Biomass-derived liquid cooking fuels for household use in rural China: potential for reducing health costs and mitigating greenhouse gas emissions

Susan L. Fischer
Division of Environmental Health Sciences, University of California, Berkeley, 140 Warren Hall #7360
Berkeley, California 94720-7360, USA

Given the prevalence of solid cooking fuels and their highly polluting nature, a large number of people worldwide – and more than half of China's total population – receive enormous doses of particulate matter (PM) from cooking with solid fuels in indoor environments. In China, hundreds of millions are routinely exposed to indoor pollutant concentrations that exceed any international or domestic standard by an order of magnitude. Accordingly, significant health benefits could be realized if solid fuels were replaced by cleaner-burning fuels in rural China. Moreover, emissions of health-damaging air pollutants (HDPs) from rural indoor use of solid fuels are concomitant with a significant share of China's greenhouse gas (GHG) emissions. Thus, parallel assessments of the magnitude of health benefits and GHG emission mitigation associated with large-scale substitution of solid cooking fuels are warranted. This paper explores the plausible scope, potential health benefits, and possible GHG emission reduction of replacing a major portion of China's rural household solid fuel combustion with liquid cooking fuels derived from agricultural residues. Health endpoints are not limited to mortality, but include several morbidity outcomes, and are assessed using the World Health Organization's yardstick of disability adjusted life years (DALYs). A range of values is presented to reflect uncertainty associated with epidemiologic dose-response functions. If biomass-derived liquid fuels were employed on a large scale, health benefits could include a dramatic reduction in rural mortality attributable to air pollution, with even greater health benefits associated with non-fatal endpoints.

1. Introduction: motivations for producing liquid cooking fuels

1.1. Health

Globally, indoor use of solid fuels for rural cooking and heating exacts an enormous toll in human health. Rural indoor exposures in developing countries account for 60% of global exposures to particulate matter less than 10 μm in diameter (PM_{10}) [Smith, 1993]. Several factors contribute to this level of exposure. First, approximately two billion people worldwide, including 600 million biomass-users in rural China, cook with solid fuels [Reddy et al., 1997; Peng et al., 1998]. Second, the dose of fine particulate matter (PM_{10}) per unit heat delivered is enormous for indoor combustion of solid fuels such as biomass and raw coal. For example, PM_{10} doses per unit heat delivered are estimated[1] as several hundred mg per GJ for raw coal, improved biomass, and traditional biomass [Wang, 1997; Wang and Smith, 1999]. "Improved" and "traditional" refer to stove types, with "improved" cookstoves delivering heat more efficiently but potentially emitting more products of incomplete combustion (PICs) and total suspended particulate matter (TSP) per unit heat delivered [Zhang et al., 2000]. In contrast, Wang [1997] estimates the particulate matter doses associated with natural gas, fossil-derived liquid petroleum gas (LPG), and biogas to be essentially zero. Thus, the cleaner-burning nature of gaseous and liquid cooking fuels can dramatically cut human exposures to particulate matter.

Relative to solid fuels, gas and liquid fuels are also far less prone to producing gaseous products of incomplete combustion, potentially a dangerously high indoor source of pollution and comprising carbon monoxide (CO), an odorless gas capable of producing acute fatalities at concentrations of less than 1000 ppm. Incomplete combustion of coal briquettes is an especially hazardous source of CO [Wang, 1997]. Despite its clean combustion nature, biomass-derived producer gas, a product of air-blown gasification which is used in several Chinese villages [e.g., Dai and Lu, 1998]), does present a risk of CO poisoning, because CO is a significant constituent of producer gas. Fuels which would be stored and transported as liquids – e.g., LPG fractions (primarily C_3 and C_4 compounds), dimethyl ether, ethanol – would not incur the risk of CO poisoning from leakage [Goldemberg et al., 2000].

1.2. Combustion efficiency

Another attractive feature of liquid fuels is that their conversion to usable heat is more efficient than that of solid fuels. For example, Reddy et al. [1997] cite a typical efficiency of 10-15% for traditional stoves using agricultural residues versus 40-50% for kerosene stoves or 55-60% for LPG stoves, where efficiency is measured as energy transferred to the cooking vessel divided by the energy (HHV) of the fuel. Similarly, Dutt and Ravindranath [1993] rank kerosene stoves as 3-7 times more efficient than a variety of methods (Indian *chula,* modified Ghanaian, and open fire) using direct combustion of wood.

1.3. Local air quality improvement

Conversion of biomass residues in rural China to liquid cooking fuels could also mitigate local air pollution and foster compliance with a 1999 government policy banning the burning of crop residues near airports, railroads, and highways. As agricultural communities move up the "energy ladder" and shift away from full utilization of crop residues for heating and cooking, field burning of crop residues has emerged as a severe source of local air pollution [Goldemberg et al., 2000].

For the reasons laid out above, development of advanced biomass fuels – namely, cleaner-burning gases and liquids – has been identified as a global priority for improving the health of rural populations while boosting efficiency, improving local air quality, and promoting local rural employment [Reddy et al., 1997; Goldemberg et al., 2000]. These issues are all particularly salient in China, where the health impacts associated with combustion of solid biomass fuels in rural households are enormous. On the basis of attributable mortality from chronic obstructive pulmonary disease, lung cancer, pulmonary heart disease, and childhood pneumonia alone, Florig [1997] estimates that air pollution accounts for 13-22% of deaths in rural China. According to China's Statistical Yearbook [1999], respiratory disease accounted for 23% of rural mortality in 1998, compared with 14% of urban mortality.

1.4. Mitigation of greenhouse gas emissions

Besides enormous potential for improving health and providing other benefits to local populations, producing liquid cooking fuels to replace rural use of solid fuels can mitigate greenhouse gas (GHG) emissions. Economic analyses identify household fuel-switching in China as a relatively cheap opportunity for reducing GHG emissions. For example, Wang and Smith [1999] indicate that substitution of improved biomass, coal briquettes, biogas, and LPG for traditional biomass and raw coal might reduce carbon emissions from household sources at costs which are competitive with the Global Environmental Facility's (GEF) \$ 10/t-C_{eq} guideline for identifying cost-effective short-term mitigation projects.

China's rural household sector provides ample ground for intervention. More than two-thirds of China's population – roughly 900 million people – lives in rural China [Wang and Smith, 1999]. Currently, roughly 70% of rural residential energy derives from solid biomass fuels, such as wood and wheat straw [Peng et al., 1998]. The balance of rural household fuel is dominated by coal. Both solid biomass and coal are net GHG emitters. In the case of solid biomass, GHG emissions derive from unsustainable harvesting, which removes more carbon from the field than is returned during regrowth, and incomplete combustion, which can form compounds with greater global warming potential than CO_2 [Zhang et al., 2000; Smith et al., 2000].

2. Structure of the analysis

In part because use of solid fuels in rural households inflicts heavy health burdens, the conversion of solid biomass fuels to liquid fuels through a Fischer-Tropsch process has recently been investigated [Larson and Jin, 1999b; Larson and Jin, 1999a; Goldemberg et al., 2000]. This process involves oxygen-blown gasification of biomass, synthesis of hydrocarbons from the CO/H_2 rich syngas, and catalytic cracking of the hydrocarbons to produce the desired fuel fractions. For illustrative purposes, this paper employs material and energy flows based on the aforementioned Fischer-Tropsch technology, but the methodology presented here is general enough to be applied to other liquid fuels and other technologies for producing them. Direct rural health benefits associated with reduced exposures to sub-10µm particulate matter (PM_{10}) are the only health benefits considered here. A more comprehensive assessment (work in progress) will extend the analysis to incorporate benefits associated with reduced exposures to other pollutants (e.g., CO, SO_2, benzo(a)pyrene), reduced occupational burdens, and potential employment gains.

The remainder of this paper presents quantitative estimates for health benefits and GHG emission abatement which could be realized if a substantial fraction of agricultural residues were converted to liquid cooking fuels for rural households in China. The framework for developing these estimates is as follows.

- The potential resource base is assessed in order to estimate the amount of agricultural residues available for liquid fuel synthesis (Sec. 3.1).
- The fuel production technology is characterized in order to derive the amount of liquid fuels which might be derived from China's agricultural residues (Sec. 3.2).
- The fuel-substitution scenario and baseline against which benefits are measured are outlined (Sec. 4).
- The potential reduction in human exposures to fine particulate matter (PM_{10}) is estimated (Sec. 5).
- Epidemiological concentration-response functions are used to quantify the health benefits of reduced cumulative exposures to particulate matter (Sec. 6.1).
- Health benefits are aggregated into a widely-used yardstick (disability adjusted life-years, DALYs) which incorporates both mortality (fatalities) and morbidity (non-fatal endpoints), and for which there exists a database of information to put the results in perspective (Sec. 6.2).

- GHG abatement potential is quantified under several assumptions regarding the fuels that biomass-derived liquid fuels might displace (Sec. 7).

It is important to note at the outset the limitations of this analysis. First of all, while the illustrative Fischer-Tropsch technology could be built today if adequate funds were forthcoming, it is considered to be “medium-term”, at least 10 years away from widespread implementation [Goldemberg et al., 2000]. Secondly, since the postulated source of liquid fuels is biomass residues, associated GHG abatement will depend on the particular accounting framework and on assumptions regarding what households *would have* used were the liquid fuels not available. Thus, attribution of GHG abatement is inherently speculative, as it involves assumptions about the mix of household cooking fuels which will prevail in China in 2020, in the absence of liquid fuel synthesis from agricultural residues. Thirdly, even though a large number of studies have been done to assess indoor air quality in Chinese households, the database in which these studies are compiled lacks information critical to precise exposure assessment, since researchers often fail to specify fuel/stove combinations and other site-specific variables (e.g., season, ventilation, type of cooking, residents’ behavioral patterns) [Sinton et al., 1995]. Accordingly, averted PM exposures associated with the scenario posed here are highly uncertain. The final step, translating reduced exposure into health benefits, draws uncertainty from the underlying epidemiological concentration-response functions and the application of those functions to populations other than the study populations from which they were derived.

Despite these limitations, the assessment presented here is useful in that it indicates the magnitude of potential benefits, illuminates important data gaps, and provides a framework for more refined assessments, as better data become available.

3. The physical potential for liquid fuels from agricultural residues

3.1. Available agricultural residue

As of 1998, half of China’s agricultural residue – approximately 376 million tonnes (Mt)/year, 4.9 EJ/yr (4.9×10^{18} J, HHV) – was deemed potentially available for energy purposes in rural China[2]. The other half is considered unavailable, as it is needed for paper-making, livestock forage, or maintenance of soil quality [Li et al., 1998]. To put the size of this resource in perspective, note that the energy content of China’s annual available agricultural residues is approximately one-fifth of its annual coal consumption [Goldemberg et al., 2000].

3.2. Conversion technology

The amount of household cooking fuel that could be produced from this biomass depends on the particular fuel considered and the conversion technologies employed. Possibilities include ethanol, dimethyl ether, and synthetic LPG. Larson and Jin [1999b] present a preliminary analysis of the production of synthetic LPG from agricultural residues. This liquid fuel option is considered here for illustrative purposes. Like conventional LPG, synthetic LPG is a mixture of C_3 and C_4 hydrocarbons which, though gaseous at atmospheric conditions, can be stored and transported as a liquid under pressure. The terminology *“syn-LPG”* will be used throughout the remainder of this paper to distinguish a biomass-derived mixture of C_3 and C_4 hydrocarbons from petroleum-derived LPG. For this preliminary analysis, syn-LPG is assumed to have the same combustion properties as fossil-derived LPG, i.e., complete combustion without production of particulate matter.

Larson and Jin’s analysis suggests that by gasifying crop residues and converting the resulting “synthesis gas” into syn-LPG using a Fischer-Tropsch process, the “available” crop residues in China could be used to produce approximately 1.4 EJ/year of syn-LPG [Goldemberg et al., 2000]. Their analysis considers facilities that produce electricity as a byproduct of syn-LPG, so that approximately 210 TWh/year of electricity would be co-produced. Larson and Jin estimate a syn-LPG cost of about 6 $/GJ from corn stalks in Jilin Province, China, at a facility producing 490 TJ/year (220 barrels/day) of syn-LPG and 9.4 MW of electricity, with by-product electricity sold for 5 ¢/kWh. (The required capital investment is about $ 30 million.) This cost for syn-LPG compares favorably with the 7.7 $/GJ cited as the current (1998) price for LPG in rural China [Larson and Jin, 1999b].

The amount of “available” crop residues in all of China is sufficient to support roughly 3000 conversion facilities of the size considered by Larson and Jin in their economic analysis [Goldemberg et al., 2000].

4. Fuel-switching scenarios

To explore the impact that biomass-derived liquid fuels could have on local and global pollutant emissions, I consider a scenario in which 1.4 EJ (1.4×10^{18} J, HHV) syn-LPG derived from agricultural residues replaces other, solid, cooking fuels. On the basis of an annual per-capita LPG cooking fuel need of 2.5 GJ/year in Jilin province [Larson and Jin, 1999a], 1.4 EJ of biomass-derived syn-LPG could provide for 560 million rural Chinese.

To assess benefits of liquid cooking fuels in rural China, one must consider what cooking fuels would be displaced. The analysis here considers that all solid biomass and raw coal fuel use would be replaced, with remaining biomass-derived syn-LPG displacing as many coal briquettes as possible.

The baseline considered here is Wang et al.’s [1999] BAU projection for 2020 (Table 1). This baseline assumes that 35% of China’s projected ca. 2020 rural population of 840 million might cook with improved biomass, 5% with traditional biomass, 25% with raw coal, 20% with coal briquettes, 3% with biogas, and 12% with LPG. Under the substitution scenario, 294 million people switch to syn-LPG from improved biomass, 42 million from traditional biomass, 210 million from raw coal, and 14 million from coal briquettes (Table 2).

Table 1. Breakdown of China's rural population by household fuel/stove combination, as hypothesized under the ca. 2020 baseline and as reported for 1990 [Wang and Smith, 1999][1]

	Baseline, ca. 2020	1990
Improved biomass	35%	60%
Traditional biomass	5%	17%
Raw coal	25%	15%
Coal briquettes	20%	5%
Biogas	3%	2%
LPG	12%	1%

Note

1. The projected rural population, ca. 2020, is taken as 840 million, as in Wang and Smith [1999].

Table 2. Millions of people switched from biomass (as solid fuel) or coal to syn-LPG derived from agricultural residues, under the fuel substitution scenario[1]

Baseline fuel type	Millions substituted with syn-LPG
Improved biomass	294
Traditional biomass	42
Raw coal	210
Coal briquettes	14
Total	560

Note

1. This scenario displaces baseline use of all solid biomass fuel and all raw coal, then as many coal briquettes as possible.

Table 3. Averted PM_{10} doses under fuel/stove substitution scenario. Doses are estimated per unit useful heat delivered [Wang, 1997][1]

Fuel/stove combination	Dose (mg-PM_{10}/GJ)	Averted PM_{10} dose (t/yr)
		Fuel substitution scenario
Improved biomass	250	83
Traditional biomass	417	20
Raw coal	307	72
Coal briquettes	8	0.1
Total		175

Note

1. These averted doses are distributed among the populations whose fuel is substituted.

5. Potential sub-10 μm particulate matter (PM_{10}) dose reduction

Because epidemiological studies have focussed on the sub-10 μm fraction of particulate matter (PM_{10}) as a predictor of health outcome, the reduced dose of PM_{10} to rural Chinese associated with the fuel-switching scenario put forth here is assessed. These estimates are uncertain because they entail generalizing from the available data – emissions of total suspended particulate matter (TSP) and ambient indoor concentrations of particulate matter – to PM_{10} doses. Accordingly, assumptions regarding the relationship between emissions, indoor particulate concentrations, and human exposures, as well as the fraction of TSP which is inhalable as PM_{10}, are required. On the basis of estimates of PM_{10} doses per GJ heat for various fuel/stove combinations, as presented by Wang [1997], and the assumption that syn-LPG produces no particles during combustion, an aggregate dose reduction for the rural population of China of about 175 t PM_{10}/yr would be attained under the fuel substitution scenario (Table 3). The mean averted annual PM_{10} dose among the 560 million whose fuel was switched would be 310 mg/yr. Given a breathing rate of 15.5 m^3/day, this is equivalent[3] to reducing the annual average PM_{10} concentration in personal breathing zones by 55μg/m^3. For context, the US annual average National Ambient Air Quality Standard (NAAQS) for PM_{10} is 50μg/m^3. On the basis of Sinton et al.'s database, Wang and Smith [1999] suggest a mean indoor concentration of PM_{10} in households burning raw coal of about 150μg/m^3, with peak concentrations as high as 5000μg/m^3.

6. Potential health benefits

Assessing the health benefits which would accrue from the proposed intervention involves translating "dose" to health impacts via epidemiological concentration-response functions. A number of studies have attempted to correlate adverse health outcomes (e.g., premature mortality, increased asthma attack incidence, chronic bronchitis, minor respiratory symptoms) to ambient air pollution concentrations. One limitation of epidemiologic studies based on ambient concentrations is that ambient concentrations are very crude markers of exposure, since the pollutant concentrations in microenvironments inhabited by people can be quite different from those where ambient concentrations are measured. Also, most of these studies have involved populations in developed countries, although some studies of increased mortality in China have been conducted. Owing to the complex nature of the studies and the heterogeneity of the populations to which they are applied, there is significant uncertainty in these concentration-response functions. For this assessment, the concentration-response functions used by Wang and Smith [1999] are adopted, with the same conventions for developing low, medium, and high estimates.

The aforementioned epidemiological concentration-response functions are linear with incremental concentration and exposed population. A linear functional form simplifies the analysis, as it obviates the need to know how the dose is distributed among members of the population. Epidemiological concentration-response functions can be translated to dose-response functions via division by a representative population breathing rate (here, 15.5 m^3/day, as in [Wang and Smith, 1999]). Dose-response functions for a number of health endpoints – namely, premature mortality, adult chronic bronchitis, respiratory hospital admission, emergency room visit, acute child bronchitis, asthma attack, restricted activity day, and respiratory symptom – are shown in Table 4. In the case of

Table 4. Epidemiological dose-response functions[1] used to calculate health benefits of reduced PM_{10} dose to rural populations in China

Additional number of cases per kg-PM_{10} inhaled by population				% population at risk	Source of dose-response function
Health endpoint	**Low**	**Central**	**High**		
Mortality	0.495	1.24	3.71	100	[Xu et al., 1994; Dockery and Pope, 1996; Pope and Dockery, 1996]
Chronic bronchitis in persons older than 16yrs	5.30	10.6	15.9	65	[Abbey et al., 1993]
Respiratory hospital admission	1.24	2.12	2.83	78	[Pope, 1991]
Emergency room visit	230	424	600	78	[Samet et al., 1981]
Acute child bronchitis	141	283	424	35	[Dockery et al., 1989]
Asthma attack	5,300	10,600	35,400	3[2]	[Ostro et al., 1991; Whittemore and Korn, 1980]
Restricted activity days in persons older than 16 yrs	7,070	10,600	15,900	65	[Ostro, 1990]
Respiratory symptom	15,900	31,800	47,700	100	[Krupnick et al., 1990]

Notes

1. These functions derive from a number of sources, as noted in the last column, following Wang and Smith [1999]. Fractions of population at risk for the various health points derive from Wang and Smith [1999], except where noted. “Central” denotes the best point estimate. “Low” and “high” estimates bracket the 95% confidence interval associated with uncertainty in the epidemiological dose-response functions.
2. Based on [Beasley et al., 1998].

Table 5. Annual averted adverse health outcomes associated with reducing the PM_{10} dose to rural Chinese by 175 t/yr in the fuel substitution scenario

Avoided adverse outcome, thousands of cases per year			
Health endpoint	**Low**	**Central**	**High**
Mortality	90	220	650
Chronic bronchitis, > 16yrs	600	1,200	1,805
Respiratory hospital admission	170	290	390
Emergency room visit	31,000	58,000	82,000
Acute child bronchitis	8,700	17,000	26,000
Asthma attack	28,000	56,000	190,000
Restricted activity days, > 16yrs	800,000	1,200,000	1,800,000
Respiratory symptom	2,800,000	5,600,000	8,400,000

premature mortality, China’s mid-1990s baseline crude mortality rate[4] of 0.007/person-yr is used to scale the epidemiological results, which are cast in terms of percentage increase in mortality rate [Wang and Smith, 1999]. Since not all members of the population are at risk for a given health endpoint – e.g., some health endpoints are restricted to adults or children – the fraction of the population at risk must be considered. For each health endpoint, the right-most column of Table 4 shows fractions-at-risk of the population whose fuel is substituted, following Wang and Smith [1999], except for the health endpoint of asthma. In the case of increased asthma attacks per asthmatic, 3% of China’s rural population is assumed to be asthmatic, on the basis of Chinese results taken from a worldwide prevalence survey of 13 and 15 year-olds [Beasley et al., 1998].

6.1. Health benefits: numbers of avoided adverse outcomes

Given the averted PM_{10} dose of about 175 t/yr under the fuel substitution scenario, as assessed in the previous section, the health benefits from substitution of the baseline rural cooking fuel mix projected for China with biomass-derived syn-LPG are as shown in Table 5. Florig [1997] attributes a central estimate of 988,000 premature deaths to air pollution in rural areas. Thus, the central avoided mortality estimates of the fuel substitution scenario, 220,000 per year, could reduce rural mortality attributable to air pollution by about 20-25%. It is worth noting that

Table 6. Annual averted adverse health outcomes associated with reducing the PM_{10} dose to rural Chinese by 175 t/yr in the fuel substitution scenario, measured in thousands of DALYs per year[1]

Annual health benefits (thousands of DALYs/yr)				DALYs per case
Health endpoint	Low	Central	High	
Chronic bronchitis, > 16 yrs	1,100	2,200	3,200	1.8E+00
Respiratory symptom	450	890	1,300	1.6E-04
Mortality	110	270	800	0.48/4.2[2]
Restricted activity days, > 16yrs	180	260	400	2.2E-04
Emergency room visit	26	47	67	8.2E-04
Asthma attack	8.6	17	58	3.1E-04
Acute child bronchitis	2.7	5.4	8.1	3.1E-04
Respiratory hospital admission	1.4	2.5	3.3	8.6E-03
Total (1000 DALYs/yr)	1,800	3,700	5,900	

Notes

1. The rightmost column denotes the amount of "healthy time lost" per case of the corresponding endpoint. In the case of mortality, DALYs are equivalent to years of life lost; for non-fatal health endpoints, time lived with the adverse health outcome is weighted according to its severity.
2. Epidemiological studies suggest that premature mortality associated with PM_{10} falls into two categories, namely "early" deaths of people who will soon die (80% of this mortality burden) and deaths of people who would otherwise have lived several years longer (20% of this mortality burden). On the basis of Hofstetter's [1998] accounting framework, this assessment assigns 0.48 DALYs to the 80% who die only a few months early, and 4.2 DALYs to the 20% who lose several years of life to PM_{10} exposure.

lower and upper estimates for averted mortality in these scenarios fall within 10-80% of Florig's 1997 central estimate of rural mortality attributable to air pollution. While some of the morbidity "endpoints" – e.g., emergency room visit – presented in Table 5 reflect an urban perspective and its associated medical infrastructure, they serve here as general markers of ill-health. Moreover, translation of these endpoints to disability-adjusted life years (DALYs), pursued in the following paragraph, facilitates a more general interpretation of these morbidity outcomes.

6.2. Health benefits aggregated in disability adjusted life-years (DALYs)

The health benefits presented in Table 5 are translated into the World Health Organization's measure of disability adjusted life-years (DALYs) [Murray and Lopez, 1996]. On the basis of "healthy time lost", this yardstick provides a scalar measure which incorporates both fatal (mortality) and non-fatal (morbidity) outcomes. Those familiar with the notion of years of life lost (YOLLs) can interpret DALYs as an extension of this "lost-life" framework to include non-fatal outcomes. While its construction inevitably involves many normative assumptions, all of which have been explicitly laid out by Murray and Lopez [1996], there is international consensus on its utility as a health yardstick as well as a vast body of health data which have been assembled in terms of DALYs.

In translating health outcomes to DALYs, the assignments of Hofstetter [1998], who carried out a thorough study to interpret epidemiological studies in a quantitative health assessment framework, are used. The annual health benefits associated with reduced PM_{10} dose from the proposed fuel substitution are aggregated in terms of DALYs (Table 6). Several features are worth noting. First, morbidity endpoints overwhelm the total DALYs, accounting for more than 90% in the central estimate – thus, an assessment of rural air pollution health burdens which focuses solely on mortality captures only a small fraction of the picture. Specifically, the central estimate of health burden attributes 60% of the health burden to chronic bronchitis, about 25% to respiratory symptoms, and 5-10% to each of mortality and restricted activity days. Secondly, uncertainty in the chronic bronchitis and respiratory symptoms account for the bulk of epidemiologic uncertainty in the results – if these uncertainties were eliminated, the interval spanned by low and high estimates would shrink from about 100% of the central estimate to about 20% of the central estimate. Finally, two of the top four health endpoints in Table 6, namely respiratory symptoms and restricted activity days, are the lowest severity per individual case. This reemphasizes the need to include morbidity in health assessments due to air pollution and stresses that the toll of PM_{10} inhalation is largely due to an enormous number of common health impairments.

On a per capita basis, based on the 560 million population whose fuel was switched, the proposed scenario would reduce the annual health burden by about 0.7 DALYs per 100 people (central estimate), with lower and upper estimates suggesting a range of 0.3-1.1 DALYs per 100 people. Relative to the Global Burden of Disease Study's assessment of China's 1990 disease burden, which suggests an annual health burden of 18 DALYs per 100 Chinese [Murray and Lopez, 1996], the proposed scenario would reduce the per capita burden of those whose

Table 7. Global warming potential (GWP) and averted annual greenhouse gas emissions under the fuel/stove substitution scenario[1]

Fuel/stove combination	GWP[2] (kg-C_{eq}/GJ)	Averted GWP (MtC_{eq}/yr)
		Fuel substitution scenario
Improved biomass	56 or 204[3]	35
Traditional biomass	94 or 340[3]	18
Raw coal	265	63
Coal briquettes	136	2
Total		117

Notes

1. GHG emissions are measured, per unit useful heat delivered, as the 20-year global warming potential associated with CO_2 and CH_4 on a fuel cycle basis.
2. GWP emission factors are taken from Wang [1997].
3. The global warming potential associated with biomass fuel/stove combinations depends on whether the biomass is assumed to be harvested renewably. Wang [1997] reports that approximately one-third of 1994 biomass fuel in China was forest wood. In this analysis, the calculation of averted GWP assumes that one-third of biomass would have been non-renewably harvested in the baseline scenario.

cooking fuel was substituted by about 4% (central estimate), with lower and upper estimates suggesting a range of about 2-6%. Another way to place the health benefits assessed here in perspective is to note that the central estimate for reduced health impacts exceeds China's 1990 childhood cluster disease[5] burden (2.2 million DALYs) and is comparable with China's 1990 disease burdens from tuberculosis (4.2 million DALYs) and diarrhoeal disease (3.7 million DALYs) [Murray and Lopez, 1996].

7. Potential greenhouse gas (GHG) abatement

Carbon dioxide (CO_2) and methane (CH_4) are the dominant greenhouse gases (GHGs) for the fuel/stove combinations considered here. Wang [1997] presents data for net fuel cycle emissions of CO_2 and CH_4 per unit heat delivered for several fuel-stove combinations. These data are summarized by their global warming potential (GWP) (Table 7). GWP is expressed in equivalent kg of carbon as CO_2 which would cause the same radiative forcing over a defined time horizon – here, 20 years – as the actual mix of GHGs emitted.

Several assumptions are involved in figuring annual averted GHG emissions associated with the fuel-switching scenario. For example, the degree to which biomass fuel is renewably harvested is the dominant determinant of (net) GHG emissions associated with its use. While renewably harvested biomass implies a carbon neutral process with respect to organic content of the soil, products of incomplete combustion (PICs), such as CH_4 and CO, are produced when it is burned as solid fuel [Zhang et al., 2000]. For example, of fuel/stove combinations tested by Zhang et al., no biomass stove produced less than 4% on an ultimate emissions[6] basis of PICs. Accordingly, even "renewably harvested" biomass incurs some GWP if it is burned as a solid fuel in household cookstoves, since these cookstoves inevitably produce some PICs. In this analysis, one-third of the baseline biomass fuel is assumed to be non-renewably harvested. Syn-LPG derived from agricultural residues is assumed, for this assessment, to burn completely (no PICs) and to be carbon-neutral with respect to extraction (renewable harvesting), so that its net GHG emissions are negligible.

Assuming LPG stoves to deliver 45% of fuel energy (HHV) to cookpots, on the basis of recent measurements by Zhang et al. [2000], the fuel substitution scenario could displace 117 Mt-C_{eq}/yr (Table 7). For context, about 800 Mt-C_{eq} were emitted by China in 1990 from all sources [World Bank, 1996]. About 45% of averted GHG emissions derive from displacing solid biomass with syn-LPG derived from agricultural residues. Accordingly, the estimate of averted GHG emissions is sensitive to estimates for GWP associated with use of solid biomass as a fuel. Further research is needed to clarify the amount of biomass available for energy purposes on a carbon-neutral basis.

8. Conclusion

It appears that China has sufficient agricultural residues to produce liquid fuels for a substantial fraction of its rural population. Under the illustrative technology scenario of residue-derived Fischer-Tropsch synthesis of syn-LPG coupled to electricity production, the cooking needs of about 560 million rural residents could be met, using processes which are technically plausible though capital-intensive. Rural health benefits associated with reduced PM_{10} exposures render the use of such technologies extremely attractive: rural mortality attributable to air pollution might be cut by about a third. In addition, the central estimate derived here suggests that health benefits associated with morbidity endpoints exceed those due to averted mortality by an order of magnitude, on a disability-adjusted life-year (DALY) basis. To reduce the uncertainty associated with estimated health benefits of fuel substitution, further research is needed to clarify the level of rural population exposures to PM_{10} from cookstoves. In addition to enormous health benefits, mitigation of GHG emissions may render production of liquid cooking fuels from agricultural residues an attractive option in a severely greenhouse-gas constrained world. If a global market for GHG emissions abatement were to emerge, potential GHG reductions achieved by a fuel substitution scenario of the type discussed in this paper could generate substantial revenues in the form of carbon credits. The disparity between stakeholders for whom it would be attractive to pursue fuel-switching (e.g., rural Chinese suffering ill-health due to air pollution) and those for whom large capital investments might be required (parties interested in GHG abatement, perhaps in an international framework) presents enormous implementation challenges. ■

The author can be contacted at:
E-mail: sfischer@uclink4.berkeley.edu
Tel: +(1)510-643-4613
Fax: +(1)510-642-5815

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Notes

1. Estimating PM_{10} dose per unit heat delivered involves estimating concentrations of cookstove-derived PM_{10} in personal breathing zones, exposure durations, and the number of people exposed per household. Estimates of PM_{10} doses per unit heat delivered derive uncertainty from gaps in data for translating emissions to indoor concentrations, disparities between ambient indoor concentrations and concentrations in personal breathing zones, and inadequate characterization of personal activity patterns.
2. Wang [1997] indicates that the quantity of agricultural residue available on a renewable basis may be significantly less than J. Li et al's [1998] estimate, in part because her work considers a smaller fraction of crop residues to be sustainably removable from the field.
3. Because the epidemiologic dose-response functions are linear, the incremental reduction in mean PM_{10} concentration suffices to provide a measure of averted ill-health.
4. The crude mortality rate expresses the number of deaths per person-year of time lived in a population, without concern for the population's age structure. Thus, China's baseline crude mortality rate of 0.007/person-yr, or one death per 143 person-years, reflects both the expected lifetime and the changing age structure of the population, with population growth decreasing the apparent death rate.
5. The childhood cluster consists of five diseases (pertussis, poliomyelitis, diphtheria, measles, and tetanus) for which there exist simple, cost-effective preventive vaccinations.
6. Ultimate emissions include emissions associated with burning of char, as explained in Zhang et al. [2000].

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