Energy and air pollution benefits of household fuel policies in northern China

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In addition to many recent actions taken to reduce emissions from energy production, industry, and transportation, a new campaign substituting residential solid fuels with electricity or natural gas has been launched in Beijing, Tianjin, and 26 other municipalities in northern China, aiming at solving severe ambient air pollution in the region. Quantitative analysis shows that the campaign can accelerate residential energy transition significantly, and if the planned target can be achieved, more than 60% of households are projected to remove solid fuels by 2021, compared with fewer than 20% without the campaign. Emissions of major air pollutants will be reduced substantially. With 60% substitution realized, emission of primary $PM_{2.5}$ and contribution to ambient $PM_{2.5}$ concentration in 2021 are projected to be 30% and 41% of those without the campaign. With 60% substitution, average indoor $PM_{2.5}$ concentrations in living rooms in winter are projected to be reduced from 209 (190 to 230) μg/m^3 to 125 (99 to 150) μg/m^3. The population-weighted $PM_{2.5}$ concentrations can be reduced from 140 μg/m^3 in 2014 to 78 μg/m^3 or 61 μg/m^3 in 2021 given that 60% or 100% substitution can be accomplished. Although the original focus of the campaign was to address ambient air quality, exposure reduction comes more from improved indoor air quality because ~90% of daily exposure of the rural population is attributable to indoor air pollution. Women benefit more than men.

residential energy | coal substitution | ambient and indoor air pollution | PM2.5 | exposure

Rural residential solid fuel burning is one of the major emission sources of air pollutants in China (1, 2). This is particularly true for incomplete combustion products such are CO (carbon monoxide), primary $PM_{2.5}$ (particulate matter with aerodyamic size less than 2.5 μm), BC (black carbon), and OC (organic carbon) (3–7). It was estimated that on average 21 ± 14% of $PM_{2.5}$ in the population-weighted exposure to ambient air of China came originally from rural residential emission in 2012 (8). Moreover, use of solid fuels dominates rural household air pollution exposure, causing a significant disease burden in China (3). It was recently reported that decrease in $PM_{2.5}$ exposure and associated premature mortality in China from 2005 to 2015 was dominantly due to changes in household energy that came from urbanization and economic growth (9).

Northern China has the highest regional levels of air pollution in the country due to intensive industrialization, dense population, and its long heating season (10, 11). The rapid transition from traditional fuels to LPG (liquified petroleum gas), biogas, and electricity for cooking is resulting in much lower emissions. Still, solid fuels remain a dominant energy source for heating (12, 13). Although a series of actions have been taken to mediate air pollution in China since 2014, residential emissions were not the major focus until recently (2, 14), when the importance of the residential sector to ambient air pollution in northern China was better recognized (2). To address the issue, a campaign (Clean Heating Plan for Northern China in Winter for 2017–2021) was launched to substitute electricity or pipeline-based natural gas (PNG) for heating in northern China, focusing on the so-called 2+26 (Beijing, Tianjin, and 26 other municipalities in the surrounding area) region (Fig. 1) (15). Heat pumps, which are much more efficient than simple electrical resistance heaters, are the primary choice for electricity heating. A novel guideline for natural gas pipeline facilities in rural areas was issued by the Ministry of Housing of Urban-Rural Development (16). It is planned that 60% of coal-using households within the 2+26 region will shift to clean fuels (PNG, LPG, and biogas) and electricity (CFE) by 2021. While only coal is referenced in the official national plans, the use of biomass is still prevalent in the area and is being eliminated as well in local projects.

This study evaluates the impacts of the campaign on rural residential energy use, emissions, ambient and indoor air quality, and population exposure to $PM_{2.5}$ in the 2+26 region (termed the study region hereafter). Because solid fuels are mostly used in rural households now and will be only used in rural households after 2021 (17), the study focused on the rural residential sector. The rural population of the study region is currently 75.5 million, roughly 41% of the total population in the region (18). Four scenarios were developed: S1 (business as usual), no intervention involved except those driven by changes in population distribution and economic growth (12); S2 (limited effort), limited and nonspecific effort on residential emission reduction as planned in the 13th Five-Year Plan for Air Pollution Control (APCP13),

Significance

Impacts of a newly launched rural residential solid fuel substitution campaign in China's Beijing–Tianjin–Hebei area on energy, emission, air quality, and exposure reveal that abating solid fuels will significantly reduce ambient and indoor air pollution, resulting in major health benefits. The campaign will help accelerate China's energy transition and reduce $PM_{2.5}$ emission and exposure. The expected exposure reduction is largely due to improved indoor air quality, resulting in greater benefits to women.

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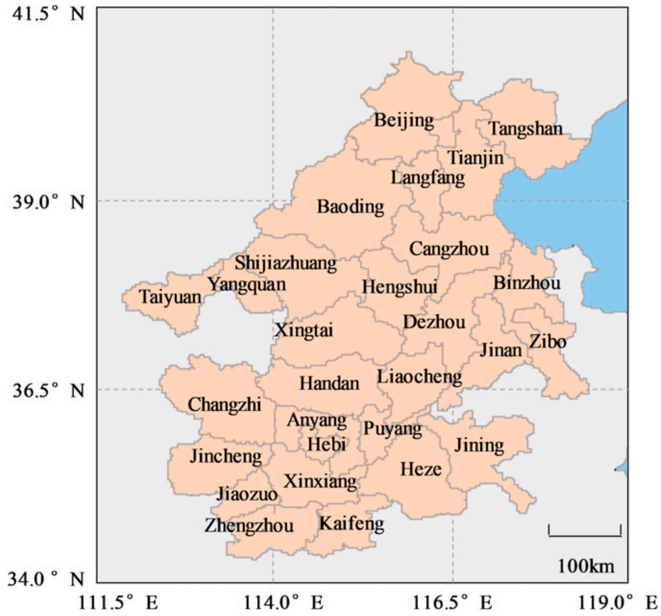

Fig. 1. The 2+26 region including Beijing, Tianjin, and 26 other municipalities.

which mainly focused on industry, transportation, and energy production (19); S3 (partial substitution), 60% substitution are projected to achieved as planned by the Clean Heating Plan for Northern China in Winter for 2017–2021 (15); and S4 (full substitution).

In brief, residential energy use was derived for a period from 1992 to 2021 for the four scenarios. Emissions of major air pollutants were calculated based on energy consumptions and corresponding emission factors (EFs, quantities of pollutants emitted from a given amount of fuel consumed). A set of recently developed regression models were applied to predict annual mean $PM_{2.5}$ concentration in ambient air by excluding meteorological confounding (20). $PM_{2.5}$ concentrations in indoor air were derived using a statistical procedure based on residential fuel types (21). Finally, population exposures to ambient and indoor air $PM_{2.5}$ were quantified and a time-weighted sum was supplied to obtain total exposure. The results were compared among the four scenarios to address the impacts on energy, environment, and health associated with the campaign.

We focus on total exposure of each main segment of the population—men, women, and children under 15 y old—which is comprised of both indoor and outdoor components. Changes in this metric are more closely related to changes in health status than are partial indicators such as ambient pollution levels.

Results and Discussion

Impact of the Campaign on Rural Residential Energy Transition. A national survey on rural residential energy consumption was conducted in 2012 (12). Detailed rural residential energy information was extracted from the survey and analyzed for the 2+26 region. At the national level, a transition of traditional cooking energy toward clean fuels or electricity (CFE) was found, but solid fuels are still extensively used for heating in rural mainland China (12). [Throughout, we adjusted household energy use by the percentages of time each was used, which were derived from surveys asking percentages of time using 10 specific energy types for five specific activities (12).] CFE contributed 59% and 15% of total energy consumption for cooking and heating, respectively, nationwide in 2012. In comparison, the CFE percentage for cooking (68%) in the study region (Fig. 2) was significantly higher than the national average, likely due to its faster socioeconomic development (22). On the other hand, the fraction of solid fuels used for heating in the study region (89%) was about the same as the national average (85%), because of its longer heating period and colder winter (8). In addition, one-third of residents (33%) in the 2+26 region were still using traditional kangs (brick heating beds) in 2012 (12), for which solid fuels are the only choice (23). The estimated total coal consumption in the rural residential sector in the study region was 17.7 million tons in 2012, contributing ∼18% of the national total residential consumption and 5% of the national coal consumption that year. In 2012, 13.2 million tons of firewood and 13.1 million tons of crop residue were burned for cooking and heating, accounting for 6% and 10% of total residential consumption in rural China.

As noted in Tao et al. (12), the survey also revealed a rapid transition of rural residential energy driven by an improvement in living conditions. Quantitative regression models for predicting CFE use based on per capita income and several other parameters have been developed (12) and applied to project the future trend for the study region in this study. For scenario S1 (without any intervention), the temporal trends (from 1992 to 2021) of energy consumptions for cooking and heating in the study region are shown in Fig. 3 along with data for mainland China. Temporal trends of CFE percentage are also shown. For the study region, percentage of CFE for cooking and heating increased from 8 (7 to 9)% to 68 (60 to 75)% and from 0.7 (0.6 to 0.8)% to 11 (10 to 12)% from 1992 to 2012, respectively, similar to those for the entire country. Without any intervention, CFE percentages for cooking and heating, respectively, would increase to 86 (76 to 96)% and 19 (18 to 21)% for the study region in 2021. As a result, residential coal consumption for cooking and heating in the study region are projected to drop from 24.2 million tons to 17.7 million tons. Similarly, quantities of fuel-wood and crop residue are projected to decrease from 53.2 million tons and 42.5 million tons to 13.2 million tons and 13.1 million tons, respectively.

With the mitigation actions, especially the coal-substitution campaign in place, accelerated rural residential energy transition is expected. The estimated changes of rural residential energy use from 2013 to 2021 are shown in Fig. 4 for the four scenarios. For cooking, the CFE percentage are projected to spontaneously increase to 86 (76 to 96)% by 2021 without intervention (S1; Fig. 4). With 60% coal substitution (S3), the fraction can reach 95 (84 to 99)% and solid fuels used for cooking are projected to be essentially eliminated in the study region. This implies that for the eight to 10 mo of the nonheating season emissions of major air pollutants from the rural residential sector would be a small fraction. Further, the emissions from gaseous fuels can almost be ignored compared with other sources (7) and it is technically and financially feasible to control emissions from power stations to low levels (24).

On the other hand, the relatively high cost of clean heating and relatively low income of local residents prevent a spontaneous transition away from solid fuel heating (12). The fraction of solid fuels used for heating in this region could be as high as 81 (79 to 82)% in 2021 if there is no intervention (S1). If 60% of solid-fuel users can shift to electricity or PNG for heating (S3), the CFE ratio is projected to increase to 74 (68 to 80)% in a few years while the quantities of coal, firewood, and crop residue used in the residential sector of the study region are projected to drop to 4.8 million tons, 2.9 million tons, and 3.0 million tons for S3. If there is not such an intervention, the total quantities are projected to be 10.1 million tons, 5.5 million tons, and 5.7 million tons, approximately twice as much as those for S3.

Although the impact of the new program on the study region is substantial, there will be limited influence on the entire country because of the limited size of the region. The location of the study region is at the edge of the county and air circulation shows

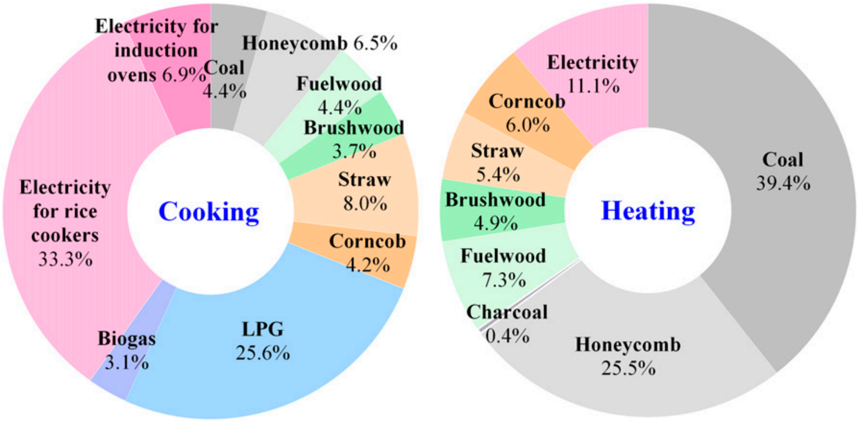

Fig. 2. Time-sharing fractions of detailed residential energy types used for cooking (*Left*) and heating (*Right*) in the study region in 2012. The data were derived from a nationwide survey on rural residential energy in mainland China (12).

that little of the pollution transports westward, although downwind countries may benefit from the added controls. In the case of S1, the relative contributions of CFE in mainland China are projected to increase from 72% in 2014 to 79% in 2021 for cooking and from 28% in 2014 to 35% in 2021 for heating.

Emissions Reduction Due to the Substitution. In 2012, only 4.4% of coal and 1.3% of gas fuels (LPG and PNG) were used in the residential sector in China (25). On the other hand, all crop residue and most fuel wood combusted for cooking and heating are carbon-neutral (26). As a result, CO_2 (carbon dioxide) emitted from this sector contributed to a rather small percentage of the total (3.6%, 3.1 to 3.9%) from all anthropogenic sources in the study region, although the fraction was as high as 20% (17 to 21%) in 1992. The rapid decrease is due to increases in fossil fuel use in other sectors. If the targeted substitution can be achieved in the study region (S3), the relative contributions are projected to decrease slightly to 3.4% (2.8 to 3.9%) in 2021, showing very limited impact on carbon emissions.

Unlike the emission of CO_2, emission of primary $PM_{2.5}$ is strongly associated with combustion conditions. Because residential stoves are typically under poor combustion conditions (27), the EFs of primary $PM_{2.5}$ for residential stoves are usually several orders of magnitude higher than those for energy production and industrial sources (28). As a consequence, 24% of the primary $PM_{2.5}$ emitted from all anthropogenic sources in the study region were from the rural residential sector in 2012 (12). The rural energy transition has reduced and will continue to reduce primary $PM_{2.5}$ emissions. In 1992, the relative contribution of this sector was as high as 61 (57 to 65)% and is expected to drop to 19 (15 to 23)% in 2021 without any intentional intervention. With the planned coal-substitution campaign implemented (S3), the percentage are projected to be as low as 7 (6 to 8)%. The estimated results are shown in *SI Appendix*, Fig. S1 as cumulative frequency distributions of grid emission densities. The results presented are baseline in 2014 and two scenarios of S1 and S3 in 2021. In 2014, emission densities of half the grid cells in the study region were higher than 760 g per grid cell, which would reduce to 640 g per grid cell in 2021 spontaneously without intervention, and to 190 g per grid cell for S3. In the scenario of S3, emission densities of more than 97% of grid cells are projected to be below 300 g per grid cell, indicating significant impact of the campaign.

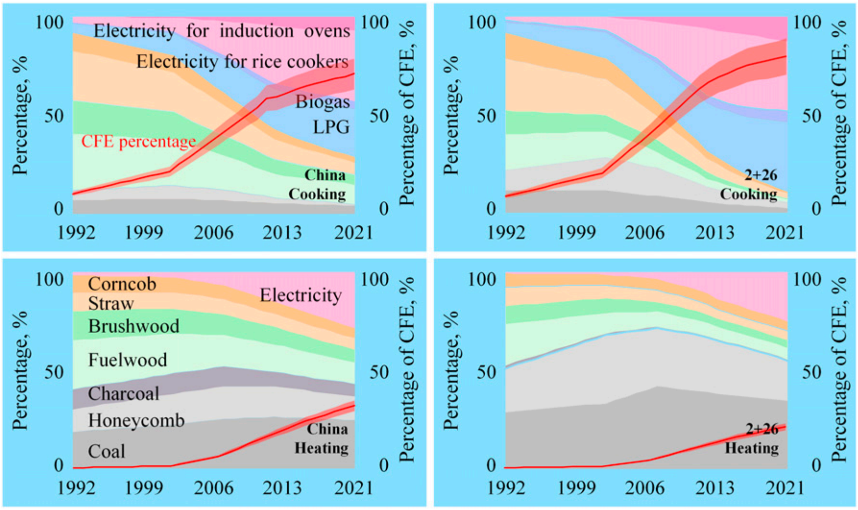

Fig. 3. Temporal trends of rural residential fuel and electricity uses for cooking (*Top*) and heating (*Bottom*) in the 2+26 region from 1992 to 2021 as percentages of time using various energy types (*Right*). The results are compared with those for the entire mainland of China (*Left*). In addition to individual energy types, CFE percentages are shown as means (solid lines) and 90% CIs (shaded area) in each panel.

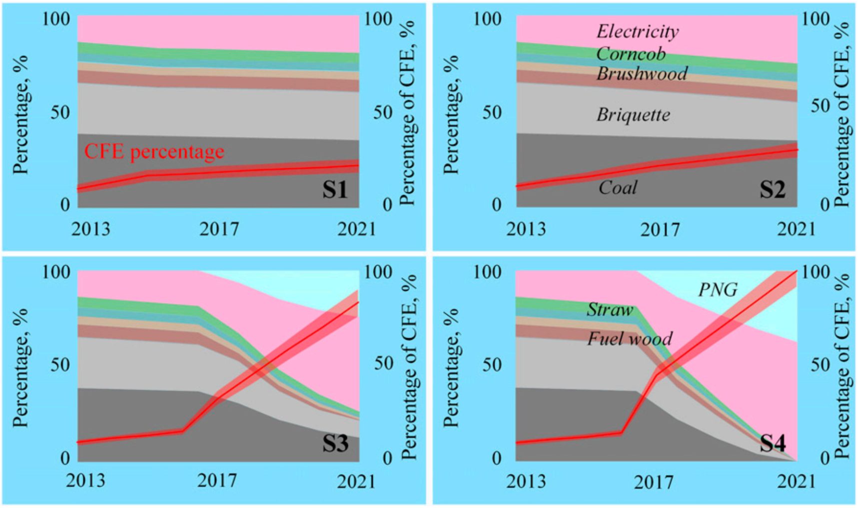

Fig. 4. Temporal trends of rural residential fuel and electricity uses for heating in the 2+26 region from 2013 to 2021 for four scenarios (S1 through S4) as percentages of time using various energy types. In addition to individual energy types, CFE percentages are shown as means (solid lines) and 90% CIs (shaded area).

Both BC and OC are critical components of primary $PM_{2.5}$ in the terms of health and climate impacts (5, 29). The fractions of BC and OC in the primary $PM_{2.5}$ from residential solid-fuel burning are much higher than those from other sources, again due to poor combustion conditions. For example, the average EF ratio of OC and primary $PM_{2.5}$ for residential coal is 0.60, more than 1 order of magnitude higher than 0.02 for a coal-fired power plant (29). Consequently, the impact of the coal-substitution campaign on BC and OC emissions is stronger than that on $PM_{2.5}$ emission. Taking BC in the study region as an example, the relative contribution of the rural residential sector to total anthropogenic emission was 55 (52 to 59)% in 1992, which was reduced to 38 (35 to 40)% in 2012 due to socioeconomic development and would further decline slowly to 33 (26 to 37)% by 2021 spontaneously. With the intervention of various levels, the relative contributions are projected to be 27 (21 to 34)% (S2), 12 (9 to 15)% (S3), and 0.07 (0.06 to 0.08)% (S4), respectively, contributing to notable emission reduction in the study region.

The influence of the campaign on emissions of various air pollutants is summarized in Fig. 5. Even without the campaign, the emission have declined and are projected to continue to decline (S1). With extra effort of the coal substitution, the processes are projected to be accelerated. The relative contributions of the rural residential sector to the total emissions of SO_2 (sulfur dioxide), NO_x (nitrogen oxides), and NH_3 (ammonia) were estimated to be 6 (4 to 8)%, 3 (2 to 4)%, and 8 (6 to 10)% only in 2012, respectively. Therefore, there is not much room for further reduction even with the extra effort. On the other hand, the differences will be substantial for primary $PM_{2.5}$ and other incomplete combustion products. For example, the total residential emissions of primary $PM_{2.5}$ in the study region in 2021 were estimated to be 230 (180 to 290) kt, 170 (130 to 210) kt, 72 (55 to 88) kt, and 5 (4 to 6) kt for the four scenarios, respectively, indicating high effectiveness of the campaign.

The Campaign Is Projected to Improve Air Quality and Reduce Exposure Substantially. Annual mean $PM_{2.5}$ concentrations in ambient air excluding the meteorology confounding effect were calculated for the four scenarios using a recently developed regression–probabilistic method (20). Details can be found in *Methods*, but it basically involves prediction of meteorology-free annual mean $PM_{2.5}$ based on emissions using a set of regression models and characterization of meteorology-associated potential variation of annual mean $PM_{2.5}$ using a set of probabilistic functions. The regression models and probabilistic functions were derived from three atmospheric chemical transport models

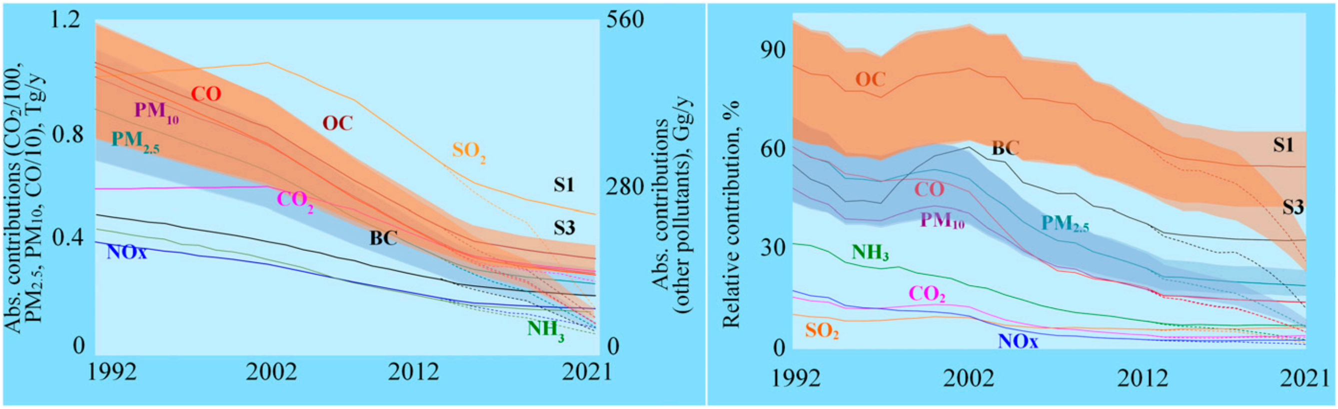

Fig. 5. Absolute (*Left*) and relative (*Right*) contributions of the rural residential sector to the total emissions of major air pollutants from all anthropogenic sources in the study area from 1992 to 2021 for two scenarios of S1 (solid lines) and S3 (dash lines). 90% CIs are shown as shaded areas for $PM_{2.5}$ and OC.

of real emissions– real meteorological conditions, fixed emissions– real meteorological conditions, and real emissions– average meteorological conditions (20). The advantages and disadvantages are also briefly discussed in *Methods*.

For each scenario, the annual mean concentrations without population weighting at individual grid cells were derived for 2 cases: with and without residential emissions. The differences between the 2 were taken as the contribution from residential emissions. Although the substitutions started in 2014 in Beijing, significant changes in the entire region did not occur until 2017 when the campaign began to extend to all municipalities (Fig. 6). With no intervention (S1), the area-weighted annual average $PM_{2.5}$ concentrations attributable to the residential sector is projected to decrease at a slower pace from 15 $\mu g/m^3$ to 12 $\mu g/m^3$. With 60% substitution achieved (S3), the contribution is projected to decrease to less than 5 $\mu g/m^3$, suggesting that the campaign will be highly effective.

Although the aim of the campaign was to improve ambient air quality, the results will directly benefit indoor air quality as well. The influence on rural indoor air quality is also quantitatively addressed using a statistical model based on the relationship between energy types and indoor $PM_{2.5}$ concentrations from the literature (21). See *SI Appendix* for details. The estimated $PM_{2.5}$ concentrations and time–activity patterns in the kitchen, living/bed rooms, and outdoors in the study area are listed in *SI Appendix*, Table S1. The medians and the 90% CIs of indoor air $PM_{2.5}$ concentrations in winter in living/bed rooms of all households in the study area are projected to be 209 (190 to 230) and 125 (99 to 150) $\mu g/m^3$ for the scenarios of S1 and S3, equivalent to 2% (S1) and 42% (S3) reductions from 2014 to 2021, respectively. The change is also obvious in kitchens (45%, S3), where solid fuels are directly burned. When solid fuels are used for cooking and heating, emissions from these activities dominate the indoor $PM_{2.5}$ sources. However, in the case of S4, $PM_{2.5}$ in indoor air is largely contributed by penetration of pollutants from the ambient environment (30).

Overall population exposure to $PM_{2.5}$ and the contributions from both indoor and outdoor exposures were also derived. Fig. 7 shows exposure levels in the form of population-weighted $PM_{2.5}$ concentrations as median values and 90% percentiles as uncertainty ranges. Contributions of residential and nonresidential emissions to $PM_{2.5}$ in indoor and outdoor environments are further distinguished. This is analogous to the method used in Aunan et al. (31) and Zhao et al. (9). With men, women, and children considered, the weighted concentration in the study region was 135 $\mu g/m^3$ in 2014 and would decrease to 109 $\mu g/m^3$ in the case of S1 and 78 $\mu g/m^3$ in the case of S3 by 2021, equivalent to 19% and 42% reductions in the two cases, respectively. In the case of S3, the remaining exposure would be dominated by nonresidential sources (72%), suggesting that the campaign can significantly reduce (S3) or even eliminate (S4) the exposure originally from the residential source.

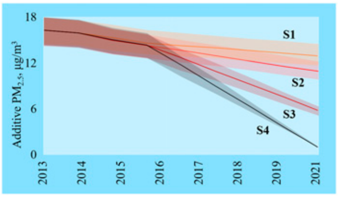

Fig. 6. Comparison of the additional annual mean ambient air $PM_{2.5}$ concentrations attributable to rural residential emissions in the 2+26 region (averaged by area) for the period from 2014 to 2021 in the four scenarios. 90% CIs are shown as shaded area.

Compared with 2014 baseline, there would be a significant reduction in exposure levels because of the campaign, and the majority of reduction would be due to indoor exposure originally from residential emissions of solid-fuel use. Although exposure due to outdoor exposure originally from residential emission would reduce significantly as well, the total contribution of this source was already very low at the beginning. The absolute contributions from indoor exposure associated with nonresidential emissions would actually increase slightly because the indoor $PM_{2.5}$ exposure in households using clean energy are predominantly from outdoor air penetration. It is interesting to note that while the substitution campaign was launched to solve ambient air pollution problems in the region (11), rural residents benefit much more from the reduced indoor air pollution simply because people spend most of their time indoors where the emissions from solid fuel-using appliances are important.

In northern China, women often do most of the cooking at home and male and female adults spend 0.8 and 2.7 h in the kitchen on average, respectively (32). Because $PM_{2.5}$ concentrations in the kitchen are typically higher than those in other rooms and outdoors, the exposures of women are higher than that for men. In 2014, the total exposure levels of women and men in the study region were 140 $\mu g/m^3$ and 130 $\mu g/m^3$, respectively, and the difference was mainly caused by relatively high exposure of women to indoor residential emissions. High lung cancer rates of nonsmoking women associated with cooking in rural China have been reported previously (33). The relatively high exposure identified in this study confirmed this adverse impact. In the case of S3, although the indoor residential contributions to women's exposure (22 $\mu g/m^3$) would still be higher than that of men (21 $\mu g/m^3$), the difference would be much smaller than that in 2014, suggesting that women benefit more from the campaign. Children's exposure (136 $\mu g/m^3$) was slightly higher than that of adults (135 $\mu g/m^3$) in 2014, because children spend more time indoors. For the same reason, they also benefit more from the campaign.

Geospatial distributions of average population exposure to $PM_{2.5}$ from all sources are mapped in *SI Appendix*, Fig. S2 for the four scenarios along with 2014 baseline. Frequency distributions are also shown for all cases. Since solid fuels would be eliminated for S4, the S4 map represents the contribution from nonresidential sources. Substantial reduction due to the campaign is shown for the entire region, demonstrated also by significant shifting of the frequency distributions. In addition, the frequency distributions become more narrow, indicating the reduced variation among municipalities. Spatially speaking, the largest relative change would occur in the northeast area where the total exposure was among the highest in 2014 and would become the lowest in 2021 with 100% substitution.

Discussion

If the target penetration rate of clean energy for rural household heating in the study region can be realized, the $PM_{2.5}$ exposure of the rural population in this region can be substantially reduced. The reduction is primarily due to reduced $PM_{2.5}$ concentrations in indoor air of rural households, although the primary, if not sole, purpose of the campaign was to improve ambient air quality.

As discussed previously, population health can benefit more from improved indoor air quality as a "side effect" than from reduced ambient air pollution. It is good news for this long-overlooked issue and rural population, who are often forgotten in air pollution policy. This benefit, which was not identified in policy documents, provides additional justification to the substitution campaign. In addition to heating fuel transition, further action can be taken for clean cooking. Although a fast transition of cooking energy toward CFE is on the way spontaneously and it was estimated that only 14% of rural households in entire China will use solid fuels for cooking by 2021 without intervention, the

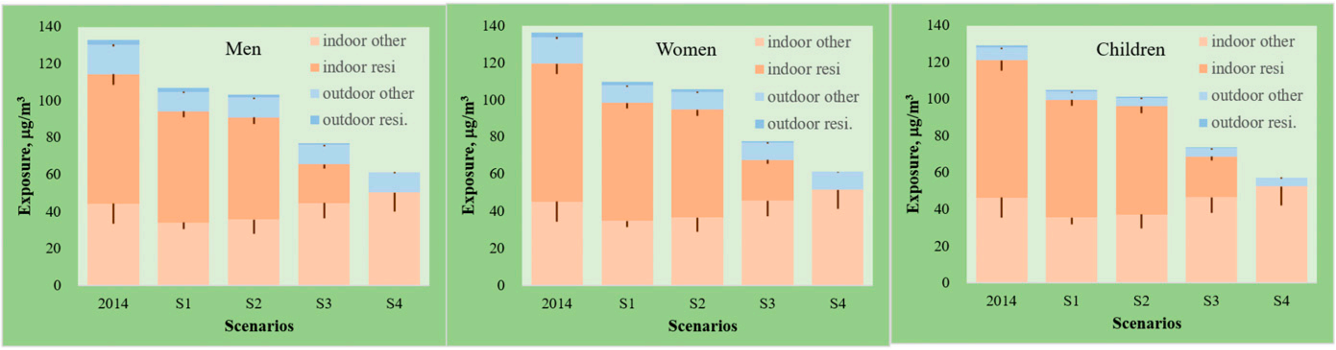

Fig. 7. Population exposure level as population weighted $PM_{2.5}$ concentrations for various scenarios in the study region. The results are presented for men (*Left*), women (*Middle*), and children (*Right*) separately. For each scenario, the total exposure concentrations are sums of those from indoor and outdoor exposure and from residential and nonresidential emission sources.

small percentage can still be translated to 106 million people. Cooking using solid fuels can also lead to severe indoor air pollution and heavy exposure (1, 3). Instead of waiting for the spontaneous transition, interventions such as promotion of electric induction stoves with limited subsidy can help to accelerate the process. If a campaign can be carried out to eliminate solid fuel for cooking, this major source of indoor air pollution exposure can be relegated to history throughout China.

Solid fuels contribute significantly to pollutant emissions, ambient and indoor air pollution, and population exposure, which can be partially solved in the study region by the campaign. However, financial burden including both infrastructure and equipment investment and long-term subsidy is a major constraint to the sustainability in this region and potential replicability for other regions in China. Although the study region is among the most developed regions in China, financial capacity of some municipalities for carrying out the campaign is questionable. For many other undeveloped regions, the high cost will surely prevent such an ambitious campaign to be carried out (34). Alternative solutions with relatively low effectiveness of reducing emissions and much lower cost should be examined (35). In fact, a number of less-polluted heating options including so-called cleaner coal stoves, pellet biomass stoves, and better house insulation are under testing (2). These technologies can perhaps provide transitional options before the ultimate solution of using CFE becomes affordable, although a clean fuel transition is most desirable as well as being appropriate for the growing Chinese middle class.

In addition to financial burden, sudden surge in CFE demand is also a challenge. There were a number of cases reported in the last winter that a PNG shortage occurred after traditional heating stoves were demolished (36, 37). The estimated annual per-household electricity consumption for heating in the study region varies from 5,400 to 12,000 kWh (*SI Appendix*, Table S2), depending on winter temperature and house size. Similarly, per-household consumption of PNG for heating ranges from 900 to 1,600 m^3 per year in this region (*SI Appendix*, Table S2). With a total rural population of 75.5 million and heating season lasting for 2 to 4 mo, annual demands for heating electricity and PNG were estimated to be 6.8×10^9 kWh and 46.1×10^9 m^3, respectively (S3), assuming that electricity and PNG contribute equally to the substitution. The quantities would be three to four times the total consumption of residential electricity (394%) and gases (PNG, LPG, and biogas, 346%) in the region in 2017. The supply depends also on infrastructure. For example, ~8,000 kWh is required to an average-size rural house with a normal electric heater, while regular feed system provides ~2,000 kWh per rural households (38). Heat pumps, while more expensive to install, provide a far more efficient system for use during the relatively mild winters in this region. They are also being installed through many programs promoted by local authorities in the study region. It remains to be seen what final sustainable pattern of fuel use, including electricity, will evolve in the region, but it seems clear that a major transition is underway, one driven largely by air pollution concerns.

Methods

Residential Energy Consumption. Historical data collected in a survey on rural residential energy covering the study region with municipality resolution were adopted for scenario S1 (12). Future energy consumption was projected using two regression models for estimating CFE fractions developed previously (12). Scenario S2 was based on the APCP13, in which a limited nonspecific target was set up for reducing residential emissions (19). For scenarios S3 and S4, 60% or 100% solid fuels used in rural households were substituted with either electricity or PNG. The 60% was targeted for rural areas of the study region set up by the Clean Heating Plan for Northern China in Winter for 2017– 2021. The total residential energy consumption in the study region with targeted substitution (S3) is listed in *SI Appendix*, Table S3. Although the planned ratios between electricity and PNG vary among municipalities, 1:1, which is close to the average value (15), was used and the effect of the ratio on the results is very limited due to very low EFs of both. The substitution rates from 2017 to 2021 were assumed to be constant despite the fact that some municipalities have more aggressive plans (39).

Emissions. Emissions of major air pollutants including CO_2, CO, primary $PM_{2.5}$, BC, OC, SO_2, NOx, and NH_3 were derived based on fuel consumption and corresponding EFs (5, 7, 20, 28, 40–48). The mean EFs for residential fuel combustion are listed in *SI Appendix*, Table S4. For the substitution of solid fuels with electricity, emissions are not only changed in quantities but also in location (from households to power stations). Additional emissions from power stations due to the small increase in electricity demand were omitted in this study because emissions from power generation associated with residential cooking and heating use are orders of magnitude lower than those from nonresidential sources and power plants are often more distant from dense urban populations.

Quantification of $PM_{2.5}$ Concentrations in Outdoor and Indoor Environments. Recently, a novel reduced-form model was developed to quantitatively distinguish influences of emissions and meteorology on $PM_{2.5}$ in air (20). The model is composed of a set of regression models and a set of probabilistic functions, both of which are spatially resolved. The models were derived from the results of three-scenario atmospheric chemical transport modeling (realistic situation, fixed emission, and fixed meteorological conditions) for 35 y from 1980 to 2014. By using the regression models, annual mean $PM_{2.5}$ concentrations at individual grid cells can be predicted based on local emissions of 4 major air pollutants (primary $PM_{2.5}$, SO_2, NOx, and NH_3) for a given scenario assuming average meteorological conditions to exclude meteorological confounding effects. The probabilistic functions can be used to characterize meteorology-associated, potentially random variation of annual mean $PM_{2.5}$ concentrations at individual grid cells as uncertainty intervals of various probabilities (e.g., 50% and 90%) (20). By using the method, not only can the computation load be reduced substantially, but also the meteorological confounding effect can be excluded and quantified, separately. The major advantage of the approach is that the contributions of emissions and meteorological influences can be quantified individually, with reduced computation load. In addition, the method can be used for future prediction. The models were evaluated in a number of ways. In brief, the basic simulation (1980 to 2014) was evaluated against field observations from a large number of stations and some stations with temporal data available. The regression models were evaluated against the output from the fixed-meteorology modeling, and model-predicted short-term annual mean concentrations (1988 to 2017) were evaluated against available observations. Detailed results of the evaluation are presented in Zhong et al. (20). A limitation of the method is that it is only able to model annual mean concentrations. The major sources of uncertainty of the model come from uncertainty from emission inventory and fractions of major pollutants. A simple statistical method following Chen et al. (21) was applied to quantify average $PM_{2.5}$ concentrations in living/bed room and kitchen of rural households given energy for cooking and heating (coal, crop residue, fuel wood, and clean energy including LPG and electricity) based on data in Chen et al. (21).

Exposure Assessment. Exposure levels were presented as population-weighted $PM_{2.5}$ concentrations and assessed for the four study scenarios. The populations were divided into two genders (male and female) and four age groups (<5, 5 to 15, 16 to 65, and >65 y). Population-weighted $PM_{2.5}$ concentrations (PWE) were calculated to assess population exposure based on $PM_{2.5}$ concentrations in indoor and outdoor environments and the behavior time model. For a given scenario, the overall population-weighted exposure (PWE_s) is

$$PWE_s = \sum \left(E_{s,g,a} / P_{g,a}\right), \quad \mathrm{s} = 1..4, \mathrm{g} = 1..2, \mathrm{a} = 1..4,$$

where $E_{s,g,a}$ is overall exposure concentration at scenario s, for gender g, and age a. $P_{g,a}$ is population of gender g and age a. Similarly, population-weighted exposure can be calculated for individual age or gender groups. For the exposure concentrations to $PM_{2.5}$,

$$E_{s,g,a} = \sum \left(C_{s,e} T'_{a,g,e}\right), \mathrm{s} = 1..4, \mathrm{g} = 1..2, \mathrm{a} = 1..4, \mathrm{e} = 1..2,$$

where $C_{s,e}$ represents $PM_{2.5}$ concentrations for scenarios s and environment e (living/bed room, kitchen, and outdoors) and $T_{a,g,e}$ are time fractions of given age a and gender g spent in environment e (32). To obtain indoor air $PM_{2.5}$ concentrations for households using different energy types, the energy mix for cooking was used in the nonheating season and the energy mix for heating was used in the heating season (49); indoor mean $PM_{2.5}$ concentrations for different kinds of fuels are listed in *SI Appendix*, Table S5. All calculations were spatially resolved at a resolution of 0.125°. Population density data were from Oak Ridge National Laboratory (50).

Uncertainty Analysis. Uncertainty analysis was conducted throughout the study from energy consumption to population exposure. For energy consumption, 90% CIs of the regression models were applied to predictions of CFE percentage (12). Monte Carlo simulation was conducted by assuming 10% coefficient of variation (CV) for daily fuel consumptions, population, and the compliance rate of the substitution campaign. For emissions, in addition to the variations derived for energy consumption, a CV of 10% was applied for all EFs (6). Similarly, 90% CIs were derived from the regression models for ambient air $PM_{2.5}$ calculation. Uncertainty for indoor air $PM_{2.5}$ concentrations was quantified following a procedure from Chen et al. (21). For exposure calculations, variations in indoor and outdoor concentration calculations as well as 5% CV for time spent indoors and population density were assumed for the Monte Carlo simulation.

Limitations. There are a few limitations of this work. First, the substitution plans announced by central or municipality governments only have overall percentages of households to be substituted. Detailed action plans are often not available, leading to uncertainty in spatial distribution. Second, fuel consumption projected after 2012 was based on the results of a survey conducted in 2012 and the projection is associated with relatively high uncertainty. Third, ambient air $PM_{2.5}$ concentrations were derived from a recently developed regression method, which was a statistical approach instead of an accurate calculation using a conventional atmospheric chemical transport model. It is also expected that the relationship between indoor air pollution and fuel types is simplified, leading to a relatively high uncertainty in the statistical model for calculating indoor air concentrations of $PM_{2.5}$. Finally, exposure avoidance behaviors such as using air purifiers were not taken into consideration.

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