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Direct Energy Consumption Associated Emissions by Rural-to-Urban Migrants in Beijing

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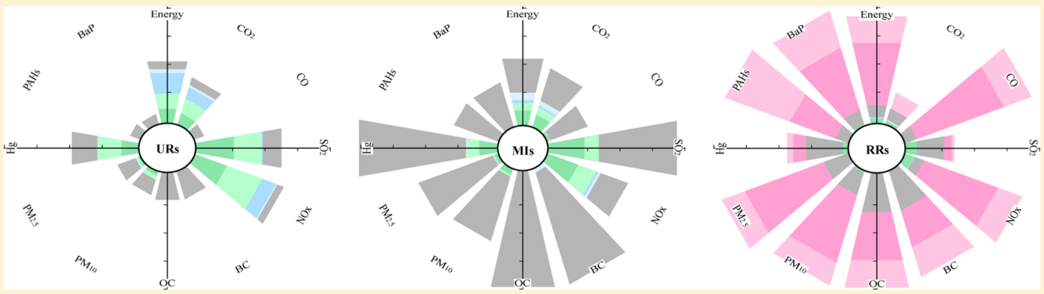
Supporting Information



ABSTRACT: Hundreds of millions of rural residents have migrated to cities in China in recent years. Different lifestyles and living conditions lead to substantial changes in their household energy. Here, we present the result of a survey on direct household energy use of low-skilled rural-to-urban migrants in Beijing. The migrants moved up the energy ladder immediately after arriving in the city by replacing biomass fuels with coal, electricity, and liquefied petroleum gas. After the original shift, pattern of household energy use by the migrants has not changed much over decades, likely due to the long-existing household registration system (Hukou). As a result, the mix of energy types used by the rural-to-urban migrants were different from those by long-term urban residents, although total quantities were similar. Shifting from biomass fuels to coal, the migrants emitted 2.4 times more non-neutral CO_2 than rural residents and 14% more than urban residents. The migration also resulted in significant increase in emissions of SO_2 and mercury but dramatic decreases in some incomplete combustion products including particulate matter. All these changes have significant implication on air quality, health, and climate considering the scale of urbanization in China.

INTRODUCTION

Rapid economic growth and urbanization have brought more than 260 million rural Chinese residents to cities during the past three decades. This represents one of the largest peacetime migrations in world history and the trend is likely to continue.[1] Among the total population of 20 million currently in Beijing, approximately one-third are new migrants.[2]

In China, residential energy consumption is an important source of greenhouse gases and many air pollutants in the form of combustion products (CO_2), fuel contaminants (such as SO_2 and metals), incomplete combustion products (such as CO, black carbon (BC), organic carbon (OC), and polycyclic aromatic hydrocarbons (PAHs) including benzo[a]pyrene (BaP)), and high-temperature reaction products (such as nitrogen oxides (NO_x)), or more complicated process products (such as particulate matter (PM)).[3−5]

It has been estimated that 50 and 62% of total emissions of BC and PAHs in China are from the residential sector,[6,7] despite the fact that only 8.8% of total energy is consumed in this sector.[8] The high contribution of residential fuels to total emissions of many air pollutants is primarily due to (1) poor combustion conditions in small appliances and the lack of abatement measures, leading to higher emission factors (EFs, defined as the mass of pollutants emitted from combustion of unit mass of fuel) and (2) poor building insulation and inefficient appliances causing lower energy service per unit fuel. Emissions within the residential sector vary significantly between urban and rural population, due to their different fuel profiles.[9] Urbanization could affect the amount and composition of residential emissions by causing changes in lifestyles and energy mix of the migrants. To date, however, the energy and pollution literature has not focused on how such large rapid changes in household status affect overall transition in energy usage or consequent emissions of health-damaging and climate-altering pollutants. Among a few studies, potential

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effects of urbanization and migration on residential energy use and CO_2 emissions in Hanoi, Vietnam, have been estimated, and it was found that rural-to-urban migration has a significantly negative influence on residential energy consumption and CO_2 emissions.[10] In one effort to evaluate the influences of urbanization and migration of rural residents (RRs) on population exposure to $PM_{2.5}$ and associated health effect in China, it was assumed that the household fuel use patterns of the migrants are the same as long-term urban residents (URs).[9] This assumption may lead to misestimation, however, because about 70% of the migrants have been low-skilled migrants (MIs).[11] They are usually prevented from having normal resident status by the official household registration (Hukou) system, resulting in discrimination in job opportunities, wages, housing, and access to public services.[12,13] The majority of them live in privately built shanties in marginalized urban villages in the city outskirts. Therefore, the energy use pattern of the migrants is likely to be different from longer-term urban residents.

The concept of a household "energy ladder" is commonly used to describe the transition from cheap and dirty household fuels to expensive and clean ones.[14] It is suggested that residents move up the energy ladder from the first stage (biomass fuels) to the second (fossil fuels such as kerosene, coal, and charcoal) and the third (clean energy, such as liquefied petroleum gas (LPG), natural gas, and electricity) during urbanization.[15]

The rural-to-Beijing migrants targeted in this study are low-skilled workers in Beijing from rural areas nationwide, since the beginning of the economic reform in the early 1980s. They are not able to be officially registered as permanent residents in Beijing under the current Chinese Hukou system. By surveying rural-to-Beijing migrants with low-skilled jobs, we explore the energy ladder concept in a semilongitudinal fashion, that is, whether it adequately describes the experience of the same group of people moving from one location to another. Here, we present the results for Beijing and speculate on what it implies for household energy and pollution of the massive ongoing rural to urban migration in China. Although conducted in Beijing, the situation of the migrants in most Chinese cities is similar in terms of social status and living conditions.[16] It should be noted that besides rural-to-urban migrants, there are even a slightly higher number of newly migrated urban-to-urban population in Beijing (3.68 million). However, this population seldom undertake low-skilled jobs and are thus not included in this study.

■ METHODOLOGY

Design of the Questionnaire. The study questionnaire covers information on personal, family, residence, and average energy use during a month or year. Personal and family information are year of arrival, family size, family members, and income; residence information includes current address, original address, housing type, and housing expenditure; and energy use covers types of and expenditures on energy used for cooking and heating, possession of electricity appliances, and total expenditure on electricity. A sample of the questionnaire is provided in Figure S1. Data on expenditures of individual energy types were converted to quantities of energy (gigajoules, GJ) consumed based on energy price and energy density (Tables S1a and S1b).

Survey. A total of 1300 questionnaires were distributed through a two-stage (community and intercept) survey (Figure S2). During the community stage, we distributed 862 questionnaires by contacting five migrant schools located at urban village complexes within the city periphery (JinZhan, Maliandao, Yamenkou, Xibeiwang, and Lugouqiao). Among the 810 questionnaires retrieved (return rate was 94%), only 440 were valid for data analysis (see details in the Supporting Information). Survey through the children in the migrant schools can cause bias on the sampled population—families without school-age children, who left their children in their hometowns, or who did not send their children to migrant schools were underrepresented. To mitigate the bias, we led an intercept survey in the second stage to complement the community survey. A team of 10 trained volunteers conducted intercept surveys during the Spring Festival in 2012, the peak time for the MIs to visit their original homes. They conducted face-to-face interviews and collected 438 questionnaires. We compared the distribution of current address in Beijing and the distribution of home places of the surveyed migrants and the total migrant population in Beijing to validate the representative of the survey. The addresses covered all major urban districts in Beijing (Figure S3). The population surveyed included people who migrated from almost all provinces in China and showed a similar pattern to that reported in a much larger survey of migrants across China[11] and that reported in the sixth National Census conducted in 2010 (Figure S4).[8]

Other Information. Information on urbanization and migrant population were extracted from the China's sixth National Census, while energy consumption of the URs and RRs was from China Energy Statistical Yearbook.[8] Energy consumption data for the URs, RRs, and MIs were converted from original units to joules (Tables S1a and S1b) based on fuels used directly in households and the primary fuel consumption used to produce the electricity and heat. Neither delivered energy nor the embodied energy in goods and services used by residents were determined. The estimated per capita energy consumption of RRs in this study was calculated as the weighted average of per capita rural energy consumption of all home provinces. The weights are the fractions of the MIs from various provinces. For household fuels, low calorific values were used to recognize the character of most residential combustion appliances. EFs for individual fuels were either from the database developed in our previous studies or from the literature and all EFs were converted into mass of pollutants per joule energy consumed in households (Table S2).

Emission Estimation. Annual per person emissions of CO_2, SO_2, CO, OC, BC, Hg, NO_x, PAHs (total of 16 U.S. EPA priority PAHs including naphthalene, acenaphthene, acenaphthylene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenz[a,h]anthracene, indeno(1,2,3-cd)pyrene, benzo(g,h,i)perylene), BaP (benzo[a]-pyrene), PM_{10} (PM with aerodynamic size less than 10 μm), and $PM_{2.5}$ (PM with aerodynamic size less than 2.5 μm) from fuel consumption were calculated for the migrants, long-term urban residents, and rural residents (RRs), individually for comparison. The emission of a specific pollutant from a given fuel was quantified as the product of the quantity of the fuel consumed and the EFs. Electricity consumption was divided into plants burning coal (76.2%), petroleum (0.5%), gas (1.5%) and all nonfossil fuel plants (2.6%, including biomass and solid waste power plants), hydropower (15.5%), and others (3.3%, nuclear, wind, solar, etc.).[8] Only emissions from fossil fuel plants are included, while nuclear power plants and renewables

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are treated as emission free. To estimate CO_2 emissions from woodfuels, we calculated the quantities of nonrenewable woodfuels for individual provinces as the products of the woodfuel consumptions of the provinces and the fractions of nonrenewable woodfuels of these provinces (Table S3).[17,18] For example, the fraction of nonrenewable woodfuel was 44.7% in Beijing.[18] We also assumed that no net CO_2 was accounted to crop residues, as is customary.

Uncertainty Analysis. Uncertainty of the emissions were characterized using Monte Carlo simulation by calculating 10 000 times based on randomly selected fuel consumptions and EFs from available distributions (Table S4). The energy consumptions and EFs for CO_2 were assumed to be normally distributed,[19] while EFs for all other air pollutants were log-normally distributed. The standard deviations of EFs were directly calculated based on the data collected from the literature (Table S2). Coefficients of variation for energy consumptions were assumed to be 5% for electricity and thermal, 10% for PNG, LPG, and coal, and 20% for biomass fuels. The results are presented using semiquartile range (75th minus 25th percentile range).

Data Analysis. Statistical tests including comparison and correlation analysis were conducted using SPSS and 0.05 was used as the significance level.

RESULTS AND DISCUSSION

Migrants' Energy Use Differs from those of both Rural and Long-term Urban Residents. Annual mean per person household energy consumptions (E_{cap}) by the RRs, MIs, and URs are shown in Figure 1 as contributions of electricity, thermal, and various fuels, including piped natural gas (PNG), LPG, coal, crop residues, woodfuels, and biogas to household energy. Detailed data are listed in Table S5. Here, we discuss the transition from RRs to MIs and the transition from MIs to URs separately.

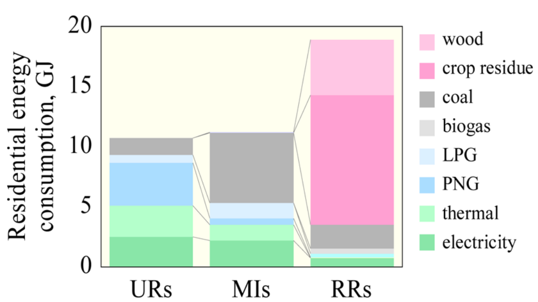

Figure 1. Fractions of various household energy used by the URs, MIs, and RRs. All energy types were converted to Joules for comparison.

Based on data from their home provinces, the mean RR usage in this study was dominated by biomass fuels including crop residues (57.0%), wood (24.4%), and biogas (2.2%). The extensive use of low efficiency biomass fuels is the primary reason causing the high E_{cap} by the RRs.[4] In addition to biomass fuels, fossil fuels including coal and LPG account for less than 13% of the household energy use by RRs, while electricity contributed a rather small fraction (4.0%) of the total. This is a typical first phase of the energy ladder characterized by heavy dependence on biomass fuels.[15]

The MIs in Beijing used 40.7% less energy per capita than the mean RRs use in the provinces from which they migrated, from 18.9 GJ (RRs) to 11.2 GJ (MIs). In addition to the change in total energy consumption, the pattern of fuel types has changed dramatically. For the MIs, coal contributed more than half (52.1%) of E_{cap} due to its easy access and low cost, as well as housing conditions. The other household energy sources for the MIs were electricity (19.6%), centralized heating (11.9%), LPG (11.3%), PNG (4.7%), and wood (0.33%). The most profound change is that biomass fuels almost totally disappeared for the MIs. Meantime, relative contributions of most other fuels to household energy for the MIs were higher than those for RRs. For instance, possessing more home appliances than the RRs, the MIs consumed much more electricity per person (2.20 GJ) than the RRs (0.76 GJ).

These findings are consistent with the few other studies in the literature. A survey comparing residential energy uses between rural and urban areas in Shaanxi, China, also suggests that more fuels were used by rural residents for cooking than by urban residents.[20] Komatsu et al. investigated the influences of migration on residential energy use in Hanoi, Vietnam, and also found that rural-to-urban, but not urban-to-urban, migration has significant negative effect on per capita energy consumption.[10]

Such differences in fuel types indicate the transitional status of the MIs from rural to urban life. Among the major factors driving the residents to move up the energy ladder, affordability and availability are the most important ones.[20−22] For example, dependence of commercial energy consumption on household income in several villages and towns was reported.[20] Although annual median income of the MIs (34 000 RMB) was much higher than that of RRs (5920 RMB),[11] relatively high cost of city life and pressure of saving for their rural relatives confined their spending.[23] One direct result was that the MIs tend to use cheap fuels for cooking and heating, resulting in a large share of coal usage comparing with the URs. As extreme cases, 13.5% of the MIs surveyed choose not to heat their homes in winter at all. On the other hand, crop residues totally disappeared in the MIs' fuel list because there was no convenient access. Total elimination of crop residues, which are used with low efficiency, is the major reason why the E_{cap} of the MIs was significantly lower than that of the RRs. Old and poor housing conditions also limit the access to central heating system and natural gas pipeline network to a large extent. Another important indication of the energy transition experienced by the MIs was the increase in electricity consumption.

Although E_{cap} by the MIs (11.20 MJ) and URs (10.72 MJ) are very close to each other, the patterns differ remarkably. The only exception is electricity and per person electricity consumptions by the MIs (2.20 MJ) and URs (2.49 MJ) are similar to each other. For the URs in Beijing, most energy used were from clean sources including electricity, centralized heating, PNG, and LPG, featuring in a third phase of the energy ladder except a small fraction of coal (13.0%). Although the energy pattern of the MIs was in between that of the RRs and URs in many aspects, it is not a typical second phase of the energy ladder dominated by fossil fuels.[15] Instead, the MIs use more clean fuels such as electricity and LPG than the RRs, while rely heavily on coal and even use some wood at the same time. The pattern presents multiple strategies, rather than linear fuel switching process.[14]

Household Energy Use of Migrants Does Not Change Much over Years. Historically, coal was the major cooking and heating fuel for the majority of the URs in Beijing and was gradually replaced by LPG since the 1970s and PNG since 1987.[24,25] Meantime, central heating system (CHS) has been

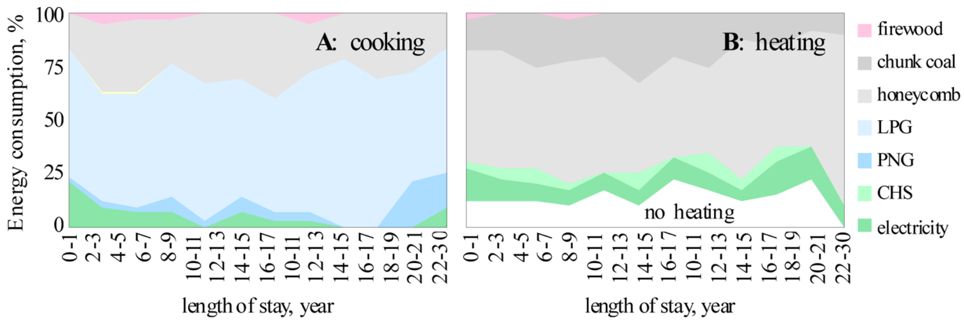

Figure 2. Time trends of relative contributions of various energy types to energy consumptions for cooking and heating by the MIs after their arrival.

widely promoted by the municipal government.[26] Energy policies in Beijing are generally incentive-based rather than regulation-based, and the incentives are often available only to those with Hukou or to the property owners. In 2007, the Beijing government started to subsidize electric stoves for heating in winter in order to eliminate coal stoves with high emissions.[27] However, only the URs in old downtown were eligible to be covered by this program. Today, a large majority of the URs in Beijing have abandoned coal stoves.[25] For MIs' communities, however, there is little evidence of a trend to replace coal with PNG or CHS. The temporal trend of energy consumptions by the MIs provides critical information on how they are being assimilated into city life. Figure 2 shows changes in relative contributions of various energy types for cooking and heating since the arrival of the MIs. The majority of them lived in shoddy bungalows and rundown buildings covered by neither newly constructed natural gas pipelines nor centralized heating networks. These conditions pose real challenges for the Chinese urbanization process.

A few changes can be identified, however, including a reduction of wood for both cooking and heating, and rises in the use of chunk coal for heating and electricity for cooking. There is also a trend of using more PNG for cooking. Wood, which is inexpensive but not readily available in urban area, was only used by people in their first decade in the city. Electricity for cooking had decreased, likely because newcomers could easily obtain electric cookware after arrival, and shifted to other less expensive energy sources given more time. Chunk coal was replaced with other energy slowly over years and a slight increase in PNG use for cooking can be seen. Electricity consumption by the MIs depended largely on the number of home appliances, which are positively correlated with both family size and years the MIs had stayed in Beijing (Figure 3). Although more appliances were owned by the family with more members, the number of appliances and family members were not proportional, suggesting sharing among household members as household size rose. In addition, large families could use energy more efficiently in lighting, cooking, and heating. As a result, a negatively linear relationship between log-transformed per person electricity consumption and family size was identified (Figure S5). Although the number of home appliances was also positively correlated with the length the MIs had stayed in Beijing, no relationship was found between the length of stay and electricity consumption, likely because electric stoves were gradually replaced with other fuels.

Although some changes were identified, the basic pattern of household energy consumption by the MIs has been relatively consistent, suggesting difficulty in blending into urban life in terms of cooking and heating energy use. For those who had

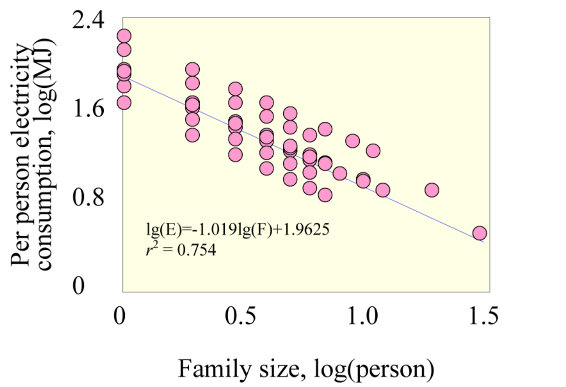

Figure 3. Dependence of per person electricity consumption on family size, both log-transformed.

been in Beijing for more than a decade, the household energy use pattern is still dominated by coal, which is very different from that of the URs.

Migrants Emit More Air Pollutants than the Long-term Urban Residents. Residential energy consumption is an important source of greenhouse gases and many air pollutants. The emissions of CO_2 and various air pollutants from fuel combustion depend not only on the quantities of fuel consumed, but also on EFs, which vary several orders of magnitude for a particular pollutant and a given fuel.[28,29] Because of poorer burning conditions, lack of abatement measures, and consequently higher EFs, residential fuels contribute to a relatively large fractions of many air pollutions, such as incomplete combustion products, to the national totals.[6,7] For example, the average EF of BC is 0.002 g/kg for coal burned in a power station,[6] more than 3 orders of magnitude lower than 4.6 g/kg for similar coal burned in residential stoves.[30] As a result, almost half of the BC emitted in China (49.8% in 2007) is from residential sector,[6] even though only 8.8% of total energy is consumed in this sector in the country.[11]

Figure 4 compares per person annual emissions (M_{cap}) of CO_2, CO, SO_2, NO_x, BC, OC, PM_{10}, $PM_{2.5}$, Hg, PAHs, and BaP from residential energy sources of the RRs, MIs, and URs (stacked bar charts with uncertainty ranges are shown in Figure S6). Energy consumption patterns are also included for a comparison.

The total M_{cap} of CO_2 for MIs was the highest (2.9×10^5 tC), with 49.7% from coal combustion, which is very different from those of URs and RRs. The RRs only produce about 41% of that of the MIs, because they largely depend on biomass for heating and cooking, taking advantage of their convenience and their being free of charge. And only a fraction of the biomass

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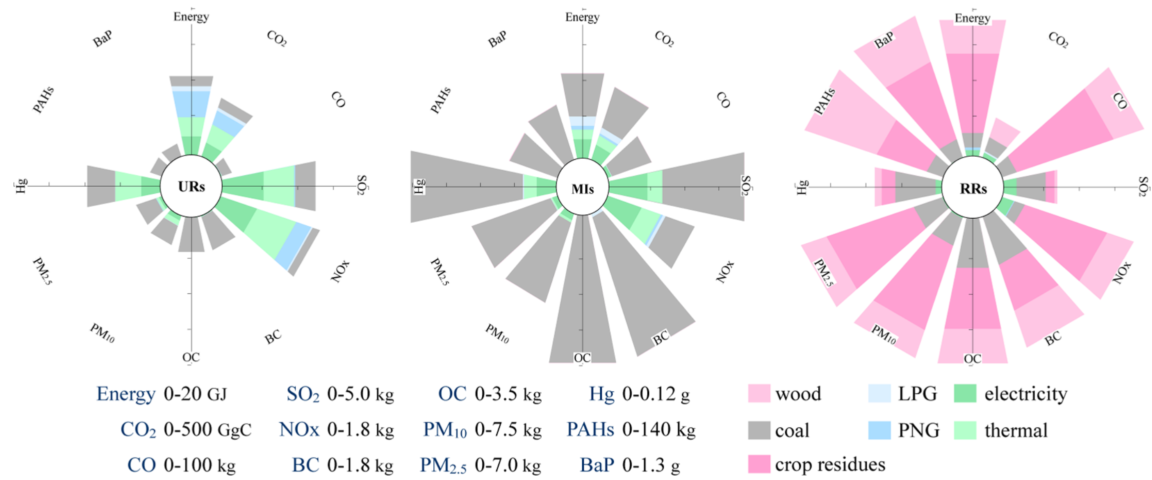

Figure 4. Per person annual household emissions of CO_2, CO, SO_2, NO_x, EC, OC, PM_{10}, $PM_{2.5}$, Hg, PAHs, and BaP from energy consumptions of the URs (urban residents), MIs (migrants), and RRs (rural residents) by fuel. The legend indicates the top end of the axis for each pollutant. The contribution by fuel type is shown as stacked bars. For comparison, energy consumptions are also shown. Different scales are used for different pollutants.

combustion, the nonrenewable woodfuels, emit CO_2. This means that the migration of the MIs to city led to a 1.4 times increase in non-neutral CO_2 emission. This result is different from the finding in the study in Vietnam, which showed that rural-to-urban migration had reduced CO_2 emissions by the migrants in Hanoi,[10] likely because there is no fuel use for space heating needs in Hanoi. The length of stay in Beijing had almost no influence on CO_2 emission produced by cooking and heating. The coal-intensive fuel patterns of the MIs, quite different from that of the URs, produce 10% more per person emissions than the URs. Still, relative contribution of residential energy use to the total CO_2 emission from all sources is small, because energy production and industry are major CO_2 emission sources and emissions from these sources are much higher than that from the residential sector.[31,32]

SO_2 mainly results from coal combustion, either in coal-fired power plants, centralized thermal stations, or household stoves. SO_2 emission from the MIs was higher than that of the URs, mainly due to much higher contribution of residential coal stoves with no abatement measures compared to industrial boilers. Meantime, low sulfur contents of biomass fuels lead to low SO_2 emission of the RRs.[33] As a result, the MIs almost tripled SO_2 emission after migrated to the city. With more household stoves being replaced with PNG and CHS in Chinese cities,[25] SO_2 emissions from residential coal combustion for the URs is expected to decrease further. However, such a decreasing trend will be much slower for the MIs who move slowly from the intermediate solid fossil phase to clean fuels phase.

The increase of per capita emission of Hg due to change from the RRs to MIs was 127%, lower than 163% for SO_2. The residential coal consumption contributed 55, 31, and 72% to the total Hg emissions of the RRs, URs, and MIs, even though their contributions to total energy consumption were only 11, 13, and 52%, respectively. The main reason is that the emissions from residential stoves are uncontrolled, while emission from coal-fired power stations and industrial sources are increasingly removed to varying degrees using emission-control technologies.[34] It appears that migration definitely leads to more Hg emission from residential sector. In the future, because of the gradual phasing out of family coal stoves in cities and accelerated replacement of residential coal with LPG and electricity for cooking and heating in rural China,[35] M_{cap} of Hg for both the URs and RRs is expected to decrease. A decrease in Hg emission for the MIs would be achieved only if they could also be benefitted from these policies.

Emissions of incomplete combustion products, BC, OC, $PM_{2.5}$, PM_{10}, PAHs, BaP, and CO are mainly from the burning of solid fuels including coal, crop residues, and wood in residential stoves with poor oxygen supply and no emission control. Indeed, most BC and OC emissions in China are from household stoves in rural areas. Coal stoves used by the MIs in cities produce slightly higher per capita emissions of BC and OC than rural household stoves. Although the energy use patterns were different between the MIs and RRs, total emissions of BC and OC did not differ significantly, even if the dominant emission sources shifted from biomass fuels almost totally to coal. BC and OC emissions of MIs, however, are more than 3 times higher than those of the URs. On the other hand, the migration led to substantial reduction in emissions of $PM_{2.5}$ (38%), PM_{10} (37%), PAHs (66%), BaP (63%), and CO (70%), simply because of the dramatic reduction in biomass fuel consumption. Still, M_{cap} of these pollutants for the MIs are 182−323% higher than those for the URs, due to relatively high emission from coal. Similar to SO_2, Hg, BC, and OC, such difference is not expected to change quickly due to slow assimilation.

NO_x is mainly from high-temperature reaction in heat engines of motor vehicles. For direct energy consumption, the emission of NO_x was relatively low and ranked as the RRs > URs > MIs. Emissions from crop residue burning were the dominate sorce because EF of NO_x for crop residues is higher than those for wood or coal in residential sector. For the URs and MIs, the main sources were electricity and thermal generation.

Our results seem consistent with the study in Hanoi, Vietnam, that found that rural-to-urban, but not urban-to-urban, migration had significantly negative effect on energy consumption and CO_2 emissions,[10] even though there is no fuel use for space heating.

Policy Implication. In addition to contributions from other economic sectors as incomes change, large-scale urbanization in

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China is a driving force leading to increase in non-neutral CO_2 emission when millions of rural residents move to cities, climbing up the energy ladder, and changing their lifestyle dramatically. This trend will continue over the next few decades as more rural Chinese immigrants will move to cities and those already in cities will continue to assimilate urban lifestyle and energy use pattern. It was predicted that urbanization rate in China will reach 70% by the year 2030.[1] Still, the urbanization and migration would have a relatively small and manageable impact on total CO_2 emission, because residential sector contributes to a relatively small fraction of total energy consumption.[31,32] Moreover, the negative impact of additional CO_2 emission can be compensated, at least partially, by the positive effect of reduction in BC emission.

On the other hand, emissions of many air pollutants associated with biomass fuel burning in residential sectors for those who migrated to cities were practically eliminated. Emissions from residential coal combustion actually increased because a large part of biomass fuels were replaced with coal, instead of clean fuels. Although a series of efforts have been made or is on the way to reduce residential coal usage in urban area in China,[35] the MIs benefit less from this progress because they have limited access to public services including more clean energy, such as PNG and CHS primarily due to low income and the current household registration system.[12,13,36] This situation would remain without a complete reform on the system. Taking the national scale of migration into consideration, demographic changes from urbanization play an important role in Chinese air pollutant emissions. This is particularly true in northern China, where heating is needed. It should be pointed out that metropolitan areas in southern China, such as the Pearl River Delta and the Yangtze River Delta where heating is limited, likely have different emission patterns for MIs. More data should be collected in other cities in China before a comprehensive picture on the situation can be drawn.

Over the past several years, air quality in Beijing has become worse.[37] The average annual concentration of $PM_{2.5}$ in Beijing was 99.8 $\mu g/m^3$ for 2013, with a maximum daily and hourly mean concentrations as high as 552 and 886 $\mu g/m^3$, respectively.[38] The results of several source apportionment studies suggested that coal combustion is one of the major emission sources of the air pollutants in the city.[13] Unfortunately, the emission of air pollutants from coal combustion in residential sector is generally overlooked in the recent discussion on the air pollution in Beijing and surrounding areas, which focused more on emissions from industry, power generation, and transportation.[13] In addition to contributing to deterioration of ambient air quality, use of coal and biomass fuel can directly cause severe household air pollution, exposure, and health impact.[39] Household air quality is a serious issue in rural China,[39] which seems to be only partly reduced by the initial stages of urban migration. Household exposure and health impact of the MIs should be taken care of as well.

Recently, the Beijing municipal government has formulated an ambitious action plan to combat air pollution, and it was proposed to eliminate all residential coal stoves in urban districts and all household chunk coal in suburban areas and to promote the use of electricity, heat pumps, and solar thermal collectors among many other measures.[27] More specific goals have been proposed in a recently issued new regulation to ban coal use in both urban and suburban areas of the city gradually in years to come, as a part of the effort to combat ambient air pollution in Beijing.[40] According to this regulation, the sale and use of coal, including coal briquette, and biomass fuels will be banned for Beijing Economic and Technological Development Zone by the end of 2014, for downtown areas by the end of 2015, for other districts by the end of 2017, and for suburban districts and 80% of ten satellite towns by the end of 2020.[40] Because most districts where the MIs currently live are covered by the new regulation, it is hoped that not only the URs but also the MIs can benefit from these actions. The forthcoming ban of coal and biomass fuels in residential sectors in Beijing would definitely reduce the emission of most air pollutants, and significantly improve air quality in terms of ambient air concentrations of PM_{10}, NO_2, and CO due to the switch from coal to gas in Beijing has been well demonstrated.[41]

Urbanization causes significant changes not only in the quantities of the emissions of air pollutants but also in geographical distribution of the emissions. One immediate result is that both population and emission are more concentrated spatially in relatively small urbanized areas, creating more heavily populated and contaminated hot spots, especially in the already overcrowded and polluted cities and metropolitan areas. Consequently, the spatial overlap of the strong emissions and high population density brings sources and receptors together to smaller spaces and amplifies the human health impact.[42] It was reported recently that ambient and household air pollution ranked fourth and fifth, respectively in leading health factors in China.[43] The migration intensifies the health issue in urban areas by moving both sources and receptors there, while somewhat alleviating the problem in rural areas as rural populations decline. On the other hand, emission sources concentrated in cities are easier to be regulated and mitigated, compared with those scattered in rural areas, if only enough attention and efforts are paid. For example, over the past decade, millions of residential stoves in cities of northern China have been replace with PNG and CHS, resulting in a huge reduction in emissions.[26,35] The strong emissions from solid fuel burning and extremely poor household air quality in rural areas have not yet been abated effectively due to both economic and management barriers.

Rapid urbanization in China is not limited to Beijing. During the past three decades, 260 million people have moved from rural areas to cities all over China. Although the major findings (changes in energy use and pollutant emissions) and general trend (slow assimilation) revealed in this study are representative in China in many aspects because general lifestyles of urban or rural populations are similar among various regions, the exact values calculated based on the data from Beijing cannot be simply extrapolated to other cities with differences in natural, social, economic, historical, and policy context. For example, heating is not required in many southern cities. More studies in other geographical regions are recommended before the influence of Chinese urbanization on energy, climate, environment, and health can be fully quantified. Globally, rural-to-urban migration represents one of the most important trends in history that will continue to influence energy and pollution patterns for decades before an equilibrium is reached.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

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Sample questionnaire, sampling locations of the survey, origins of the survey targets, data for and results of energy consumption and emission calculations, result of uncertainty analysis, and dependence of appliances and electricity consumption on family size and stay length, and uncertainty of emission of various pollutants. (PDF)

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Notes

The authors declare no competing financial interest.

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