHs was generally expressed by the toxic equivalent quantity (TEQ, μg MJ\(_{net}\)), which could be calculated by using the following equation:

\[
TEQ = \sum (TEF_i \times \rho_{PAH_i}) \tag{7}
\]

where \(i\) represents the individual PAH; TEF is the toxic equivalent factor by taking Benzo[a]pyrene (BaP) as a toxic benchmark; and corresponding TEF values of 16 typical PAHs are recommended by published investigations.

2.4 Data analysis

Each experiment was repeated at least three times. Statistical analysis was performed by using SPSS 20.0 software (SPSS Inc., Chicago, IL, USA) and values were determined in mean ± standard deviation. Duncan test was used to check the significance of the analysis results when necessary at a 95% confidence level.

3 RESULTS AND DISCUSSIONS

3.1 Current air quality and control polices in Hebei Province

Hebei Province, home to several of China’s top 10 polluted cities, typically is shrouded by heavy smog in winter because low atmospheric pressure, slow winds, and high humidity stop airborne pollutants to disperse. According to the MEE, the overall average of air quality composite index (AQCI) for Hebei Province in 2017 was 7.08 (a novel Chinese atmosphere environmental index shown in Supporting Information), Zhangjiakou and Chengde were the only two cities where the air quality were good with the primary pollutant of O\(_3\) and PM\(_{10}\), respectively, while the rest were all PM\(_{2.5}\) (Figure 2).

To cope with that, Hebei Province has launched several policies to replace coal with clean energy in household heating including shutting down coal-fire stove companies and limiting coal production (Table 2).  

3.2 Clean heating replacement

According to the energy sector’s 5-year plan for 2016-2020 from the NEA, Chinese government aims to slash the share of coal in the country’s energy mix down to below 58%. The proportion of high-quality energy consumption is expected to exceed 95%, and clean heating will reach 40% in 2019 and 60% in 2021 in rural areas (the share of 10% for natural gas and 17% for electricity) according to the NDRC. Hebei Province plans to reduce annual coal consumption of 5 million tons by promoting the use of clean energy in 2018.

Raw coal burning in rural homes will be banned in 18 counties and districts including 404 villages in the city and 3345 rural villages under the jurisdiction of Langfang City and Baoding City to build coal-free zone. This province has ordered its rural areas to use natural gas and electricity to replace coal and removed traditional coal-fire stove with the expectation of reduction of 40 600, 12 700, and 71 400 tons for SO\(_2\), NO\(_X\), and dust, respectively. So far in early 2018, Hebei Province has completed 2.53 million households of clean heating replacement (2.32 million for natural gas and 0.22 million for electricity) with 2 million clean stove and the reduction of 6.34 million...
tons raw coal consumption according to Hebei Development and Reform Commission and Hebei Province Environment Monitoring Center. Moreover, 2.42 million households of clean stoves have been put into use (2.20 million for natural gas and 0.21 million for electricity). The provincial subsidy for each clean stove is no less than 700 RMB (1 RMB = 0.1506 US dollar, 2017) and other financial support for household reform and energy price in heating season are shown in Table 4, according to Hebei Province Department of Finance.

3.3 | Emission performance

The switching from raw coal toward natural gas or electricity for energy demands in winter has offered primary energy supplies for Hebei Province since 2017. The majority of rural homes are using natural gas or electricity stove to produce clean energy for activities such as cleaning, bathing, cooking, space heating, clothes washing, and dishwashing. To aid in the quantification of emission performance of coal-to-natural gas or -electricity switching, some sets of indices are employed in Table 3. It showed that traditional baseline stove fueled with raw coal emitted more gaseous pollutants and PM$_{2.5}$ than clean stove fueled with natural gas or electricity. After replacing from coal to natural gas, a significant emission reduction in PM$_{2.5}$, CO, CO$_2$, NO$_X$, and CH$_4$ was 99%, 98%, 54%, 99%, and 57%, respectively. The rich air/fuel mixture in natural gas stove would result in a more complete combustion, explaining this reduction effect. The reduction in PM$_{2.5}$, CO, CO$_2$, NO$_X$, and SO$_2$ after replacing from coal to electricity was 95%, 93%, 90%, 99%, and 99%, respectively. All emissions reduction levels could meet the goals proposed by the provincial government. It was important to point out that emission levels of electricity stoves were in consideration of upstream emission from power plant. When only emissions at the point-of-use were considered, electricity stoves had more advantage for residential consumer due to a near-zero emission characteristic compared to natural gas. But when considering upstream emissions during electricity generation in power plant, natural gas performed better especially for some emissions indices, such as PM$_{2.5}$, CO, and SO$_2$.
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Figure 3A summarized the changes in 16 PAHs emissions after replacing coal to natural gas and electricity. The emission level of coal-burning stoves was not stable due to frequent artificial operation, directly resulting in a relatively large deviation in emission values in this table. All PAHs emissions were minimized obviously after replacing from TABLE 2

| Document name | Level | Year | Content |
|---------------|-------|------|---------|
| Air Pollution Prevention and Control Action Plan | Nation | 2013 | Zero growth in the consumption of coal in key areas of the country, the emission reduction in SO2, NOx, PM, VOCs for 6.41 × 10^6 t, 8.59 × 10^6 t, 5.47 × 10^6 t, 6.27 × 10^6 t, respectively, and the annual average PM2.5 concentration reduction in Beijing-Tianjin-Hebei Region, Yangtze River Delta, Pearl River Delta for 22.08%, 33.99%, 23.98%, and 24.04%, respectively. |
| Law of the People’s Republic of China on the Prevention and Control of Atmospheric Pollution (revised) | Nation | 2016 | Takes measures to control or gradually reduce the total amount of the main atmospheric pollutants discharged in local areas. |
| Prevention and Control Plan of Atmosphere Pollution for Beijing-Tianjin-Hebei Region and Surrounding Areas in 2017 | Nation | 2017 | Clean heating in winter with appropriate energy (natural gas or electricity) and remove small coal-burning boiler (less than 7 MW). |
| Comprehensive Control Plan of Atmosphere Pollution for Beijing-Tianjin-Hebei Region in autumn and winter (2017-2018) | Nation | 2017 | Cuts inferior coal production, improve cities and countries with high AQCI value, the PM2.5 concentration reduction for 15%, and heavily polluted days reduction for 15%. |
| Hebei Action Plan for strengthening Atmosphere pollution Control Measures (2016-2017) | Province | 2016 | PM2.5 concentration of 77, 65, 32, 41, 46, 65, 76, 72, 84, 83, 75 mg/m^3, respectively, for Baoding, Langfang, Zhangjiakou, Chengde, Qinhuangdao, Cangzhou, Shijiazhuang, Tangshan, Hengshui, Xingtai, and Handan Cities in 2017. |
| Hebei Air Pollution Prevention and Control Program | Province | 2016 | The coal-free region for 80% of the urban construction, central heating, clean fuel, and stove. |
| 2016 Action Plan for Rural Clean Energy Development and Utilization Project | Province | 2016 | Pilot cities of Shijiazhuang and Baoding for switching coal with carbon fiber electric heating, electricity heating boiler, and air-source heating pump. |
| Hebei Opinion on the Promotion of the Comprehensive Control of Atmosphere Pollution | Province | 2017 | Raw coal reduction for 30 million tons and PM2.5 concentration of 57 mg/m^3 in 2020. |
| Provincial Financial Subsidy Management for Comprehensive Atmosphere Pollution Control | Province | 2017 | Priority support for replacing coal with natural gas and electricity in rural areas. |
| Hebei 13th Five-Year Plan for Energy Development | Province | 2017 | Coal production of 60 million tons, coal consumption of 260 million tons, natural gas share of 10%, and optimize fuel quality. |

TABLE 3 Emission performance of raw coal, natural gas, and electricity stoves

| Energy          | PM2.5 (mg/MJnet) | CO (g/MJnet) | CO2 (g/MJnet) | NOX (g/MJnet) | SO2 (g/MJnet) | CH4 (g/MJnet) |
|-----------------|------------------|--------------|--------------|--------------|--------------|--------------|
| Raw coal        | 105.70 ± 4.31c   | 6.33 ± 1.15c | 350.21 ± 23.33c | 238.77 ± 9.01c | 13.33 ± 3.01b | 0.96 ± 0.02b |
| Natural gas     | 0.12 ± 0.02a     | 0.04 ± 0.02a | 160.42 ± 20.25b | 0.09 ± 0.04b  | 0             | 0.41 ± 0.18a  |
| Electricity     | 5.48 ± 1.13b     | 0.42 ± 0.02b | 34.80 ± 1.84a  | 0.03 ± 0.01a  | 0.03 ± 0.02a  | ND           |

Means on the same column with different lower case are significantly different (P < 0.05) by using Duncan test; the zero value of SO2 is because the measured emission concentration of SO2 from natural gas stoves is lower than the detection limit of gas analyzer; ND indicates that there are presently no standards for calculating CH4 emission from power plants.
coal to natural gas or electricity especially for high carcinogens of BaP and DbA proposed by the EPA. The total 16 PAHs emitted from coal, natural gas, and electricity was 30.89, 0.38, and 0.71 μg/MJ<sub>net</sub>, respectively. The average values of BaP emissions from coal, natural gas, and electricity were 2.55, 0.03, and 0.03 μg/MJ<sub>net</sub>. The reductions

**FIGURE 3** Sixteen typical PAHs of raw coal, natural gas, and electricity in stoves (A) and distribution with different rings (B) (Note: the zero values are because that the measured emission concentrations of individual PAHs are lower than the detection limits of standard determination method; different lower cases in the same PAH indicate significant differences between raw coal and clean energy)
in BaA, BbF, Chr, and InP was 99%, 99%, 98%, and 98% for natural gas switching, and the reduction in BbF, Chr, and BaA was 99%, 98%, 98%, and 98% for electricity switching. The PAHs oxidation due to enriched air/fuel rate of natural gas was one of the important reason for this reduction effect.\textsuperscript{45}

PAHs profiles according to their different number of rings were illustrated in Figure 3B. PAHs in smoke after the combustion were predominated by four-ring PAHs (eg, PyT, BaA, Chr, BbF, and BkF) while the proportions of low-ring PAHs were relatively small. It was explained that this study only characterized particulate PAHs and majority of low-ring PAHs with low molecular weight existed as gas phase.\textsuperscript{46} The mean PAHs emissions concentrations for different rings follow this order: four-ring (50.22%) > five-ring (17.09%) > two-ring (15.89%) > three-ring (13.25%) > six-ring (3.57%) for raw coal, four-ring (44.82%) > three-ring (22.66%) > five-ring (13.55%) > two-ring (11.77%) > six-ring (7.21%) for natural gas; and four-ring (38.75%) > three-ring (24.30%) > two-ring (21.94%) > five-ring (11.33%) > six-ring (3.69%) for electricity. The clean heating replacement significantly contributed to the four- and five-ring PAHs reductions. TEQ value of PAHs was also a meaningful index for evaluating indoor air quality, which decreased from 4.89 (coal) to 0.03 (natural gas) and 0.07 μg/MJ\textsubscript{net} (electricity). As the large percentage of the five-ring PAHs accounted for the majority of TEQ, the reduction in five-ring PAHs TEQ was more effective to improve indoor air quality for human health.

3.4 | Economic evaluation

The heating modes of natural gas and electricity had higher energy efficiency and more financial subsidy than coal (Table 4). When only considering the energy efficiency at the point-of-use, electricity stoves (99%) had a relatively higher value than natural gas (84%). However, majority of energy losses often occurred at the power plant when converting primary energy into electric energy, leading to a decrease in efficiency (60%).\textsuperscript{47} The heating value of unit natural gas or electricity (equivalent of coal) was obviously higher than unit coal. Clean stoves could simplify daily running option such as refueling, ventilating, and ash dumping, and save lots of manpower. Moreover, poor-performance coal stoves with high emissions would be fined with more fee if the emission was higher than limiting value. Figure 4A compared mean cost of coal, natural gas, and electricity heating modes in a heating season (121 days) with a 120 m\textsuperscript{2} room in rural areas of Hebei Province, including initial investment (eg, stove and house upgrading fee) and annual operation (eg, energy price). The initial investment of natural gas and electricity was reduced substantially by the support of government subsidy with a not significant variance from coal. Moreover, the operation cost of natural gas and electricity was also subsidized in the first 3 years after buying a clean stove, but increasing obviously beyond 3 years. When comparing the price on an energy basis, a significant benefit could be attained by using natural gas or electricity energy whose price was even cheaper than coal (Figure 4B).

In China, the most significant concern of rural resident was actual cost when they chose heating mode. This might be on of the reason why expensive electricity heating mode only concentrated in Shijiazhuang and Baoding surroundings (8%), although the price on an energy basis of electricity was cheaper than natural gas in fact. Natural gas stoves were dominant everywhere in Hebei Province (92%) due to relatively cheaper cost.

3.5 | Limiting factors and recommendations

The average values of AQCI, PM\textsubscript{2.5}, and SO\textsubscript{2} level in 2017 were 6.59, 60.2 μg/m\textsuperscript{3}, and 22 μg/m\textsuperscript{3} with the year-on-year improvements of 17.45%, 24.06%, and 48.56% for clean heating replacement area compared to 2016, while the AQCI, PM\textsubscript{2.5}, and SO\textsubscript{2} levels were 7.14, 70.4 μg/m\textsuperscript{3}, and 43 μg/m\textsuperscript{3} with the year-on-year improvements of 7.75%, 9.59%, and 37.68% for nonreplacement areas (Figure 5) according to the NEMC. Approximately 30% contribution on air pollution control in Hebei Province can be achieved after clean heating replacement. However, poor public perception, lacking of environmental awareness, and peer effect would still limit the dissemination of clean heating replacement in rural areas.\textsuperscript{48} Some suggestions are proposed to promote the future development of clean heating replacement project as follows.

3.5.1 | Low actual energy efficiency

The actual energy efficiency of a domestic stove is often 10%-20% less than its posted value in brand because the posted value only characterizes the site efficiency at the point-of-use but neglecting the upstream losses.\textsuperscript{49} Besides, the site efficiency is also affected by ambient environment with an energy losses caused by low temperature and high humidity.\textsuperscript{50} Developing and improving metrics that reflect the actual energy efficiency could provide more useful information regarding the performance of domestic stoves and energy use characteristics.

3.5.2 | Natural gas shortage

China is an indigent-natural gas resource country (only 3.5% share of the global production), dependent on imports.\textsuperscript{51} The short supply of natural gas in Hebei Province limits the use of clean energy and raises natural gas price. The country should maintain a stable external supply from other gas-rich
countries such as Russia and Turkmenistan. Moreover, national and local government need improve the exploitation, refining, and storage technologies, optimize current energy structure including continuing the gas west-east transfer project, and launching the gas south-north transfer project. Developing renewable biogas and purification technologies may be also a promising solution to plug the natural gas shortfall.

3.5.3 | Emission from coal-fired power and high electricity price

Coal-fired power still represents a significant fraction (nearly 94%) of electricity production in Hebei Province. Rural residents would not afford the expensive electricity price without financial support from government after the 3-year subsidy period. Government should adjust electricity structure by executing time-dependent electricity price, developing local power grid, and encouraging private enterprises for power production. The renewable energy (wind, hydroelectricity, solar, geothermal, natural gas, biomass, nuclear, and hydrogen) used for power production should be also promoted by the government.

3.5.4 | Incomplete emission standards

Current emission standards mainly limit SO$_2$, NO$_X$, CO, and PM emission values in China without CO$_2$ and CH$_4$ limiting value. The two gases are typical greenhouse gas, which are the contributors of global warming.$^{52}$ The lack of definitions will prevent quantifying emission and pollution control. Government sectors should develop related standards to curb greenhouse gas emissions especially for power plants and boilers.

4 | CONCLUSIONS

Replacing rural coal-based energy supply system with cleaner energy is the important part of Rural Energy Revolution reported by the Chinese top leader, directly related to residential daily energy needs and air quality control. With the progress of clean heating replacement, coal-burning stoves for heating and cooking are gradually becoming history in rural areas of Hebei Province.

| TABLE 4 | The economic performance of coal, natural gas, and electricity used in heating season (121 d) in rural areas of Hebei Province (120 m$^2$ room space) |
|-----------------|------------------|------------------|------------------|------------------|------------------|
| Type            | Subsidy          | Stove (RMB)      | House upgrading (RMB) | Heating value | |
| Coal            | None             | 1500-2500        | None               | 23.02 MJ/kg   | |
| Natural gas     | Stove: 70% (≤2700 RMB); House upgrading: ≤4000 RMB; Energy: 1 RMB/m$^3$ (≤1200 m$^3$/y, within 3 y) | 3500-5000 | 4000-5000 | 35.53 MJ/m$^3$ |
| Electricity     | Stove: 85% (≤7400 RMB); House upgrading: ≤5000 RMB; Energy: 0.2 RMB/kW h (≤10 000 kW h/y, within 3 y) | 5000-9000 | 6000-7000 | 8.90 MJ/kW h |

FIGURE 4 Annual investment (A) and energy price (B) of coal, natural gas, and electricity in rural areas in Hebei Province, China (Note: the different lower cases in initial investment [or operation, or energy price] indicate significant differences between raw coal and clean energy)
by national and local efforts. Natural gas and electricity will be the main energy supply with lower emissions and higher energy efficiency, which are the solution to the protection of atmospheric environment and human health. This project has achieved a 30% contribution on provincial pollution control. The emission reductions in CO, CO₂, NOₓ, and CH₄ were 99%, 98%, 54%, 99%, and 57% after replacing coal stoves with natural gas stoves, while the emission reductions in these pollutants were 95%, 93%, 90%, 99%, and 99% after replacing coal stoves with electricity stoves. PAHs were also reduced significantly. The low cost of clean heating mode can be attained after financial subsidy from the governments.

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| Fuel price                  | Daily consumption | Energy efficiency (%) | Depreciation (y) | Emission fee                                      |
|-----------------------------|-------------------|-----------------------|------------------|---------------------------------------------------|
| 1100 RMB/ton (containing transformation fee) | 25-30 kg          | 48                    | 15               | 4.8 RMB/pollutional equivalent in 2017 and six RMB/pollutional equivalent for SO₂ and NOₓ emissions |
| 2.35 RMB/m³                | 15-20 m³          | 84                    | 8                | way higher efficiency in 2017 and six RMB/pollutional equivalent for SO₂ and NOₓ emissions |

**TABLE 4** The economic performance of coal, natural gas, and electricity used in heating season (121 d) in rural areas of Hebei Province (120 m² room space)

| Type                     | Subsidy Stove (RMB) | House upgrading (RMB) | Fuel price | Energy efficiency (%) | Depreciation | Emission fee |
|--------------------------|---------------------|-----------------------|------------|-----------------------|--------------|--------------|
| Coal                     | None                | 1500-2500             | 23.02 MJ/kg | 1100 RMB/ton (containing transformation fee) | 15           | 4.8          |
| Natural gas              | Stove: 70% (≤2700 RMB); House upgrading: ≤4000 RMB; Energy: 1 RMB/m³ (≤1200 m³/y, within 3 y) | 3500-5000 | 35.53 MJ/m³ | 2.35 RMB/m³ | 15-20 m³ | 84           |
| Electricity              | Stove: 85% (≤7400 RMB); House upgrading: ≤5000 RMB; Energy: 0.2 RMB/kW h (≤10 000 kW h/y, within 3 y) | 5000-9000 | 8.90 MJ/kW h | 33.26 MJ/kg (equivalent of coal) | 120-150 kW h | 100 (60 when considering upstream loss) |

**FIGURE 5** Comparison on improvement of air quality of selected 10 counties or districts in clean heating replacement area and nonreplacement area in Hebei Province, China in 2017
Utilization of Renewable Energy, Ministry of Agriculture and Rural Affairs, China Agricultural University; National Center for International Research of BioEnergy Science and Technology, Ministry of Science and Technology, China Agricultural University; Beijing Municipal Key Discipline of Biomass Engineering; and Beijing Kunhe Environment Technology, Co., Ltd.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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