Policy Analysis

Deployment of Coal Briquettes and Improved Stoves: Possibly an Option for both Environment and Climate

GUORUI ZHI,1,‡ CONGHU PENG,‖ YINGJUN CHEN,*,§ DONGYAN LIU,§ GUOYING SHENG,‡ AND JIAMO FU‡

Key Laboratory for Atmospheric Chemistry, Centre for Atmosphere Watch & Services of CMA, Chinese Academy of Meteorological Sciences, Beijing 100081, China, State Key Laboratory of Organic Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China, Yantai Institute of Coastal Zone Research for Sustainable Development, Chinese Academy of Sciences, Yantai, Shandong Province 264003, China, and Department of Chemical and Environmental Engineering, Anyang Institute of Technology, Anyang, Henan Province 455000, China

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The use of coal briquettes and improved stoves by Chinese households has been encouraged by the government as a means of reducing air pollution and health impacts. In this study we have shown that these two improvements also relate to climate change. Our experimental measurements indicate that, if all coal were burned as briquettes in improved stoves, particulate matter (PM), organic carbon (OC), and black carbon (BC) could be annually reduced by 63 ± 12%, 61 ± 10%, and 98 ± 1.7%, respectively. Also, the ratio of BC to OC (BC/OC) could be reduced by about 97%, from 0.49 to 0.016, which would make the primary emissions of household coal combustion more optically scattering. Therefore, it is suggested that the government consider the possibility of: (i) phasing out direct burning of bituminous raw-coal-chunks in households; (ii) phasing out simple stoves in households; and, (iii) financially supporting the research, production, and popularization of improved stoves and efficient coal briquettes. These actions may have considerable environmental benefits by reducing emissions and mitigating some of the impacts of household coal burning on the climate. International cooperation is required both technologically and financially to accelerate the emission reduction in the world.

Introduction

The deployment of improved stoves and coal briquettes (hereafter referred to as “two deployments”) in China has long been included in the governmental advocacies, mainly for pollution abatement and health improvements. It is reported that household coal-burning cookstoves in China turn more than 10% of fuel carbon into particles from incomplete combustion, many of which are air polluting and health harming (1). For example, carcinogenic PAHs, methylated PAHs, and nitrogen-containing heterocyclic aromatic compounds were found abundant in the particles released from bituminous coal combustion, as is typically found in numerous households of Xuanwei in China’s Yunnan Province, a county well-known for its unusually high incidence of lung cancer (2). In the early 1980s, the world’s largest publicly financed initiative—the National Improved Stove Program (NISP)—was launched, aimed at providing rural households with more efficient biomass cookers, later the coal stoves for both cooking and heating (3). As a result, significant health benefits have been observed, including a declined lung cancer rate in Xuanwei County (4). In addition, the Chinese government has supported clean coal technology (CCT) through the use of coal briquettes to reduce air pollution and improve energy efficiency (5). Although these two deployments have been suggested as conducive to black carbon (BC) reduction (6–8), measurements-based evidence of this reduction has rarely been reported through systematic and convincing experiments.

Our previous studies (9–11), which initially focused on the emission factors (EFs) of primary carbonaceous particles from household coal burning, raised the suggestion that emissions, especially for BC, are somewhat related to the method of coal burning and the stove efficiency, as well as the geological maturities of coals. However, differences in the coals used in these previous three experiments, as well as alterations in sampling processes and analytical procedures, raised doubts about the validity of the suggestion. Here, we present the results from experiments designed to assess the benefits of using coal briquettes and improved stoves on emissions. Coals, the sampling system, and analytical methods have been kept consistent in these experiments to study how the two deployments act on the changes in emissions.

Changes in primary emissions can significantly impact the concentration of atmospheric aerosols. Atmospheric aerosols have been regarded as one of the factors that could counteract global warming (12–14), which include some airborne pollutants from fossil fuel combustion and biomass burning. Thus, a conflict has been raised for policy makers faced with choices about air pollution control and climate stabilization (13, 15–17).

However, there are many uncertainties on how the aerosols impact on the climate, and the largest uncertainty is associated with carbonaceous aerosols (18). In general, carbonaceous aerosols are composed of two dominant fractions, BC and organic carbon (OC). BC is the strongest absorber of visible and near-IR light while OC is usually scattering agent of solar radiation (15). Thus, the direct effects of BC and OC on radiation combined with their indirect effects on cloud properties have made it difficult to determine whether the net impact of “soot” (BC + OC) emissions results in warming or in cooling (16). Meanwhile, the mixing states of BC with other components (15), and the existence of brown carbon (19) make the effects of carbonaceous aerosols on the climate complicated. Moreover, the quantification of BC and/or OC is operationally defined; many factors, such as mineral dust, filter matrix, and temperature protocols, can exert varied interferences in measurements (20). Consequently, these can make the emission inventories and the modeling results uncertain to a large extent (21). In addition,
the lack of long-term global and regional monitoring for these aerosol species has increased the difficulties in understanding the aerosol loadings, optical properties, and even aerosol solubility (12, 22).

In spite of the uncertainties described above, reducing the share of BC fraction in carbonaceous aerosol (or BC/OC ratio) is still recommendable. BC and OC are always released simultaneously during the combustion of carbon-containing fuels. Technologies favoring the decrease of BC/OC ratio can inevitably reduce the light-absorbing of carbonaceous aerosol. The two deployments with an initial purpose for environment and energy efficiency could coincide with such kinds of technologies. The findings of this work have been expected to give some recommendations for policy-making when environmental and climatic steps are considered in combination.

Methods

Two household coal stoves were selected for this study. The first one is a traditional stove, which is small, portable, and extensively used in rural households or by street vendors for cooking and/or heating (9, 10); the second one is an improved stove, with an upper lid and a galvanized flue pipe, which channels the smoke through the chimney (11).

Six bituminous coals were chosen in this study. Based on our previous research, bituminous coal contributes 99% of the total BC emissions from the burning of household coal, whereas anthracite coal appears to be negligible (11). Therefore we used only bituminous coals in our investigations, disregarding anthracites. In addition bituminous coals can generally be classified into 3 categories, i.e., low-volatile bituminous (LVB), medium-volatile bituminous (MVB), and high-volatile bituminous (HVB) coals (23), with MVB coal releasing much more BC than the others (10, 11). In our experiments, six bituminous coals containing two LVBs, two MVBs, and two HVBs were selected to be representative of Chinese bituminous coals. Table 1 gives the basic information for the six selected coals, of which C4 is a new inclusion, while the others have been used previously by Zhi et al. (11).

Each coal was burned in two styles: raw-coal-chunk (3–5 cm in diameter) and briquette (9–11), in the two stoves, so that the effects of stove improvement and coal briquettes could both be measured.

The sampling system, procedure, and carbon analysis method are detailed elsewhere (11) have been directly applied to this study. Total suspended particles were collected onto quartz filters using the previously documented sampling system (11). Although the differences between BC and elemental carbon (EC) have been repeatedly reported (24), in this study, EC is still regarded as equivalent to BC due to current lack of a standard BC quantification method. Hereafter, only the term "BC" is used in this paper to denote light-absorbing carbon.

### Results and Discussion

**Reduction of Emission Factors.** A series of emission factors for PM, OC, and BC were calculated according to the method described elsewhere (10, 11) and are presented in Table 2. According to this table, the two deployments do reduce the emissions of PM, OC, and BC by various magnitudes.

To systematically and comprehensively compare the impacts of the two deployments, we divide the combustions listed in Table 2 into 4 cases, i.e., chunk/traditional stove (case-1), chunk/improved stove (case-2), briquette/traditional stove (case-3), and briquette/improved stove (case-4) (Figure 1). As shown in Figure 1, case-1 emitted highest PM, OC, and BC and it was treated as the reference for the other cases. For case-2, PM, OC, and BC were reduced by 44%, 39%, and 86%, respectively, compared to case-1. Similar changes were also observed for case-3, with PM, OC, and BC down 34%, 28%, and 90%, respectively. The greatest changes occurred in case-4, in which PM, OC, and BC were reduced by 63%, 61%, and 98% relative to case-1, implying that when all coals were burned in briquettes with properly improved stoves (two deployments), PM, OC, and particularly BC emissions were reduced dramatically.

This could be primarily attributed to clay elements in briquettes. During briquette combustion, the binding effect of clay increases the chances for combustion of volatile matter; meanwhile, clay catalyzed the cracking process of coal tar to carbon and hydrogen. Consequently, briquetting accelerated the transfer from gas to solid phase combustion and solid combustion phase generated lower EFs, especially BC (25).

As for stoves, the improved stove was designed with an upper lid and a galvanized flue pipe to ease smoke ventilation; moreover, a cast iron ring was located above the ceramic chamber to improve heat-exchange efficiency. Both designs increased chances of volatile matter in fuels for complete combustion, and hence the emission reduction (especially BC) (11).

It is worth noting that the effects of briquetting and stove improvement both have some associated uncertainties. For instance, the effectiveness of briquettes in reducing emissions, to some extent, is dependent on many factors such as the ratio of coal particle capture by clay, and the size of the particles and the mix of clay and coal (25, 26). Some so-called improved stoves may even release more pollutants than traditional ones (11, 27), perhaps because the improved coal stoves may have a higher heat-exchange efficiency but compromise the combustion efficiency. Therefore, both coal briquettes and improved stoves require some further detailed investigations.

**Decrease of BC/OC Ratio.** In addition to substantial decreases of BC and OC emissions, the two deployments also resulted in significant declines of BC/OC ratios in flue particles. This can be observed from Figure 1, which clearly demonstrates that BC was reduced more substantially than OC. As shown in Figure 2, BC/OC ratios for raw-coal–chucks were 0.492 ± 0.035 (case-1) and 0.135 ± 0.018 (case-2) with traditional and improved stoves, respectively, whereas those for briquettes were 0.049 ± 0.016 (case-3) and 0.016 ± 0.006 (case-4) with traditional and improved stoves, respectively. From these data, case-4 was about 97% lower than case-1, from 0.49 to 0.016, suggesting that the deployments result in greater BC reduction relative to OC reduction, thus the resulting combustion emissions may become more optically scattering (28).

In addition, it was also believed that the two deployments had little influence on SO2 emission. SO2 is concurrently released with carbonaceous particles during coal combustion and is the precursor of sulfate aerosol, the typical cooling agent in the atmosphere (29). Generally, for the same mass of coal (e.g., 1 kg), the amount of SO2 released during

### Table 1. Coals Used in This Study

<table>
<thead>
<tr>
<th>Coal ID</th>
<th>Va (%)</th>
<th>Av (%)</th>
<th>Rf (%)</th>
<th>Rank</th>
<th>Source Locality</th>
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<tr>
<td>C1</td>
<td>38.42</td>
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<td>HVB</td>
<td>Zhunge’er, Inner Mongolia</td>
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<td>C2</td>
<td>37.34</td>
<td>8.35</td>
<td>0.72</td>
<td>HVB</td>
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<tr>
<td>C3</td>
<td>30.83</td>
<td>23.32</td>
<td>1.12</td>
<td>MVB</td>
<td>Xuanwei, Yunnan Province</td>
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<td>C4</td>
<td>28.92</td>
<td>15.63</td>
<td>1.19</td>
<td>MVB</td>
<td>Yuanping, Shanxi Province</td>
</tr>
<tr>
<td>C5</td>
<td>20.74</td>
<td>26.87</td>
<td>1.70</td>
<td>LVB</td>
<td>Xin’an, He’nan Province</td>
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<td>C6</td>
<td>16.00</td>
<td>7.60</td>
<td>1.90</td>
<td>LVB</td>
<td>Changzhi, Shanxi Province</td>
</tr>
</tbody>
</table>

*a Volatile matter on dry ash-free basis.
*b Ash on dry basis.
*c Mean reflectance of vitrinite in coal.

**TABLE 1. Coals Used in This Study**

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### References

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2. To systematically and comprehensively compare the impacts of the two deployments, we divide the combustions listed in Table 2 into 4 cases, i.e., chunk/traditional stove (case-1), chunk/improved stove (case-2), briquette/traditional stove (case-3), and briquette/improved stove (case-4) (Figure 1). As shown in Figure 1, case-1 emitted highest PM, OC, and BC and it was treated as the reference for the other cases. For case-2, PM, OC, and BC were reduced by 44%, 39%, and 86%, respectively, compared to case-1. Similar changes were also observed for case-3, with PM, OC, and BC down 34%, 28%, and 90%, respectively. The greatest changes occurred in case-4, in which PM, OC, and BC were reduced by 63%, 61%, and 98% relative to case-1, implying that when all coals were burned in briquettes with properly improved stoves (two deployments), PM, OC, and particularly BC emissions were reduced dramatically.

3. This could be primarily attributed to clay elements in briquettes. During briquette combustion, the binding effect of clay increases the chances for combustion of volatile matter; meanwhile, clay catalyzed the cracking process of coal tar to carbon and hydrogen. Consequently, briquetting accelerated the transfer from gas to solid phase combustion and solid combustion phase generated lower EFs, especially BC (25).

4. As for stoves, the improved stove was designed with an upper lid and a galvanized flue pipe to ease smoke ventilation; moreover, a cast iron ring was located above the ceramic chamber to improve heat-exchange efficiency. Both designs increased chances of volatile matter in fuels for complete combustion, and hence the emission reduction (especially BC) (11).

5. It is worth noting that the effects of briquetting and stove improvement both have some associated uncertainties. For instance, the effectiveness of briquettes in reducing emissions, to some extent, is dependent on many factors such as the ratio of coal particle capture by clay, and the size of the particles and the mix of clay and coal (25, 26). Some so-called improved stoves may even release more pollutants than traditional ones (11, 27), perhaps because the improved coal stoves may have a higher heat-exchange efficiency but compromise the combustion efficiency. Therefore, both coal briquettes and improved stoves require some further detailed investigations.

6. **Decrease of BC/OC Ratio.** In addition to substantial decreases of BC and OC emissions, the two deployments also resulted in significant declines of BC/OC ratios in flue particles. This can be observed from Figure 1, which clearly demonstrates that BC was reduced more substantially than OC. As shown in Figure 2, BC/OC ratios for raw-coal–chucks were 0.492 ± 0.035 (case-1) and 0.135 ± 0.018 (case-2) with traditional and improved stoves, respectively, whereas those for briquettes were 0.049 ± 0.016 (case-3) and 0.016 ± 0.006 (case-4) with traditional and improved stoves, respectively. From these data, case-4 was about 97% lower than case-1, from 0.49 to 0.016, suggesting that the deployments result in greater BC reduction relative to OC reduction, thus the resulting combustion emissions may become more optically scattering (28).

7. In addition, it was also believed that the two deployments had little influence on SO2 emission. SO2 is concurrently released with carbonaceous particles during coal combustion and is the precursor of sulfate aerosol, the typical cooling agent in the atmosphere (29). Generally, for the same mass of coal (e.g., 1 kg), the amount of SO2 released during
combustion is linked to the sulfur content of the coal (%), and is almost independent of burning methods or stoves, at least in theory (i.e., $S + O_2 = SO_2$). The most noteworthy exception relates to the addition of Ca(OH)$_2$ into coal. (less SO$_2$ is generated because the two deployments lead to higher energy efficiency and therefore a little less consumption of coals), impact on the entire SO$_2$ family would be insignificant. However, the impact of two deployments on the entire BC family holds the balance, because household coal use is the major contributor of BC emissions (7, 31). This reminds us once again that any action for mitigation should take into account all of the climate-sensitive agents, as a whole.

Benefits in Environment and Health. The two deployments have positive influences on environment and health. As far as PM is concerned, it was reported that the annual premature deaths caused by cardiovascular and pulmonary diseases following ambient PM exposure are estimated to be 800,000 (32). Also, respirable suspended particles (PM10) was the major urban air pollutant monitored in Chinese cities (Report on the State of Environment in China 2006, http://english.mep.gov.cn/standards_reports). Therefore, these two deployments which contribute to PM control are also likely to have health benefits. As for carbonaceous particles (OC + BC), there are many organic compounds contained in fine carbonaceous aerosols that can penetrate deep into the respiratory system and present a health hazard (33–35). For example, the presence of well-known toxics, such as oxy- and nitro-polychlorinated dibenzodioxins/furans have been recorded in carbonaceous aerosols (18). Recent epidemiological studies have demonstrated that there is a statistical association between carbonaceous aerosol concentrations and the number of cardiovascular emergency department visits. Additionally, BC may reduce atmospheric visibility, damage the appearance of buildings, and even affect crop yields (7). Obviously, the reduction of carbonaceous particles by the two deployments has explicit benefits to both human health and the environment.

**Possible Benefits in Climate.** Although BC is said to be the second most important contributor to global warming after CO$_2$ (15), the effect on the climate of BC is still uncertain and debated (12). In this paper, attention is paid only to the direct radiative forcing (RF) of fossil-fuel BC, which is regarded to be positive in warming (12).

Since the ratio of BC/OC governs the net RF of carbonaceous aerosols (21, 25, 36), the apparent decline of BC/OC ratios as a result of the two deployments weakens the absorption of solar radiation by carbonaceous particles. Hansen et al. (37) proposed that smoke from fossil fuels has a positive climate forcing whereas smoke from biofuel, in contrast, has a negative climate forcing, attributable to the large differences of BC/OC ratios between them. Reported BC/OC ratios of primary carbonaceous aerosols in China are 0.53 for 1996 (21), 0.31 (38) or 0.37 for 2000 (31), and the average of reported BC/OC ratios in atmospheric aerosols for 1990–2000 in China is 0.43 (39). Based on the nationwide

<table>
<thead>
<tr>
<th>coal ID</th>
<th>burning style</th>
<th>traditional stove</th>
<th>improved stove</th>
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<tr>
<td></td>
<td>PM</td>
<td>BC</td>
<td>OC</td>
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<td>chunk</td>
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<td>chunk</td>
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<td>18.95</td>
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<td></td>
<td>briquette</td>
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<td>chunk</td>
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<tr>
<td></td>
<td>briquette</td>
<td>4.38</td>
<td>0.084</td>
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observation by 18 stations of the China Atmosphere Watch Network (CAWNET). Zhang et al. (22) found that urban BC/OC ratio was approximately 0.32 on average whereas rural BC/OC ratio could reach as low as 0.17. Obviously the transfer from case-1 to case-4 will “dilute” the atmospheric BC/OC ratios, and hence may curb the warming by soot emissions.

When both declines (BC emissions and BC/OC ratio) are considered in combination, the final benefits of the two deployments will be further increased. It may be reasonable to speculate that the two deployments stand a good chance for listing coal burning emissions as cooling agents though they are still environmental pollutants. Consequently the prevailing belief that emissions from fossil fuels (e.g., coal) have much higher BC/OC ratios than those from biofuels should be challenged, and the logic of source characterization associated with BC/OC ratios may need reappraisal (37, 40).

It should be noted that biases of BC/OC ratios originating from analytical methods (24, 41, 42) and sampling artifacts (43, 44) were not considered in this paper, mainly because of consistency in analytical procedure and sampling system for all samples. Therefore, the comparability of BC/OC ratios between stoves or coal styles is little affected.

The BC emission reduction (by 98%) due to two deployments may lead to considerable modification of estimates in existing emission inventories. So far, several inventories relate to the estimated annual BC emissions for China in existing emission inventories. So far, several inventories (7, 21, 31, 45, 46) and the most well-known one was developed by Streets et al. (7). According to this inventory, China emitted 1342 Gg (104 kg) of BC in 1995, with 605 Gg (45%) originating from domestic coal burning and 38%, 3%, 6%, and 6% from biofuel, diesel vehicles, industry coal, and field combustion, respectively. Assuming that all coals had been burned as in case-4, BC emissions from household coal burning would have fallen to about 12 Gg, and the total BC emissions in that year would be reduced to 749 Gg, a decrease of nearly 600 Gg, and representing 7.5% of the total world BC emissions in 1996 (7951 Gg) (21). Our study indicates that domestic coal, having been deemed the largest BC source in China, if burned as briquettes with properly improved stoves, would become a much smaller contributor to total BC emissions.

To assess the possible impacts of BC emission reduction on warming mitigation, the GWP (Global Warming Potential) Metric is introduced to this paper. According to the IPCC (12), GWP is the total top-of-atmosphere RF of 1 kg of emitted greenhouse species during a specific time after emission, relative to the that of 1 kg of reference gas emission (usually CO2). Such a metric can be used in policy discussions by comparing the radiative effects of different species in reference to CO2. Although the GWP of BC was not definitely dwelt on in the IPCC assessment report, it has been further developed by some scientists with the method presented by IPCC (12). For example, Bond and Sun (47) examined the published results of 7 global models and derived the direct GWP for BC (ignoring indirect effects) over different periods after emission. For a 100-year time scale, GWPBC,100 averages 680, ranging from 210 to 1500, and for a 20-year time period, the GWPBC,20 averages 2200, in a range from 690 to 4700.

The GWP Metric for BC facilitates an assessment of the role of the “two deployments” in meeting the global mitigation targets. Considering that BC is proposed by some people as one of the priority reduction options to avoid crossing the threshold of so-called “dangerous climate change” (e.g., refs 6 and 15), the 20-year integration period for GWP of BC, instead of 100 years, has been adopted in this paper. In this sense, the impact by 1 kg of BC equals that of 2200 kg of CO2 on climate warming, and the reduced BC emissions of about 600 Gg from the “two deployments” (hereinafter referred to as BCred) are equivalent to 1320 Mt CO2. As shown in Figure 3, BCred represents a quarter of the 2004 CO2 emissions from fossil fuels in China (48). More comparisons of yearly effects of different policy measures are also given in Figure 3, such as energy-efficiency improvement, use of renewable energies, bioenergy, family planning program, and afforestation (48).

Although we have dwelt on the possible effects of BC reduction with GWP, we are unable to assess the possible effects of OC reduction using a similar approach. However, in view of the decline of BC to OC ratios related to the two deployments, the primary emissions from household coal combustion become more optically scattering (21).

**Policy Implications.** In summarizing the above results and discussions, two main conclusions can be reached. First, emissions including PM, OC, and BC can all be significantly reduced using the two deployments (briquettes and improved stove design), which would be very helpful in improving the environment, as well as improving community health. This is the prime purpose of the two deployments. Second, BC is reduced more significantly than OC, with the ratio of BC/OC considerably lowered. This makes the soot emissions optically more scattering.

It would seem imperative that Chinese stakeholders and the international community attach greater importance to these conclusions and formulate policies to accelerate the “two deployments”. Domestically, it would be beneficial to rapidly enforce the conversion from raw coal to briquettes and from traditional simple stoves to improved ones. We strongly suggest that the stakeholders consider the possibility of phasing out direct burning of bituminous raw-coal-chunks and polluting stoves, and of financially supporting the research, production, and application of improved stoves and coal briquettes. Internationally, if developed countries provide technologies and funds for the deployment of improved stoves and coal briquettes, emissions from household coal burning could be reduced rapidly.

Our proposals are viable for the following reasons. First, ameliorated coal briquettes and stoves have only to do with how coal is burned, rather than how much coal is burned. This fits with China’s coal burning situation without affecting China’s overall development strategy. Second, the technologies required for these changes are already available in China, as well as in other countries (although progressively improved techniques may be useful in further reducing emissions). Third, impact on global energy budget is only the byproduct; the direct benefit is pollution abatement and health improvements. In other words, the byproduct, or rather bonus benefit, further justifies the “two deployments” initiative, which already has environment and human health benefits.
Finally, the techniques involved with these “two deployments” may in principle be transferred to domestic biofuel or industrial boiler coal combustion. We may thereby have a chance to see a further reduction of PM, OC, and BC emissions from household biofuel use, which is the second largest contributor to BC emissions in China (7, 21, 31). Future research needs to investigate this possibility.

It is not the intention to depend on solely the “two deployments” for emission reduction. In fact, any other approaches, if proven cost-efficient, reliable, and practical, are equally welcome. For example, BC EFs for coal used in power generation are several orders of magnitude lower than those for household coal (7); therefore, transformation from coal to electricity is one option for household BC reduction. As a developing country with a population more than 1.3 billion, it is impossible for China to provide all residents, especially rural people with sufficient electricity for cooking/heating for the time being or in a foreseeable future, but it does not necessarily mean that coal-to-power transformation counts for nothing, because the reduction of household-coal BC emission via progressive deployment of ameliorated briquettes and improved stoves can be quickened in combination with other means such as the transformation from coal to gas or electricity.

The projected effects of the “two deployments” in China on emissions would contribute to the worldwide reduction targets. Many developing countries like China are seeking the alleviation of indoor air pollution by introducing improved stoves as a viable option (49, 50), which is very likely to cause PM, OC, and BC reductions. However, in the least developed countries, the most important factor affecting the deployment is household income (3). Therefore it is necessary to help poor residents purchase and keep using the improved stoves and fuels. In some regard, financial assistance to these countries and low-income residents determines the rate of reduction in the world.

In summary, the two deployments lead to significant decreases of PM, OC, BC, and BC/OC ratio for household coal burning, bringing about explicit benefits in environment and health, together with possible gains in climate stabilization. In fact, any effective approaches, including the promotion of these two deployments, should be priority actions as they assist in the worldwide goal of improving the environment and reducing emissions. Such a global impact can only be achieved through concerted efforts and positive local actions.

Acknowledgments

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