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The Indian National Initiative for Advanced Biomass Cookstoves: The benefits of clean combustion

C. Venkataraman [a], A.D. Sagar [b], G. Habib [b], N. Lam [c], K.R. Smith [c,*]

[a] Indian Institute of Technology Bombay, Mumbai, India
[b] Indian Institute of Technology Delhi, New Delhi, India
[c] University of California, Berkeley, USA

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ABSTRACT

India has recently launched the National Biomass Cookstoves Initiative (NCI) to develop next-generation cleaner biomass cookstoves and deploy them to all Indian households that currently use traditional cookstoves. The initiative has set itself the lofty aim of providing energy service comparable to clean sources such as LPG but using the same solid biomass fuels commonly used today. Such a clean energy option for the estimated 160 million Indian households now cooking with inefficient and polluting biomass and coal cookstoves could yield enormous gains in health and welfare for the weakest and most vulnerable sections of society. At the same time, cleaner household cooking energy through substitution by advanced-combustion biomass stoves (or other options such as clean fuels) can nearly eliminate the several important products of incomplete combustion that come from today's practices and are important outdoor and greenhouse pollutants. Using national surveys, published literature and assessments, and measurements of cookstove performance solely from India, we find that about 570,000 premature deaths in poor women and children and over 4% of India's estimated greenhouse emissions could be avoided if such an initiative were in place today. These avoided emissions currently would be worth more than US$1 billion on the international carbon market. In addition, about one-third of India's black carbon emissions can be reduced along with a range of other health- and climate-active pollutants that affect regional air quality and climate. Although current advanced biomass stoves show substantial emissions reductions over traditional stoves, there is still additional improvement needed to reach LPG-like emission levels. We recognize that the technology development and deployment challenges to meet NCI goals of this scale are formidable and a forthcoming companion paper focuses on what program design elements might best be able to overcome these challenges.

1. The Indian National Biomass Cookstove Initiative — a new beginning

The National Biomass Cookstoves Initiative (NCI) was launched in India in late 2009 to extend the use of clean energy to all of India's households through the development of "the next-generation of household cookstoves, biomass-processing technologies, and deployment models" (MNRE, 2009). Providing an affordable and reliable clean cooking energy option for the poorest households now relying on traditional biomass technologies is expected to yield enormous gains in health and welfare for the weakest and most vulnerable sections of society. At the same time, cleaner household combustion is expected to reduce the several products of incomplete combustion that are important outdoor and climate-active pollutants, thus helping combat regional environmental impacts and global climate change.

In contrast to any other large-scale improved biomass stove program in the world, past or present, the new Indian National Cookstove Initiative has set itself a lofty goal for all Indian households (MNRE, 2009):

> *"Our aim is to achieve the quality of energy services from cookstoves comparable to that from other clean energy sources such as LPG."*

In this paper, we focus on what is known about the health, environment, energy security, and climate impacts of the current pattern of biomass use in the country for cooking in relation to cleaner cooking options such as LPG. We draw on this knowledge base to assess the potential full benefits of meeting this Initiative's goal, i.e., bringing all India's citizens the level of cooking energy service now already available to about a quarter of Indian households and, worldwide, nearly half of humanity. In a companion paper, we discuss current thinking on the technologies, dissemination modes, financing, potential rates of implementation, and other aspects of the new national program that will lead toward this goal.

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* Corresponding author. Global Environmental Health, 747 University Hall, School of Public Health, University of California, Berkeley CA 94720-7360, USA. Tel.: +1 51 643 0793.
E-mail address: krksmith@berkeley.edu (K.R. Smith).

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Table 1
Distribution of household cooking fuel use in India in 2005 based on the question: "what is the main fuel used for cooking?" Many households use more than one fuel over the course of the year, of course. The last column indicates the number of households in each fuel category out of 225 million total in the country (IIPS, 2007).

	Urban (%)	Rural (%)	National (%)	Households (million)
Dung	2.8	14.4	10.6	24
Biogas	0.50	0.40	0.50	1.1
Crop waste[a]	1.3	13.0	9.2	21
Wood	22.0	61.8	48.7	110.5
Charcoal	0.50	0.30	0.40	0.9
Coal	4.3	0.80	1.9	4.3
Kerosene	8.2	0.80	3.2	7.2
LPG	58.7	8.2	24.7	56
Elec.	0.90	0.10	0.40	0.9
Other	0.80	0.20	0.40	0.9
Biomass Total	27	90	69	156
Solid Fuel Total	31	90	71	160

[a] Includes the category entitled "straw/grass/shrubs".

India's previous stove program in the late 20th century, the National Program for Improved Chulhas (NPIC), was credited with introducing cookstoves to a few tens of millions of households before it ended, but was initiated in a completely different context in which fuel efficiency was the major criterion as the full benefits of clean combustion were not well understood and stove technologies to achieve it were not well developed. In the intervening period, however, there have been major changes in our understanding of the impacts of traditional biomass use, especially relating to human health as well as climate change. At the same time, improvements in technology and dissemination models, combined with changed political and institutional approaches have changed the landscape for improved biomass stove programs. Although some are described in detail later in the paper, the main issues are summarized here:

1.1. Benefits

- We now understand much more thoroughly the health impacts of indoor biomass use in traditional stoves with hundreds of papers published in the international biomedical literature documenting a range of health impacts from the air pollution including pneumonia and low birth weight in children and chronic lung disease, cataracts, and heart disease in women. Based on available evidence for 2000, the World Health Organization (WHO) estimated that about 420 thousand premature deaths were caused annually in India by household fuel air pollution (Ezzati et al., 2004). We also understand that in order to make significant gains in terms of health benefits, it is critical to reduce the emissions from these devices as low as possible since there seems to be no 'safe' level of exposure and that the drop off

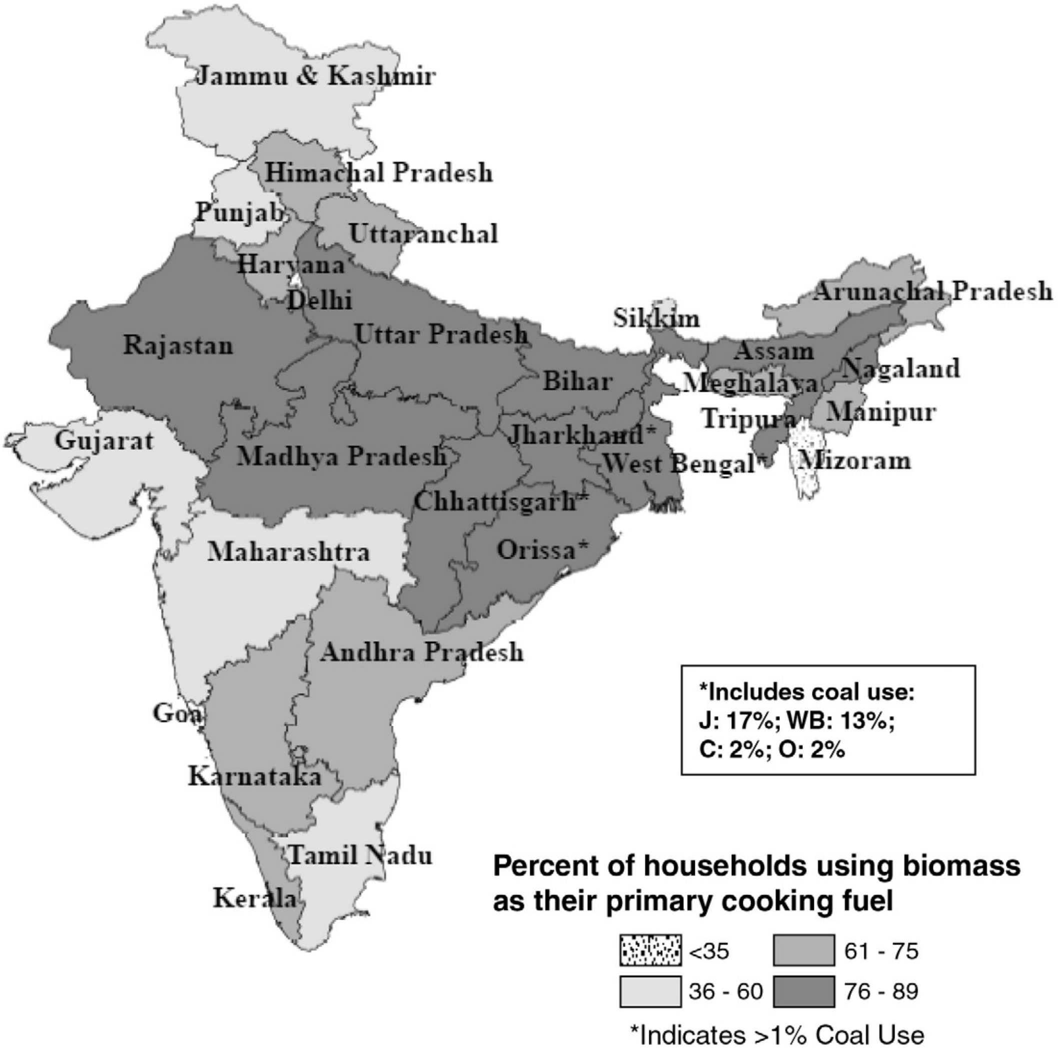

Fig. 1. Distribution by state of households using biomass or coal as their main cooking fuel in 2005. From (IIPS, 2007).

in health impacts is significant even down to low levels of exposure (WHO, 2006).

- We now understand that the international price of LPG, being a petroleum product, likely will continue to increase faster than rural incomes, thus making the transition to modern household fuels difficult and, if subsidized by government, increasingly expensive. This adds to the attraction of deploying advanced biomass stoves that provide high performance using local renewable resources and relieve the government of the cost of fuel subsidies.
- It is now recognized that climate change is a major threat and household biomass fuel combustion is a contributor with significant greenhouse impacts *per unit energy delivered* (from emissions of nitrous oxide, methane and other important greenhouse pollutants) compared to nearly all other human uses of energy, although not a large contribution in total compared to other sectors. In addition, biomass fuel combustion emits other shorter-lived pollutants (like black carbon) that contribute to reduction of crop yields and may contribute to accelerated melting of glaciers and disruption of the monsoon.
- It is now understood that rural outdoor air pollution is a significant problem in India, with average levels of pollution in the Ganga River Basin, for example, being substantially above Indian and WHO health-based norms. Biomass combustion plays an important role in creating this pollution.

1.2. Technology

- Given the combined goals of fuel efficiency, health protection, low climate impacts, and reduction of outdoor pollution it is now realized that the best approach is to move toward high-combustion-efficiency and low-emissions advanced-combustion devices that do not produce any significant pollution in the first place. Well-operating chimneys may mitigate indoor air pollution but transfer the pollution outdoors (which still may result in substantial human exposure). There are now solid-biomass-using stoves, however, which produce emissions per meal that are less than one-fifteenth that of traditional stoves in lab tests, with greater reductions seemingly possible.
- To achieve reliable long-term high performance, stoves must use either advanced ceramics or metal alloys as well as other components (such as blowers), which must be made in centralized manufacturing facilities with good quality control and other modern mass production techniques. The incorporation of these materials and components in artisanal manufacturing is not easy, given the processing as well as other engineering requirements — in fact, it generally requires the development of sophisticated supply chains since such materials and components mostly are developed by specialized firms. For the first time in world history, there are now emergent examples of such sophisticated supply chains for household biomass stoves.
- Truly improved stoves tend to have a narrower tolerance to biomass size and moisture content and thus generally require more fuel processing at the household or, for high performance, preprocessing as pellets or briquettes.
- Hybrid gasifier stoves (with small electric blowers), however, effectively maintain good performance over a wider variety of fuel characteristics. Some half a million such stoves have been sold in India to date, but of course only to the more well-to-do segments of rural populations because of their higher cost, and need for electric connection. There also are technologies now becoming available, however, that at relatively small additional cost generate the electricity for a stove's blower from the heat produced by the stove — thus eliminating the need for access to power in the household.
- The communication and information revolutions are offering cost-effective ways to monitor and evaluate programs covering millions of households through the use of technologies such as microchips and wireless networks to collect large amounts of data and software to process it. Such monitoring is crucial for modifying programs to optimize effectiveness as well as demonstrating their benefits under conditions of real-world use.

These new understandings, as well as advances in stove technologies, have underscored both the urgent need and the potential for widespread dissemination of significantly improved technologies aimed at clean biomass combustion, while also achieving fuel efficiency, reliability, and user satisfaction. Thus, the major premise behind the NCI is that the combination of newly understood benefits and new technologies provides a renewed rationale, and brand new set of possibilities, to pursue this goal.

2. Background of the initiative

Biomass fuels in the form of wood, crop residues, and animal dung, continue to be the dominant source of cooking energy in India. The National Family Health Survey for 2005–2006, NFHS-3 (IIPS, 2007), which provides the most detailed survey questions on household cooking fuel of available routinely conducted national surveys, indicated that 71% of households in India rely primarily on solid fuels for cooking.[1] As shown in Table 1, 27% of urban households and 90% of rural households used biomass as their primary cooking fuel in 2005, 69% nationally. These estimates indicate that in 2005 over 770 million Indians living in nearly 160 million households remained primarily dependent on solid fuel for their cooking needs, 97% of which is biomass, the rest coal. Fig. 1 shows the distribution by state in India showing that highest usage is in the middle part of the country, but with significant use in all areas.

Given the slow decline in the fraction of the population using biomass (in large part because the shift from biomass to other fuels is closely correlated with income growth and the price of LPG, the main alternative source of cooking energy) – about 0.7% per year between 1998–1999 and 2005–2006 (IIPS, 2007) – and the rate of increase in the total population in the country (currently, about 1.5% per year), the absolute number of biomass users in the country will not change appreciably, or may even rise slowly (as the population grows), in the next decade barring any major interventions.[2]

Furthermore, the total potential households needing advanced-combustion biomass stoves (ABS) will be larger than the population fraction indicated by Table 1. This is illustrated by the diagram in Fig. 2, which takes into account that there is a transition income band in which households use both LPG/kerosene and biomass, the main alternatives in the country. Thus, more households have biomass stoves than those that respond with "biomass" when questioned what fuel is primarily used. The impacts per traditional biomass stove in the transition zone, however, are lower than those in households using only biomass fuel because they are used less than full time. Given this complex situation, we use an estimate of 160 million stove-equivalents to calculate the impacts of not providing combustion services equivalent to LPG, which is the key goal of the NCI. This assumes that the reduction of impacts due

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[1] There are two sources of repeated household surveys in India: the National Sample Survey Organization (NSS0, 2006) and the National Family Health Survey (IIPS, 2007). In one respect, the NSSO surveys are attractive in that they are repeated much more often than the NFHS. On closer look, however, there are some unexplained instabilities in the results over time — major shifts in usage are indicated between surveys just a year apart. NSSO surveys also do not distinguish wood from crop residues, when these involve important differences in stove design, emissions, and net-carbon. Perhaps the most problematic aspect, however, is the large "other" category, while the NFHS has a very low "other" number. These concerns, combined with the fact that the NFHS uses widely reviewed methods applied in dozens of other countries, led us to use the NFHS-3 data as the basis of our current household cooking energy baseline. Another source of household fuel use data is the India Human Development Survey conducted in 2005 by the University of Maryland and the National Council of Applied Economic Research (http://www.ihds.umd.edu/). When released, the 2011 National Census will provide authoritative and geographically detailed estimates.

[2] Availability of LPG connections and supply has also been a constraint in much of the country.

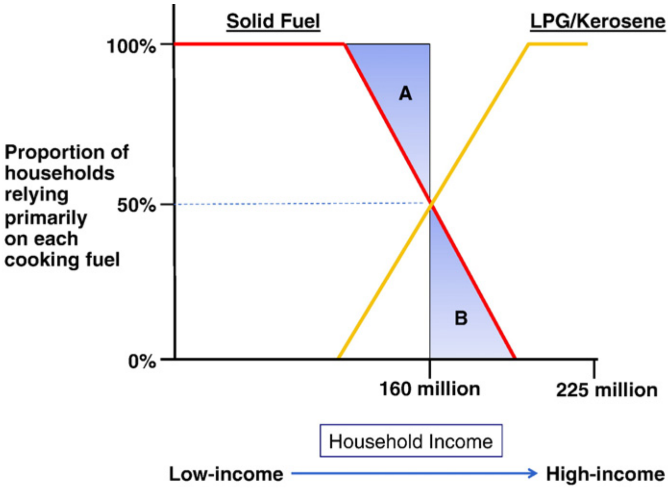

Fig. 2. Conceptual distribution of cooking fuel use in India by household income. Note transition area between 100% biomass and 100% LPG where households use some of each. According to Table 1, about 160 million households report that they mainly use biomass, but millions more use biomass at least part of the time. We use 160 million stoves for our calculations, which assumes that the lower impacts in area A roughly equal the extra impacts in area B.

to the shaded area A in the figure is roughly matched by the extra impacts in area B. As a real program proceeds, however, some of the early adopters are likely to be those in the transition zone where the benefits per stove are less than for households using only biomass.

Currently dominant biomass energy technologies for cooking in households and institutions are largely traditional *chulhas*, i.e., mud stoves along with some metal, cement and pottery or brick stoves, normally with no operating chimneys or hoods. They have low thermal efficiency, i.e., poor extraction of energy contained in the fuel and significant emissions of pollutants which have negative impacts on human health in the households, regional air pollution, and climate.

India's previous national stove program, the National Program on Improved Chulhas (NPIC: 1985–2002) aimed to achieve fuelwood conservation and, secondarily, smoke reduction in kitchens through use of chimneys. It resulted in the development of more than 60 designs of natural draft fixed and portable models of improved *chulhas* for family, institutional and commercial applications. Total installations under this program reportedly reached 35 million units (MNRE, 2004). Independent evaluations of the program, however, questioned the success in meeting its objectives largely because of the low durability, usage, and performance of the stoves in the field. The program was discontinued in 2002. Many of the concerns centered on stove design – the emphasis was on use of materials and skills available in rural India and production at the cheapest cost – as well as the delivery and maintenance approaches used in NPIC. In fact, independent studies revealed that NPIC “improved” stoves often had higher emissions than traditional stoves and similar efficiency (Smith, 1989). The NPIC also relied on government subsidy-based delivery mechanisms without provision of maintenance/repair services, leading to poor user adoption rates of the delivered technology (Kishore and Ramana, 2002). In addition, there was little formal monitoring of the use and performance of stoves in practice, thus making it difficult both to objectively evaluate the program's achievements and to develop needed mid-course corrections in stove design and dissemination methods (Parikh et al., 1999).

Therefore the unmet challenge of delivering clean cooking energy for the poor continues to loom large. Given the projected dominance of solid biomass as the cooking energy source for a majority of Indians, there remains the need for ensuring the availability of stove technologies that can deliver truly superior performance, both in terms of thermal efficiency and emissions as well as effective delivery mechanisms.

Recent years have seen the emergence of newer and significantly improved stove designs as well as dissemination programs in the country, funded mostly through private initiatives, which, while innovative, have resulted only in limited penetration. But it is becoming clear that improved biomass stoves can provide air pollution (local and global) and health performance that was not imaginable two decades ago. We also have the benefit of learning – in the areas of technology design and innovation, delivery approaches and models, program monitoring and evaluation – from the various improved cookstoves schemes in India and other parts of the world over the past 30 years.

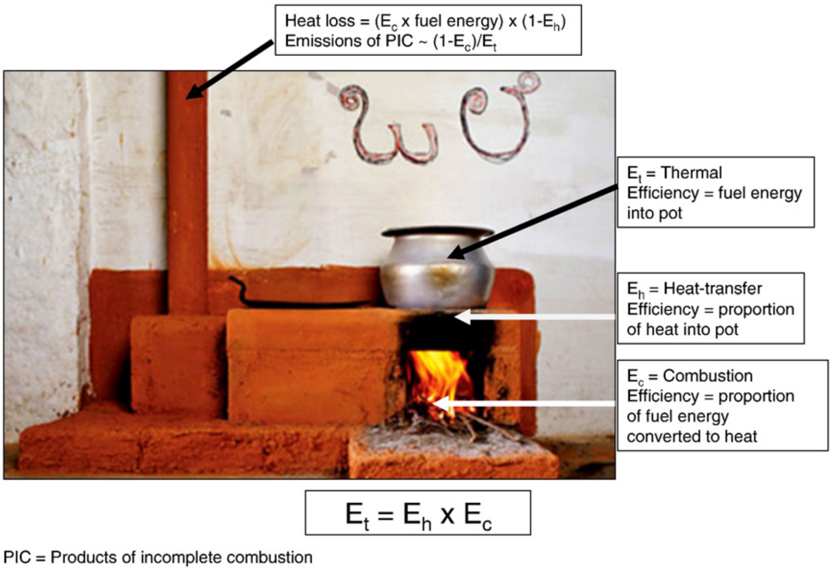

Fig. 3. Stove efficiencies and their relationships. Note that emissions are a strong function of combustion efficiency, but only a weak function of thermal efficiency and heat-transfer efficiency. A 5% increase in combustion efficiency, from 90% to ~95%, for example, would decrease total emissions of products of incomplete combustion by about 50% while increasing overall stove energy efficiency by only about 5%. See Smith (1995).

Table 2

Stove emissions (g/kg fuel) from laboratory tests using the water-boiling test to determine emissions biomass fuel types in Indian stoves. Also shown are the emissions for LPG stoves, the comparison used in this paper. Note actual emissions depend also on the thermal efficiency, i.e., how much fuel is used per meal. See Table 3.

Stove/fuel	Pollutant emission factors (g/kg)							
	Short-lived pollutants					Long-lived pollutants		
	CO	NMVOC	PM	BC	OM	CO_2	CH_4	N_2O
BBS/wood	69 ± 15[a]	7.0 ± 3.0[b]	3.2 ± 2.0[c]	0.60 ± 0.15[d]	2.8 ± 2.5[d]	1358 ± 43[b]	5.0 ± 4.0[b]	0.09 ± 0.09[b]
BBS/Agri. Res.	65.6[e]	8.5[e]	6.3 ± 2.9[e,f]	0.60 ± 0.23[f]	4.6 ± 3.3[f]	1302[e]	7.6[e]	0.050[e]
BBS/Dung	39.9[e]	24.2[e]	3.0 ± 1.9[e,f]	0.12[f]	2.5[f]	1046[e]	4.5[e]	0.30[e]
BBS/Coal	275.1[e]	10.5[e]	17.9[g]	5.42[g]	8.78[g]	2411[e]	7.9[e]	0.24[e]
Liquefied Petroleum Gas	14.9[e]	18.8[e]	0.32 (0.51–0.20)[e,f]	0.010[d]	0.080[d]	3085[e]	0.050[e]	0.15[e]

[a] (Smith et al., 2000a,b; Jetter and Kariher, 2008; MacCarty et al. 2008); USEPA number reported in Jetter's paper, Emission factors are averaged for traditional mud stove, 3-Rock stove (Smith et al., 2000a,b) and three stone fire (MacCarty et al., 2008; Jetter and Kariher, 2008; USEPA).

[b] (Smith et al., 2000a,b; Jetter and Kariher, 2008; MacCarty et al., 2008); Only the emission factor for acacia wood combustion in traditional stove has been considered because eucalyptus are not used much for cooking purpose.

[c] (Habib et al., 2008; Jetter and Kariher, 2008; MacCarty et al., 2008).

[d] (Habib et al., 2008) — low and high burn rates, (MacCarty et al., 2008) — 3stone fire.

[e] (Smith et al., 2000a,b) ; In case of agricultural residue emission factors mustard stalk combustion in traditional mud stove has been used. Rice straw has not been chosen because it is mostly used to feed cattle and only about 2–5% of total generated waste is used as fuel (Ravindranath and Hall, 1995).

[f] (Habib et al., 2008) (mustard, tur, cotton, soybean, jute stalks); dung.

[g] (Zhang et al., 2000; Zhi et al., 2008) No studies report emissions from Indian coal, emission factors reported here are for Chinese coal.

This is the context that led to the emergence of the ambitious new NCI. It is important to emphasize at the start that the major technical distinction between the new national program and the old NPIC is the dominating focus on combustion efficiency in the NCI, i.e., avoiding the generation of the pollution in the first place and not just moving it to the outside of the house through a chimney.

The rest of this paper presents the estimated impacts of current patterns of traditional stove and fuel use in the country in terms of pollutant emissions, health, energy, and climate and hence the benefits that would be available through the implementation of the NCI. We also briefly discuss the performance of recently introduced advanced biomass cookstoves in India that provide intriguing but not yet conclusive evidence that such stoves can potentially achieve the stated goal of the NCI, i.e., performance similar to LPG stoves but without reliance on a costly imported non-renewable fuel. How to potentially develop such advanced cookstoves and deploy them widely will be the subject of the companion paper mentioned earlier.

3. Performance of traditional biomass stoves

As shown in Fig. 3, a cookstove's performance can characterized by three processes: combustion efficiency: how much of the energy and carbon in the fuel is converted to heat and carbon dioxide; heat transfer efficiency: how much of the heat is absorbed by the pot; and overall thermal efficiency: how much energy in the fuel is absorbed by the pot (the product of multiplying the first two efficiencies together). Overall thermal efficiency can be improved by working on either combustion or heat transfer efficiencies, but the easiest and biggest improvements come from the latter, which, therefore, was the focus of most efforts to improve stoves in India and elsewhere in the past. Pollution emissions, on the other hand, are most strongly influenced by changes in combustion efficiency. Typical traditional biomass cookstoves in India, for example, achieve combustion efficiencies of 84–94% meaning that 6–16% of the energy in the fuel is not converted to heat, but retained in a large range of products of incomplete combustion (PICs) (Smith et al., 2000a). Small changes in combustion efficiency, e.g. from 90% to 95% which would have relatively small impact on the amount of fuel left unburnt but have large impacts on emissions. Put most simply, recent advanced cookstove technologies generally try to go beyond earlier approaches in that they now also aim to achieve high combustion efficiencies, i.e., convert almost all the energy in the fuel to heat, leaving only a small production of PICs. Only in this way can the full set of health, energy, pollution, and climate benefits be achieved.

As in the smoke from tobacco, another form of biomass combustion, there are hundreds of chemicals in biomass fuel smoke with many different kinds of toxic properties (Naeher et al., 2007). In common with tobacco smoke, however, it is thought that most of the toxic nature of the smoke mixture can be encapsulated by the levels of just two constituents: the gas, carbon monoxide (CO), and fine particulate matter ($PM_{2.5}$: particles small enough – less than 2.5 μm –

Table 3

Emissions per day for major current and advanced stove/fuel combinations taking into account stove thermal efficiency. Assumes 11 MJ/day delivered to the cooking vessel as the mean usage in India, which of course actually varies by food type, household size, and other factors. Based on NFHS data (IIPS, 2007) on fuel use and NSSO data (NSSO, 2006) on national mean rural food consumption.

Stove/fuel	Thermal efficiency (%)	g/stove-day							
		Short-lived pollutants					Long-lived pollutants		
		CO	NMVOC	PM	BC	OM	CO_2[a]	CH_4	N_2O
BBS/wood	18	264 ± 57	27 ± 11	12 ± 8	2.3 ± .6	11 ± 9.5	778 ± 25 519 ± 16 259 ± 8.2	19.1 ± 15.3	0.34 ± 0.34
BBS/Agri. Res.	11	410	53	39 ± 18	3.8 ± 1.4	29 ± 21	0	47.5	0.31
BBS/Dung	10.5	348	211	27 ± 17	1.1	22	0	39.3	2.61
BBS/Coal	14.3	784	30	51	16	25	6870	22.5	0.68
Liquefied Petroleum Gas	57	6.3	7.9	0.13	0.0042	0.034	1290	0.021	0.063

[a] $\%NRB_{wood} = (15\%, 10\%, 5\%) \pm 1$Std.Deviation; $\%NRB_{ag.residue} = 100\%$; $\%NRB_{Dung} = 100\%$; $\%NRB_{Coal} = 0\%$; $\%NRB_{LPG} = 0\%$. See endnote vi for more details ± 1 Standard deviation (presented for fuel/stove combinations with > 3 sources).

to penetrate deep into the respiratory system), which is termed "tar" when coming from cigarettes. These thus are currently the main components of health-based performance measures of stoves.

Basic performance criteria for stoves include thermal and emissions performance. Thermal performance is expressed either as a thermal efficiency (ratio of the amount of useful heat for cooking to the heat contained in the fuel) or more simply as specific fuel consumption (kg of fuel burned per kg of food cooked), which, however, is situation/device specific. Emissions performance includes the emissions of pollutants per kg of fuel (or per unit of energy in the fuel, if one is comparing very different fuels) burned, typically for CO and PM. A key measure of combustion efficiency, or clean burning, is the CO/CO_2 ratio. Note that CO emissions do not bear a simple relationship to PM emissions, and therefore both pollutants need to be individually addressed. There is some evidence that while CO emissions bear a clear inverse relationship to combustion temperature, PM emissions are more strongly affected by mixing, with combustion-generated hydrocarbons condensing to form organic carbon, a major particle constituent, in low temperature flame regions.

Discussions of stove performance are commonly based on laboratory measurements. Although such tests are useful during the design phase of stoves and give some idea of comparative performance, studies in India and elsewhere (e.g., Smith et al., 2007) show they often do not indicate true performance in the field, i.e., at the population level in households where operator behavior varies from the ideal, fuels vary in composition and moisture, and cooking patterns vary according to local and family needs and by season. In addition, of course, stoves, like other devices, decay in performance over time, something that is not possible to replicate accurately in a lab.

Laboratory tests of cookstoves bear some similarity to those for other consumer devices, such as automobiles, which are not operated at constant load all the time, unlike many industrial devices. It is thus necessary to employ a standard use cycle for every test so that comparisons can be made in a repeatable manner even if the standard cooking (or driving) cycle is not completely representative of use in all situations. Development of one or more "Indian Cooking Cycles" is being considered as part of the National Cookstove Initiative.

In the last 25 years though, cooking tests have usually come to rely on a simple water-boiling test (WBT) with high and low power phases for simultaneous measurement of thermal and emissions performance, even if not all cooking actually involves the boiling of water in this manner. Unfortunately, reported results come from different laboratories that utilize test conditions that vary in amounts of water boiled, the length and definition of low and high power phases, the moisture content of the fuel, the use of a lid on the pot, the method of measuring emissions and other parameters, yet represent currently best available numbers.

Keeping these difficulties in mind, we review the performance of traditional stove/fuel combinations commonly in use in India, as well as those using coal in Tables 2 and 3. Since the field performance of improved stoves disseminated in the NPIC was found not to be significantly different from traditional U-shaped metal or mud *chulhas* (e.g., Ramakrishna et al., 1989), we treat them together to develop the performance baseline for traditional, biomass stoves (BBS) that are now used in India, reporting separately for three major biomass fuels — wood, crop residues, and dung. The performance of LPG stoves is shown for comparison.

Emissions in Table 2 are presented per unit mass of fuel used, while those in Table 3 are stated as the total per day assuming standard cooking practices, which accounts both for variations in thermal efficiency and emissions per kg of fuel. The former is best used to determine total emissions if fuel-use data are available and the latter to estimate the benefit from a switch from one stove to another with the same cooking requirements.

As tabulated in Table 4, with the assumption that an ABS can be developed for all major biomass types (wood, crop residues, dung) that will be no more polluting in health terms than LPG stoves, a fully implemented NCI using such an ABS would result in the annual reduction in CO and particulate emissions of about 18 and 1.1 million tonnes (MT), respectively. These are not insignificant nationally, being perhaps 25% of total national outdoor emissions of these pollutants (IIASA, 2005).

4. Health impacts and benefits

Nearly all research and policy related to the health risk of air pollution focuses on ambient air pollution in urban areas. Most people in India, however, still breathe in rural areas and will do so for some decades to come. In addition, the pollution levels inside solid-fuel-using households are many times higher than typical outdoor levels, even those in highly polluted Indian cities. A method to estimate the burden of disease (premature death and illness) from household fuels was proposed in 2000 (Smith, 2000) and then utilized as part of the large international Comparative Risk Assessment (CRA) study of the World Health Organization (Ezzati et al., 2004). This remains the only international risk assessment using common databases, rules of evidence, calculation procedures, extensive peer review and other quality-control procedures to assess the burden of ill-health in a systematic way across a wide range of risk factors, including indoor and outdoor air pollution and other environmental risk factors, but also non-environmental risks, such as malnutrition, unsafe sex, high blood pressure. Thus, it provides policy makers a more unbiased assessment of the potential for health improvements across a set of possible interventions, both in and out of the health sector per se.[3]

Close to 3 million premature deaths globally were attributed in 2000 to combustion particle exposures in occupational, indoor, and outdoor environments in the CRA, mainly fossil and biomass fuels and passive tobacco smoking (not counting active smoking). More than half of this toll was due to solid fuel use in households. Most of the impact occurs in developing countries, a significant fraction in young children. The Indian portion of the burden of disease from household solid fuels found it was the third highest risk factor nationally behind malnutrition and unsafe water/sanitation, accounting about 420,000 annual excess deaths (Smith et al., 2004). This was for the year 2000 when the percent of households using solid fuels was estimated at 81% based on the census.

In 2009, the methods used in the CRA were applied to determine the health benefits in India of a major national cookstove program that would introduce 150 million advanced biomass stoves in 10 years, 2010–2020 (Wilkinson et al., 2009). This was part of a series in the health journal, *Lancet*, on co-benefits — projects that achieve both climate and health benefits (Haines et al., 2009). The input data were updated to reflect projected solid fuel usage, household size, population distributions, and background disease rates for this period in India. It thus represents a more realistic scenario than a hypothetical 100% instantaneous intervention (such as that assumed in Tables 4 and 5 in this paper). It showed that about 2.2 million premature deaths could be avoided over this period in the country and that the reduction in health burden in 2020 (measured in lost healthy life years) would be equivalent to about half the total national cancer burden projected that year, although the benefits would accrue mostly in the form of less pneumonia in young children and chronic lung and heart diseases in women. The calculations of health benefit are parallel to those used here, i.e., in comparison to a stove with LPG-like emissions characteristics.

Here, to put the health benefits in the framework set out at the start of the paper, i.e., the annual impact of not having LPG stoves for everyone, we adjust the model used in the *Lancet* article (Wilkinson et al., 2009) to estimate the attributable burden in 2005 due to

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[3] The international CRA is now being updated for publication in early 2011. See http://www.who.int/healthinfo/global_burden_disease/GBD_2005_study/en/index.html.

Table 4
National emissions from current stoves in India based on distribution of full time stove equivalents in 2005 from Table 1 and emissions per day in Table 3. Assumes 365 days of cooking/year.

Stove/Fuel	Million stoves	Annual Emissions							
		Short-lived pollutants					Long-lived pollutants		
		CO (MT/year)	NMVOC (MT/year)	PM (kT/year)	BC (kT/year)	OM (kT/year)	CO_2[a] (MT/year)	CH_4 (kT/year)	N_2O (kT/year)
BBS/wood-charcoal	110.5	10.6 ± 2.3	1.08 ± 0.46	493 ± 308	92 ± 23	431 ± 385	31.4 ± 1.0 20.9 ± 0.7 10.5 ± 0.3	770 ± 616	13.9 ± 13.9
BBS/Agri. Res-straw/grass/ shrubs.	20.7	3.1	0.40	297 ± 137	28 ± 11	217 ± 156	0.00	359	2.4
BBS/Dung	23.9	3.0	1.8	231 ± 145	9.1	190	0.00	343	22.8
BBS/Coal	4.3	1.2	0.047	80.1	24	39	10.9	35	1.1
Liquefied Petroleum Gas	56	0.15	0.18	3.1	0.10	0.78	30.2	0.49	1.5
Total	215[b]	18.1	3.6	1104	154	879	72.5	1508	41.6

BBS stands for "baseline biomass stove" and represents a traditional chulha or equivalent.

[a] $\%NRB_{wood} = (15\%, 10\%, 5\%) \pm 1$Std.Deviation; $\%NRB_{ag.residue} = 0\%$; $\%NRB_{Dung} = 0\%$; $\%NRB_{Coal} = 100\%$; $\%NRB_{LPG} = 100\%$.

[b] Plus 10 million households using kerosene, electricity, biogas, or "other" fuels. ± 1 Standard deviation (presented for fuel/stove combinations with > 3 sources).

household solid fuel use. Unfortunately, available health studies do not allow a distinction of the risk among the different solid fuel types. Thus, most risk assessments treat all equally, except that coal use is also assigned a risk for lung cancer. In reality, however, it can be expected that the health impacts of biomass fuel vary with emissions and exposures. Thus, here, we calculate the total impact in this fashion, but parse it out in rough fashion among the different biomass fuel types according to the emissions of PM per day, as shown in Table 3. To be done in detail, however, one would need to know the relative family sizes, background disease rates, and household types of the different fuel groups to enable this to be done more precisely. The results are shown in Table 5 in two metrics – premature deaths and percent of the national burden of disease in terms of lost healthy life years (DALYs). It shows that, in 2005, roughly 570 thousand premature deaths and 3.2% of the national burden of disease could be attributed to household fuel use. Of this, woodfuel accounted for about half. This was the health burden of not having LPG-quality combustion for all Indian households and therefore a move to clean cookstoves with emissions performance equivalent to LPG stoves will mitigate this health burden.[4]

5. Fuelwood conservation and energy security

As shown in Table 1, in 2005, biomass was the primary cooking fuel for 69% of Indian households with coal accounting for an additional 2%. Although Table 1 divides the total into the different biomass types, many households use multiple fuels depending on their availability — for instance, after harvest, crop residues are used extensively till they are exhausted, after which they revert to using wood. As noted above, many households also use multiple cooking devices such as kerosene or LPG stoves, in addition to biomass stoves, and no current surveys adequately capture this information, leading to uncertainty in the fuel-use estimates. A more accurate approach, therefore, is to interpret the 69% as the average percent of meals cooked daily with biomass in the country, but actually involving over the year more than 69% of households. See Fig. 2.

Using current data on food consumption and household size, Habib et al. (2004) estimated a mean end-use energy need of 11 MJ (stove-day)$^{-1}$ for cooking in India. The amount of biomass (wood and crop residues) needed in a BBS used for all cooking was estimated as 4 kg day^{-1}, with an efficiency varying from 11 to 18% depending on biomass type. To determine the maximum savings in Table 5, a mean efficiency of 47% was assumed for all biomass use, which is the best measured for gasifiers and rocket stoves (Jetter and Kariher, 2008). Thus, if fully implemented, the NCI could achieve a total fuel savings of about 196 MT solid fuel per year, including 95 MT of wood and 6 MT of coal. See Table 5. This reduced demand for biomass, especially fuelwood, may have benefits in terms of conserving village trees or forests.

Of interest to energy security is the offset of LPG imports with clean biomass fuels. Offsetting 1 MT y^{-1} of LPG consumption would need 4.3 MT y^{-1} of biomass fuels combusted in advanced stoves. The offset of LPG using advanced biomass stoves is most likely to occur in institutional cooking, but as shown recently with the introduction of advanced biomass stoves, some households may also switch back to ABS if the advanced stoves are nearly as convenient to use and save money. As the Government now subsidizes domestic LPG quite heavily — in 2008–2009, the domestic consumption of LPG was about 12.3 million tons, translating to about US$4 billion (Rs.17,600 crores)[5] in subsidies (GOI, 2010) — there is a financial advantage in moving people away from or delaying the movement to LPG. There is also a climate advantage of moving away from fossil fuel to renewable biomass, but there may actually be a slight health and regional environmental penalty unless ABS are actually as clean as LPG.

6. Climate and regional pollution co-benefits

Several pollutants in biomass smoke are also climate active. The most important are nitrous oxide and methane, both well-understood greenhouse gases with much higher global warming potentials per tonne than CO_2 (Smith et al., 2000b). CO and the entire mixture of non-methane volatile organic compounds (NMVOCs) in biomass smoke also act as indirect warming agents (Solomon et al., 2007). The particles in biomass smoke are climate active, but the extent of warming depends on the ratio of black (warming) to organic (lighter-colored and cooling) particles in the smoke, which varies substantially by combustion conditions but the mechanism is still not well understood. Finally, although not major sources worldwide, there are sufficient emissions of sulfur and nitrogen oxides from biomass combustion to produce some cooling from the sulfate and nitrate particles created downwind.

The CO_2 produced by biomass stoves in which the fuel is harvested renewably, for example as crop residues or dung, does not contribute to global warming. The CO_2 from burning wood that was not harvested renewably (leading to deforestation) or from coal, which is used for cooking by about 20 million people in eastern India, does contribute to warming, however. Here, we assume a 10% non-renewability for wood

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[4] Studies of the cost-effectiveness and cost-benefit for health of improvements show attractive results, even without considering the current generation of advanced-combustion stoves (Hutton et al., 2007; Mehta and Shahpar, 2004).

[5] The exact size of the subsidy varies with fluctuations in global prices.

harvested in India, but recognizing that this is quite uncertain, we have provided calculations for 5% and 15% as well.[6]

Biomass smoke thus has constituents with quite different modes of action on the climate that act over significantly different time spans (days to centuries). In addition, the impact of many of these pollutants depends on local conditions, including season, sunlight, clouds, and altitude as well as complex interactions among them. Also the emission factors for most of the climate-active constituents are poorly measured even in lab conditions, let alone with real households and fuels. Finally, climate models to estimate impacts of some of the constituents, particularly the particles, are still evolving. As a result, the relationship of household biomass combustion to global warming is difficult to pin down with accuracy at present and depends on the future time period considered, among other factors.[7]

Whether cooling or warming, however, the particles from biomass combustion contribute to regional air pollution. Partly due to household combustion from rural households, the outdoor particle levels even far from cities, e.g. in the Ganga River Basin substantially exceed WHO guidelines to protect health (Nair et al., 2007). In addition, particle pollution over South Asia is responsible for significant blockage of sunlight, so-called "surface dimming", which affects agricultural production (Chung et al., 2010). Heavy particle pollution in South Asia is thought by some observers to affect monsoon rainfall (Ramanathan et al., 2005). Finally, the deposition of black carbon particles onto snow and ice in the Himalayas may be associated with accelerated melting of glaciers that would eventually have significant hydrological impacts in the region (Ramanathan and Carmichael, 2008).

The methane, NMVOCs, and CO from household fuels are also contributors to the rise of regional tropospheric (ground-level) ozone levels. In addition to being a powerful greenhouse gas, ozone damages human health, ecosystems, and agriculture (West et al., 2006). Cookstoves are not a small contributor to ozone levels — one estimate put their contribution of ozone precursors as one-sixth globally and perhaps one-quarter in South Asia and their contribution to carbon monoxide emissions as one-third globally (Unger et al., 2006).

Table 5

Annual attributable impacts of not having household combustion equivalent to LPG for all Indian households in 2005. Only greenhouse gases with official global warming potentials are included: CO_2, CH_4, and N_2O. Others, such as black carbon, carbon monoxide, and volatile organic compounds, are not included, nor are cooling agents such as organic carbon aerosols, sulfates, and nitrates from household fuels.

Stove/fuel	Lives lost[a] (Thousands)	Percent of national burden[a]	Fuel saved[b] (MT)	CO_2-eq emissions reduction (MT)[c]	Percent reduction of national GHG emissions[d]
BBS/wood	225	1.4%	95	43.5	2.2%
BBS/Agri. Res.	154	0.9%	36	9.5	0.5%
BBS/Dung	119	0.7%	59	15.2	0.8%
BBS/Coal	41	0.2%	6.1	12.0	0.6%
Total	570	3.2%	196	91 (15%NRB) **80** (10%NRB) 70 (5%NRB)	**4.1%**

[a] The calculation is based on the methods and risk factors from the Comparative Risk Assessment published by the WHO (Ezzati et al., 2004), which calculated the impacts for 2000. Here, we update using the WHO database for background diseases in India for the year 2004, the latest available.

[b] Assuming 47% thermal efficiency in advanced biomass stoves, except for coal where the total annual consumption is reported (all coal assumed to be replaced by renewable biomass).

[c] Difference between CO_2-eq emitted under BBS scenario and the CO_2-eq emitted from the same number of stoves under LPG emissions parameters of CH_4, PM, and N_2O and 100% renewable biomass. Current non-renewable biomass as woodfuel (NRB_{wood}) = 10% (as well as 15% and 5% for comparison); $\%\text{NRB}_{\text{ag.residue}} = 0\%$; $\%\text{NRB}_{\text{Dung}} = 0\%$; $\%\text{NRB}_{\text{Coal}} = 100\%$. Considers only Kyoto gases (CO_2, CH_4, and N_2O) using 2007 IPCC 100-year GWPs of 1, 25, 298, respectively. (Solomon et al., 2007).

[d] Indian 2005 national GHG emissions for CO_2, CH_4 and N_2O of 1234.8, 26.1, 0.23 MT from CAIT 7.0, 2005 (WRI 2010). We applied the updated GWPs as noted above to obtain the national CO_2-eq value.

Although difficult to fully quantify, it is nevertheless fair to say that improved household combustion will likely decrease global warming and will certainly benefit the atmosphere and other environments of South Asia. It is not appropriate here, however, to attempt to evaluate the various climate and regional pollution models that attempt to be more precise about the impacts. We can, however, do so for the three important greenhouse gases, nitrous oxide, methane, and CO_2, which, unlike all the other climate active pollutants in biomass smoke, are longer lived, more well characterized, and already included in international agreements such as the Kyoto Protocol, official national and other inventories including those of India, and carbon trading regimes including the Clean Development Mechanism (of the Kyoto Protocol) in which India participates.

At present, black and organic carbon, sulfates, nitrates, CO, and NMVOCs, are not included in such international efforts. Thus, even if we were able to derive climate-impact estimates for these pollutants from Indian stoves, until such estimates were done in the same way for all other emission sources to obtain full inventories, we would not be able to compare them with anything.

Based on the annual emissions in Tables 4 and 5 shows the total global warming committed from Indian solid-fuel stoves in 2005 for three relevant Kyoto GHGs. The nitrous oxide and methane commitments are what was emitted above what would have occurred if the same cooking was done with LPG — consistent with the framing of the NCI and the way health effects were calculated, i.e. net of LPG combustion. For CO_2, however, the assumption is that the alternative would be renewable biomass, in other words that there would be no net-CO_2 emissions. The CO_2 emissions shown, therefore, are the difference between cooking done with partly non-renewable woodfuel compared to completely renewable woodfuel. This assumes that the large savings in biomass fuel use described above would be sufficient to move all woodfuel into the renewable mode. For coal,

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[6] A preliminary estimate of Non-renewability of Biomass (NRB) in India was used to estimate annual CO_2 emissions and potential savings under the ABS scenario using standard methods as recommended by FAO (see Ghilardi et al., 2007 for the application of this method to Mexico). NRB is defined as the percent of woodfuel that is harvested on a non-renewable basis. Assumptions of woodfuel demand and supply were based on current and relevant literature and the advice of Omar Masera of the National University of Mexico, expert in such assessments. In some cases, literature was not available for local parameters used to calculate woodfuel supply (e.g. accessibility), in such cases we reviewed the data from similar studies in other countries (Ghilardi et al., 2009) and applied optimistic estimates to err on the side of higher renewability.

Woodfuel Supply (140MT/yr):

Standing wood biomass (dead wood + above ground biomass): 4700MT (FAO, 2006).
Biomass growth rate: 5%/yr
Fraction of biomass growth that could be used as fuel (e.g. no leaves, and leaving some biomass for conserving soil carbon): 70%
Accessibility: 85%
4700MT * (5%/yr) * (85%) * (70%) = **140MT/yr**

Woodfuel Demand from Cooking (154 MT/yr): Current woodfuel demand for cooking was estimated for this study assuming 11 MJ/day delivered (estimated from NSSO, 2006), 365 days/yr of stove use, 18% thermal efficiency of the stove (Jetter and Kariher, 2008; Smith et al., 2000a), 110.5 million wood stoves (IIPS, 2007), and 16 MJ/kg as the energy density of wood. To be clear, we estimate the wood demand from cooking only, and do not consider wood demands from small industry which would contribute significantly to total demand. Our estimate of 154 MT/yr is low relative to previous estimates for cooking wood demand in India but do not include wood for community/institutional cooking or shrubs, which are sometimes included in other estimates. For example, estimates by Habib et al. (2004) fell in the range of 182–432 MT/yr, 28 MT/yr greater at the lower end of the range than this study's estimate.

%NRB = (demand − supply)/supply = (154MT − 140MT)/140MT = 10%

[7] For a discussion of some of these issues in the context of household fuels, see Bond et al. (2004).

the CO_2 is the total CO_2 emitted with the assumption that it would be substituted by renewable biomass (wood or other) burned in advanced stoves.

The tonnes of nitrous oxide and methane are multiplied by the most recent global warming potentials (GWPs) provided by the IPCC (Solomon et al., 2007) and added to the mass of CO_2 emitted to determine the total tonnes of CO_2-equivalent as explained in the footnotes to the table. GWPs are weighting factors from IPCC that allow emissions of different longer-lived greenhouse gases to be combined together. No consensus (or broadly accepted) GWPs are or are likely soon to become available for the other climate-active pollutants in biomass smoke, partly because they are so short-lived as not to be globally mixed. Researchers nevertheless continue to evaluate the potential application of GWP and a global temperature change potential (GTP) to assess trade-off among multiple short-lived and long-lived pollutants including warming and cooling agents (e.g. Boucher and Reddy, 2008; Shine et al., 2005)).

Based on data in Table 4, the total potential benefit of a fully implemented NCI in 2005 would have been reductions of 61.9, 1.5, and 0.042 MT annually of CO_2, methane, and nitrous oxide. As shown in Table 5, this amounts to 80 MT CO_2-eq per year or over 4% of India's total estimated GHG emissions (WRI, 2010). This assumes 10% non-renewability for woodfuel making the improvements in 110 million woodfuel stoves responsible for about 50% of the total CO_2-eq savings. In addition, it would reduce Indian black carbon emissions by about 0.15 MT annually, which is approximately one-third of the total national human-caused emissions of this pollutant.[8] Even with no credit for black carbon, an annual emission reduction of 80 MT of CO_2-eq is currently worth about US$1.4 billion annually on the international carbon market.[9] As indicated in Table 5, if only 5% of wood is found to be harvested non-renewably, the 70 MT of CO_2-eq reduced annually would still be potentially worth $1.2 billion annually. If tapped, therefore, carbon credits could go some distance toward funding a major stove program.[10]

7. Current advanced stoves: are they clean enough?

Currently there are two broad categories of ABSs – so-called “gasifier” stoves with two-stage combustion and improved one-stage burning using the so-called “rocket elbow” combustion chamber. As far as we know, these are the only varieties that are currently available, although with variations depending on whether using an electric blower and designed for using loose or processed biomass, such as pellets. See Box for tentative performance comparisons.

Before final assessments can be made, more systematic lab testing is needed using protocols and methods that are published in the scientific literature to assure reliability, accuracy, and repeatability. Furthermore, since little information is currently openly available about actual field performance, usage rates, sensitivities to fuel variation, need for fuel processing, or lifetimes of ABS in India, much work of this kind is needed as soon as possible. Particularly uncertain are the measurements of the important climate-related pollutants, methane, nitrous oxide, and black/organic carbon.

Importantly, of course, these few advanced stoves in India represent just a portion of those currently deployed worldwide. In at least two cases, however, they have had sales measured in the 100s of thousands in recent years, which provides considerable evidence of acceptability. In addition, although there are other ABSs operating elsewhere, we are not aware of any major ABS technologies other than gasifiers and rockets, which implies that overall performance may not be substantially different in other countries in the same price ranges. China, for example, has a number of gasifier stoves with chimneys being sold, both with and without blowers, which seem to perform quite well in carefully controlled lab settings, but are substantially larger, heavier, and more expensive than the current Indian models (Charron et al., 2010).

It is clear, however, that to meet the requirements of true “LPG-like” combustion, even greater emissions reductions will be needed than now achieved by available technologies. For example, perhaps a factor of 50 reduction in PM may be needed as opposed to the current best of around 20. Nevertheless, current advanced biomass stoves represent major improvement over those deployed in past improved stove programs.

Box

These highly tentative general conclusions about the performance of current ABS in India based on the extremely limited inventory of tests and our impression of other often-unpublished tests around the world are as below (comparisons with BBS on emissions per day):[11]

- Natural draft rocket stoves achieve a modest (2–3 fold) reduction in the emissions of key health-related pollutants; this is due mainly to changes in heat transfer rather than combustion efficiency (comparison in emissions per day, Table 3).
- Natural draft gasifiers burning loose biomass (wood) can currently achieve somewhat greater (5–6×) reduction in emissions.
- Stoves using uniform fuels (pellets made from crop residues, wood chips, corn cobs) perform better than ABS using loose biomass.
- Use of blowers can lead to greatly reduced emissions (10–20×), with more reliability using pellets or chips.
- CO and PM, and black carbon reductions often diverge, i.e., one changing more than the other.
- All stoves must be operated carefully according to their manufacturer's specifications to achieve good emissions performance.
- No ABSs seem yet to have been specifically designed for crop residues or dung, even though these fuels make up the primary cooking fuel for about 20% of all households.

8. A long and winding road

As summarized in Table 5, the NCI has the potential for significant direct developmental and environmental benefits through reduction in health damage, improved energy security and sustainability, and reduction in emissions of pollutants causing regional environmental damage and contributing to climate change. Therefore one must hope that this initiative is a full success; in fact, one could almost say that with such potential benefits, failure cannot be an option. But we also recognize that capturing a good fraction of these potential benefits will depend both on the ability to develop the next-generation of cookstoves that offer performance approaching that of LPG and deploying them widely to the target populations. In addition, very

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[8] This is lower than previous estimates published by two of us (Habib et al., 2004; Venkataraman et al., 2005). The difference in the two estimates is explained by the lower mean thermal efficiency of baseline biomass stoves and the higher fraction of wood use in the NFHS database of 1998–1999, used in the previous calculation. Both values lie within the large uncertainty band (factor of ~2.5) typical of such inventory calculations.

[9] Although variable and uncertain for the post-2012 period, the price of a Certified Emissions Reduction (CER) has typically been about 13 Euro/tonne of CO2-eq in recent years (CarbonPositive, 2010).

[10] Approaches to make this linkage have been explored for India (Reddy and Balachandra, 2006).

[11] Lab tests of Indian stoves are reported in IISc (2008), Jetter and Kariher (2008), and Mukunda et al. (2010). MacCarty et al. (2008) and MacCarty et al. (submitted for publication) have carried out a comparison of different stoves across the world using a somewhat different protocol than those used by others.

careful testing, certification, and field performance monitoring will be needed — "you don't get what you expect, but what you inspect." (Smith, 2007). These technology development and deployment challenges are not trivial but we believe also not insurmountable, especially if we build on the lessons from the broad arena of technology innovation as well as recent initiatives in the cookstoves arena by corporate organizations, foundations, and NGOs. The key elements of a program designed to meet the goals of this initiative will be discussed in a forthcoming companion paper. Experience tells us that it will be a long and winding road for this initiative but it will be a one worth travelling.

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