

# GREENHOUSE IMPLICATIONS OF HOUSEHOLD STOVES: An Analysis for India

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■ **Abstract** It is commonly assumed that biomass fuel cycles based on renewable harvesting of wood or agricultural wastes are greenhouse-gas (GHG) neutral because the combusted carbon in the form of CO<sub>2</sub> is soon taken up by regrowing vegetation. Thus, the two fifths or more of the world's households relying on such fuels are generally not thought to play a significant role in GHG emissions, except where the wood or other biomass they use is not harvested renewably. This review examines this assumption using an emissions database of CO<sub>2</sub>, CO, CH<sub>4</sub>, NMHC, N<sub>2</sub>O, and total suspended particulate emissions from a range of household stoves in common use in India using six biomass fuels, kerosene, liquefied petroleum gas, and biogas. Because typical biomass stoves are thermally inefficient and divert substantial fuel carbon to products of incomplete combustion, their global warming commitment (GWC) per meal is high. Depending on time horizons and which GHGs are measured, the GWC of a meal cooked on a biomass stove can actually exceed that of the fossil fuels, even if based on renewably harvested fuel. Biogas, being based on a renewable fuel and, because it is a gas, being combusted with high efficiency in simple devices, has by far the lowest GWC emitted at the stove per meal and is indicative of the advantage that upgraded fuels made from biomass have in moving toward sustainable development goals. There are a number of policy implications of this work, including revelation of a range of win-win opportunities for international investment in rural energy development that would achieve cost-effective GHG reduction as well as substantial local benefits.

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## INTRODUCTION

Humanity's first combustion device is still the most common today, the home hearth. In rural areas of developing countries, where about 40% of all people live, the household stove accounts for more than half of human energy use. In many of the poorest countries, 80% or more of all national fuel combustion occurs under cooking pots. In the early 1990s, nearly half the households in the world, mainly in rural areas and urban slums of developing countries, rely on unprocessed solid fuels (biomass or coal) for cooking and heating. Such fuel use has been shown to produce substantial health-damaging pollution and because of its ubiquity may be a significant contributor to the global burden of disease (1–3).

Solid household fuels probably account for only 10–15% of global energy use and thus do not often figure prominently in discussions of the fluxes of and means to reduce the greenhouse gas (GHG) contributions of human fuel use. In particular, the emissions from household use of biomass (wood, crop residues, and animal dung) are often ignored in such discussions because it is assumed that as long as biomass fuel cycles rely on renewable harvesting they are GHG neutral. Indeed, essentially all dung and crop residues and a large portion of the wood is harvested on a sustainable basis globally and thus the carbon is recycled within a short period compared with climate change processes.

Unfortunately, however, this picture is flawed. Simple stoves using solid fuels do not merely convert fuel carbon into carbon dioxide (CO<sub>2</sub>), which is then taken up by vegetation during the next growing season. Because of poor combustion conditions, such stoves actually divert a significant portion of the fuel carbon into products of incomplete combustion (PICs), which in general have greater impacts on climate than CO<sub>2</sub>. Eventually most PICs are oxidized to CO<sub>2</sub>, but in the meantime they have greater global warming potentials than CO<sub>2</sub> by itself. Indeed, if one is going to put carbon gases into the atmosphere, the least damaging from a global warming standpoint is CO<sub>2</sub>, most PICs have a higher impact per carbon atom. The policy implications of this diversion of carbon to PICs are profound.

The importance of biomass combustion in the global carbon cycle is well recognized, although compared with large-scale open burning, relatively few emission factor measurements are available for small-scale, semi-enclosed combustion (4, 5). To obtain an idea of the overall contribution of household stoves, therefore, it has been necessary to combine scattered measurements of one or a few gases at a

time, made using different methods by different investigators in different regions. Streets & Waldhoff (6) and Bhattacharya et al (23), for example, used this method to derive emission factors they could use to estimate inventories of GHG emissions from biofuel combustion in Asia. Such combining efforts were also used to develop the default GHG emission factors for household fuels in the country inventory handbook of the Intergovernmental Panel on Climate Change (IPCC) (7). Other investigators have examined emissions of health-damaging pollutants from different fuels and stoves, (e.g. 8–10). Of these, however, only carbon monoxide (CO) figures significantly in GHG calculations (11).

Until recently, however, no coherent data have been available from repeated simultaneous measurements of GHG emissions and fuel/stove parameters across a range of typical fuel/stove combinations used in developing countries, although a few such data are becoming available for related developed-country technologies (12). To derive valid policy recommendations for substituting, promoting, or discouraging actual stove technologies and fuels in developing countries, however, such data are needed. Estimates of global or regional averages, accurate or not, do not suffice for this purpose, although perhaps being adequate for determining national or larger-scale inventories.

This paper explores some of the implications of this diversion using a recently published database containing systematic emissions measurements of several important GHGs (CO<sub>2</sub>, CH<sub>4</sub>, CO, NMHC, and N<sub>2</sub>O) from household stoves in common use in India (13). As such, they do not directly represent fuel/stove combinations elsewhere in the developing world. Parallel measurements in China using fuel/stove combinations commonly in use there, however, indicate quite similar values (14). Between them, of course, India and China contain a large fraction (about half) of developing-country household stoves and thus represent a large sample of the whole. Here, we use the India database to explore some of the apparent policy implications, recognizing that locally specific analyses may be needed later in other parts of the world.

## THE DATABASE

Used here here are the results of tests with several stove types using 6 biomass fuels, kerosene, liquefied petroleum gas (LPG), and biogas—a total of 26 fuel/stove combinations (12).<sup>1</sup> Table 1 shows the breakdown of biomass stoves. Only one stove type was used with both LPG and biogas, although both kerosene wick and pressure stove were monitored.<sup>2</sup> Because energy and ultimate analyses were

<sup>1</sup>This database is available from the US Environmental Protection Agency at <http://www.epa.gov/crb/apb/publications.htm>

<sup>2</sup>The former cheaper device draws fuel through a multiple stranded wick with capillary action like a simple candle. The latter forces fuel from a tank pressurized using a hand-operated pump.

**TABLE 1** Fuels and stoves investigated (from Reference 13)<sup>a</sup>

Stove (abbreviation)	Wood <sup>b</sup>	Root	Crop residues <sup>c</sup>	Dung <sup>d</sup>	Description
Traditional mud (tm)	X 86.8%	X	XX 94.8%	X 58.8%	Simple u-shaped block of mud—most common biomass stove in India
Improved metal (imet)	XX 0.4%	X	X 0.5%		Portable 3-legged circular device with no flue
Improved vented mud (ivm)	XX 2.9%	X	XX 4.2%	X 4.7%	Most popular improved stove with flue (chimney)
Improved vented ceramic (ivc)	XX 0.3%		X 0.5%	X 0.5%	Ceramic combustion chamber with flue
3-rock (3-R)	XX 9.6%				Simplest stove design—often used by nomads and street dwellers
Hara				X 36%	Hollowed out mud-lined pit often used for long-term simmering of milk
Total national consumption-MT	200.5	negligible	61.8	53.5	Early 1990s

<sup>a</sup>X, fuel/stove combinations tested at least three times; XX, both biomass species in that category were tested three times; percentages are estimates of the amount of each fuel used nationally in each stove design.

<sup>b</sup>Two species tested: Eucalyptus and Acacia.

<sup>c</sup>Two types tested: mustard stalk and rice straw.

<sup>d</sup>Mixture of cow and water buffalo dung tested; camel dung is used in some areas.

done for all solids, including fuel, left-over char, and solid particle emissions [total suspended particulates (TSP)], along with simultaneous stove efficiency measurements, the database allows examination of emissions per unit fuel mass, fuel energy, and delivered energy as well as construction of complete carbon, energy, and mass balances.

We estimate that national cookstove kerosene in India is split roughly 54/46, respectively, between wick and pressure stoves, with a higher pressure-stove fraction in urban areas. The relative use patterns of biomass stoves and fuels are shown in Table 1, based on national fuel use surveys, data from the Ministry of Non-Conventional Energy Sources, and other sources (15). Although in the early 1990s some 15 million improved stoves had been disseminated, their lifetimes have been shown to be relatively short (16). Thus, we estimate that about 60% were still in operation, of which 10% were portable metal, 10% were improved vented ceramic, and 80% were improved vented mud. The remaining biomass is used mainly in traditional mud stoves, with about 10% of wood only thought to be used in three-rock stoves. Root fuels today are found only in the northwest and do not make up a significant percentage of the national totals (for more details, see 13). [In total, India had some 150 million households in the early 1990s (17).]

## INSTANT AND ULTIMATE EMISSIONS

Each of the three emissions experiments for each fuel/stove combination was done while performing a standardized cooking test, which consists of heating 2.2 kg of water from ambient temperature to boiling, followed by simmering (9). The carbon balance method (18, 19) was used to calculate GHG emission factors from measured ratios to CO<sub>2</sub> in the flue gas. We found, however, the need to break down the emission calculations into two parts. The first, called instant emissions, addresses the emissions during a particular test. The rate of these emissions is appropriate for estimating indoor or local pollutant concentrations. The second, called ultimate emissions, is an estimate of the ultimate emissions in typical household conditions in India from a unit of fuel and is most appropriate for determining GHG inventories or other large-scale impacts from fuel demand, such as acid precipitation. The two types of emissions differ only for the solid fuels that produce a significant amount of char at the end of a burn cycle. The calculation of each differs solely in the way the remaining partly charred fuel is handled.

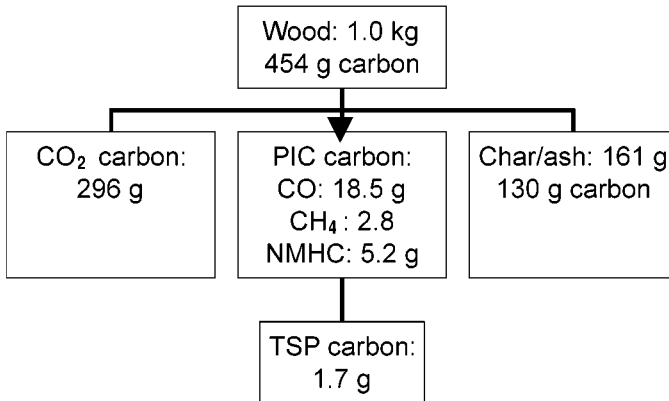
The instant emissions measured in a single experiment are specific to the conditions of the tests, but need modification to reflect actual field conditions when a significant amount of fuel carbon is diverted into production of low-quality charcoal in the root and wood stoves. In households, of course, this charcoal is usually not wasted, being either left in the stove to be burned along with fresh fuel at the next meal or extracted and stored for later use to cook a meal entirely with charcoal fuel. Both practices are common in India, but we have no data indicating the actual percentage breakdown.

Figure 1a shows a typical result for a wood-fired stove in this study, in this case Eucalyptus in the improved vented ceramic (ivc) stove, which tends to produce high charcoal yields. Note that a kilogram of wood produces 161 g of charcoal containing 130 g, or 29%, of the original carbon. The results shown are from the instant analysis. Included is the k-factor, defined as:

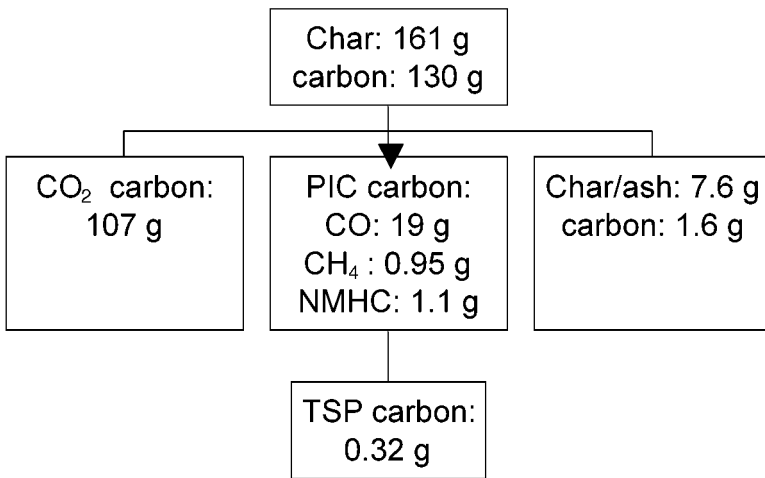
$$K = (\text{PIC})/(\text{PIC} + \text{CO}_2). \quad 1.$$

Calculated in terms of carbon, it represents the airborne fraction of carbon released as PIC, which is defined as all carbon in airborne emissions, including TSP.

Because this charcoal would be burned eventually in field conditions, however, these numbers cannot be used directly to calculate ultimate emissions. To handle this situation, we also measured the emissions from burning the low-quality charcoal produced in such stoves. Figure 1b shows the additional emissions that would result from burning the 161 g of charcoal produced from the original wood in Figure 1a. Note that the remaining char produced in this case contains less than 0.4% of the original carbon (1.6 g) in material that is only 20% carbon, i.e. too low to be attractive as fuel. It seems justifiable, therefore, to consider this as the solid carbon that becomes part of the disposed ash and char and is thus sequestered from the atmosphere, if not permanently, at least for long periods.



**Figure 1a** Instant carbon balance: eucalyptus in improved vented ceramic (instant k-factor = 0.095).



**Figure 1b** Carbon balance of char combustion after primary combustion (ultimate k-factor = 0.123).

The ultimate emissions per kilogram of wood in this case, therefore, are the total of those shown in Figure 1a,b. Note that compared with instant emissions alone, all the major emissions increase by roughly the same amount as the fraction of charcoal carbon compared with the fuel carbon, i.e. 20–30%, except for CO, which nearly doubles. The larger increase for CO reflects the dominance of char burning compared with flaming combustion because of charcoal's low volatile content compared with wood. In reporting emissions per unit delivered energy, we take the energy efficiency measured in the primary stove (the one using the original solid fuel) for the entire process because the practice of saving char for

use in a special charcoal stove is reported relatively rarely in India.<sup>3</sup> Only ultimate emissions are reported below.

## MEASUREMENT RESULTS

Confirming previous results of an earlier Manila pilot study (18, 19), the Indian database shows that solid biomass fuels are typically burned with substantial production of PIC. As shown in Table 2, some fuel/stove combinations diverted more than 20% of the fuel carbon into PIC. No biomass stove produced less than 5%. Kerosene, LPG, and biogas, however, were all burned with more than 99% combustion efficiency. Some typical carbon, energy, and mass balances of a few of the key fuel/stove combinations are shown in Figure 2.

As shown in Table 3, the default emission factors recommended by the IPCC (7) for residential fuel use generally lie within the range of values found in this database for various biomass-stove combinations in India. Compared with those for kerosene and LPG, however, the IPCC values for household use of "oil" and natural gas, however, are substantially lower for CO, NMHC, and N<sub>2</sub>O, and are similar for methane (13). These differences indicate that the IPCC values are probably not suitable for use with these cooking fuels, at least under Indian conditions. Being overall means of gross fuel types (dung and crop residues, for example, are grouped together) and not specifying stove types or efficiencies, of course, IPCC values cannot be used by themselves to examine the kind of technology and fuel-specific trade-offs being considered here.<sup>4</sup>

As has often been shown in the past, biomass stoves usually have substantially lower thermal efficiencies than those using liquid and gaseous fuels. As a result, the total CO<sub>2</sub> and PIC emissions per unit delivered energy are substantially greater in the biomass stoves, as listed in Table 4. In general, the ranking follows what has been called the "household energy ladder" from lower to higher quality fuels, i.e. emissions decrease and efficiencies increase in the following order: dung, crop residues, wood, kerosene, gas. There are important variations, however, depending on specific stove designs.

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<sup>3</sup>This assumption only affects emissions estimates from wood and root fuels, which leave significant char residues. The simple charcoal stove used in India has an efficiency of about 17.5%, which is at the lower end of the range of wood and root fuel stoves (13). If its efficiency were applied to char combustion instead of the primary stove efficiency, the resulting emission estimates would rise for all stoves except one (Root-tm), for which it would decline by only 5%. Thus, this assumption is conservative with regard to GHG emissions.

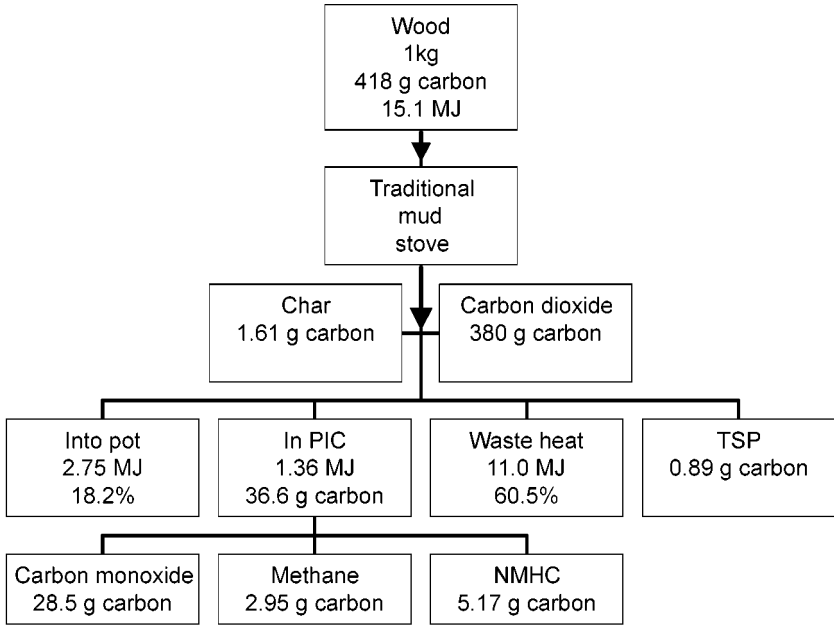
<sup>4</sup>A review by Streets & Waldhoff (6) of biomass measurements reported in References 5, 7, 19–22 and a conference paper presenting early results from Reference 13 found measurements nearly within the ranges found in Reference 13. A similar review by Bhattachayra et al used these same references and a number of unpublished reports to update these estimates (23).

**TABLE 2** Ultimate carbon balances (grams carbon based on 1.0 kilogram fuel input). Ultimate k-factors, nominal combustion efficiencies (NCEs), heat transfer efficiencies (HTEs), and total energy efficiencies (TEE) are also shown

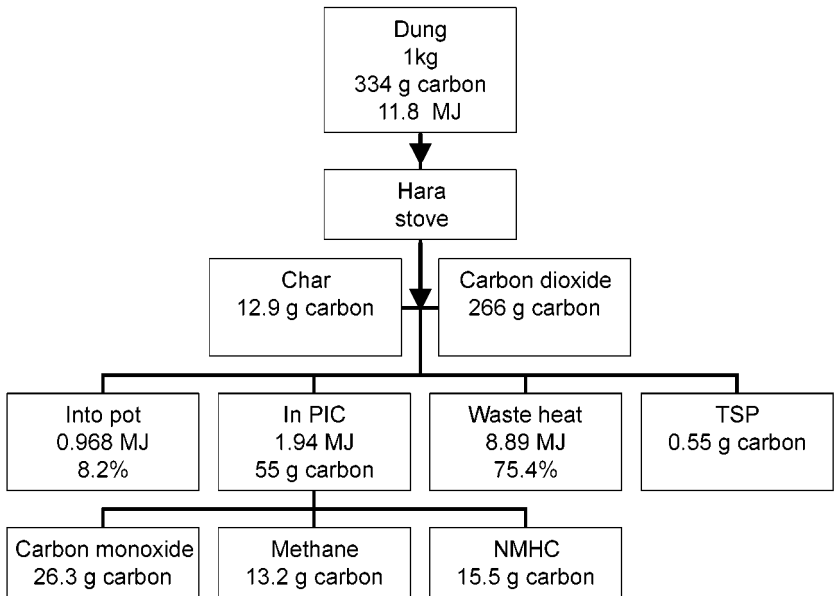
Fuel/stove <sup>a</sup>	Fuel g-C	Char/ ash g-C	CO <sub>2</sub> g-C	PIC g-C	TSP g-C	k-factor	NCE	HTE	TEE
Biogas	396	0	393.8	1.97	0.247	0.00562	0.995	0.577	0.574
LPG	860	0	841.4	19	0.514	0.0231	0.978	0.548	0.536
Kero-press	843	0	802.6	40.2	0.699	0.051	0.951	0.494	0.470
Kero-wick	843	0	825.5	17.7	0.449	0.022	0.978	0.511	0.500
Eucal-imet	454	0.954	409	41.7	2.16	0.107	0.902	0.237	0.214
Eucal-ivm	454	1.94	364.9	85	2.32	0.239	0.807	0.273	0.220
Eucal-ivc	454	1.62	402.9	47.8	2.09	0.124	0.889	0.323	0.287
Eucal-3R	454	1.23	418.9	33.2	0.936	0.0815	0.924	0.191	0.176
Acacia-tm	418	1.61	379.5	36.6	0.888	0.0988	0.91	0.2	0.182
Acacia-imet	418	1.26	375.1	37	3.84	0.109	0.902	0.285	0.257
Acacia-ivm	418	2.09	343.6	70	3.02	0.212	0.824	0.285	0.235
Acacia-ivc	418	2.34	368	44.9	3.35	0.131	0.884	0.328	0.290
Acacia-3R	418	1.49	374.8	41.2	1.97	0.115	0.896	0.202	0.181
Root-tm	518	0.699	475.1	41.1	1.02	0.0886	0.917	0.155	0.142
Root-imet	518	0.924	473.6	42.5	1.12	0.0921	0.915	0.249	0.228
Root-ivm	518	1.36	466.3	47.9	3.36	0.11	0.921	0.219	0.202
Must-tm	421	26.2	355.1	39.4	0.631	0.113	0.898	0.138	0.124
Must-imet	421	15	368.7	35.3	2.22	0.102	0.907	0.239	0.217
Must-ivm	421	48.2	291.5	77.6	3.71	0.279	0.781	0.173	0.135
Must-ivc	421	62	309.5	45.3	4.26	0.16	0.861	0.215	0.185
Rice-tm	381	49.2	300.3	31.2	0.802	0.106	0.903	0.108	0.098
Rice-ivm	381	46	268.1	51.8	14.9	0.249	0.769	0.136	0.105
Dung-tm	334	14.4	280.1	38.1	1.61	0.142	0.822	0.107	0.088
Dung-ivm	334	7.07	290.5	35.2	1.63	0.126	0.887	0.113	0.100
Dung-ivc	334	9.56	285.3	37.4	2.03	0.138	0.877	0.146	0.128
Dung-Hara	334	12.9	265.6	55	0.545	0.209	0.824	0.099	0.082

<sup>a</sup>Abbreviations of stove types as described in Table 1. PIC, products of incomplete combustion: CO, CH<sub>4</sub>, and total nonmethane organic compounds; TSP, total suspended particulates; k-factor = PIC/(PIC + CO<sub>2</sub>); Nominal combustion efficiency (NCE) = 1/(k + 1) = fraction airborne fuel carbon release as CO<sub>2</sub>; Heat transfer efficiency (HTE) = TEE/HCE = fraction of heat released from fuel going into pot; Total energy efficiency (TEE) = fraction of fuel energy going into pot (measured during tests).

(a)

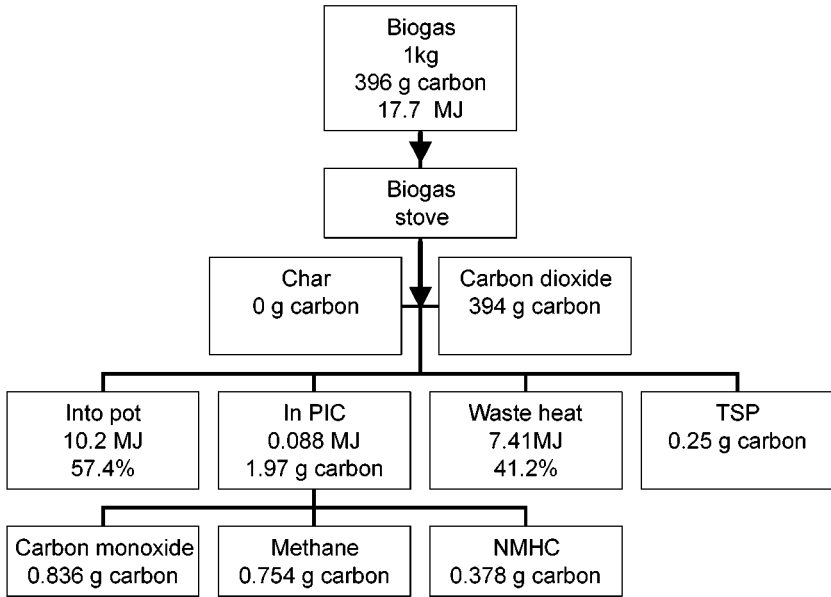


(b)



**Figure 2** Energy and carbon flows in typical Indian cookstoves. (a) Traditional mud with wood; (b) hara with dung; (c) biogas stove; (d) kerosene wick stove.

(c)



(d)

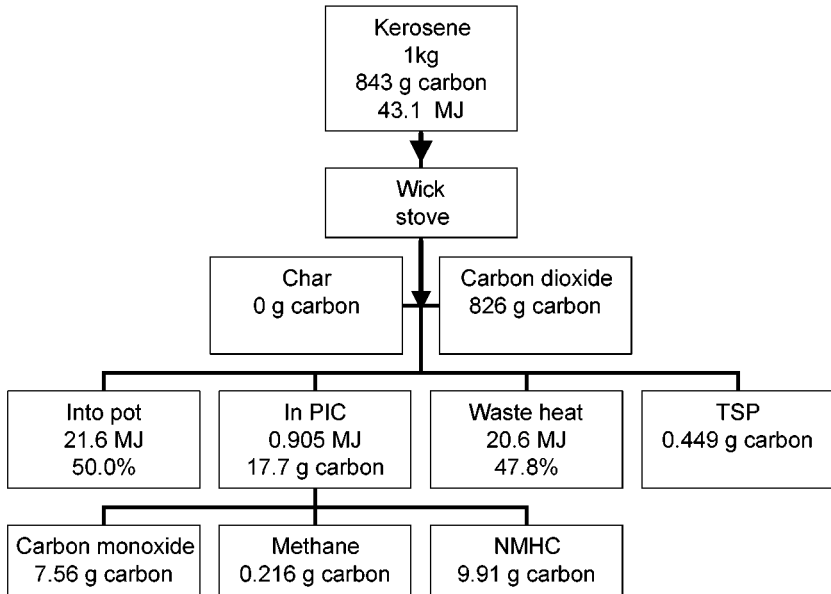


Figure 2 (Continued)

**TABLE 3** Comparison with Intergovernmental Panel on Climate Change (IPCC) default (uncontrolled) emission factors for residential fuel combustion (g/kg)<sup>a</sup>

	CO	CH <sub>4</sub>	NMHC	N <sub>2</sub> O
Gas-IPCC <sup>b</sup>	2	0.2	0.2	0.005
Biogas-LPG—India Dataset	2–15	1–0.05	0.6–19	0.10–0.15
Oil-IPCC <sup>c</sup>	0.9	0.4	0.2	0.03
Kerosene—India Dataset	18–62	0.3–1.1	15–19	0.08–0.10
Wood-IPCC	80	5	9	0.06
Wood—India Dataset	60–139	3.4–11	8–25	0.07–0.28
Dung/Ag Wastes—IPCC <sup>d</sup>	68	4	8	0.05
Ag Waste—India Dataset	55–101	3.8–25	8–28	0.05–0.22
Dung—India Dataset	32–60	3.3–17	19–32	0.29–0.32

<sup>a</sup>IPCC data from Reference 7. India Dataset data from Reference 13.

<sup>b</sup>Determined using the IPCC emission factors given for “natural gas” and the net calorific value given for “LPG.”

<sup>c</sup>Determined using the IPCC emission factors given for “oil” and the net calorific value given for “other kerosene.”

<sup>d</sup>Determined using the IPCC emission factors given for “other biomass and wastes” and the average of the net calorific values given for “dung” and “agricultural waste.”

## GLOBAL WARMING COMMITMENT

Since there are several GHGs emitted from the fuel/stove combinations in different absolute and relative amounts, it is necessary to have an aggregate index to make comparisons. To calculate the climate change implications of household stoves, therefore, we define the Global Warming Commitment (GWC) as

$$\text{GWC} = \sum_i \text{GHG}_i * \text{GWP}_i, \quad 2.$$

where  $\text{GHG}_i$  is the quantity of  $i$ th GHG in question, and  $\text{GWP}_i$  is the global warming potential of that particular  $\text{GWP}_i$  (total warming per molecule compared with  $\text{CO}_2$  (24, 25). The GWPs used here have been published by the IPCC (26, 27), although there are a number of uncertainties remaining in their estimation. They state the warming potential of each gas as the equivalent amount of  $\text{CO}_2$  that would produce the same warming (radiative forcing). Because GHGs have different atmospheric lifetimes, however, GWPs vary according to the time horizon chosen. The IPCC publishes GWPs with 20, 100, and 500-year horizons. A number of incompletely resolved scientific and policy issues surround the calculation and use of GWPs (28, 29), but there are good arguments for why such weighting factors are better made explicit rather than left implicit (30).

**TABLE 4** Ultimate emission factors of pollutant mass per unit delivered energy to pot (g/MJ-del) and fuel energy content (kJ/kg)

Fuel/Stove	Fuel kJ/kg	CO <sub>2</sub> g/MJ	CO g/MJ	CH <sub>4</sub> g/MJ	NMHC g/MJ	N <sub>2</sub> O g/MJ
Biogas	17710	142	0.1918	0.0989	0.0558	0.00935
LPG	45840	125.6	0.6076	0.00203	0.7643	0.00598
Kero-wick	43120	140.4	0.8186	0.0134	0.6892	0.00366
Kero-press	43120	145.2	3.064	0.0528	0.9474	0.00503
Eucal-imet	15330	457.2	19.72	1.184	5.059	0.0586
Eucal-ivm	15330	396.7	41.26	3.396	7.452	0.0472
Eucal-ivc	15330	335.8	19.99	1.148	2.145	0.0391
Eucal-3R	15330	566.1	22.17	1.044	2.942	0.0268
Acacia-tm	15100	506.3	24.19	1.432	2.824	0.0335
Acacia-imet	15100	353.9	16.39	1.059	2.519	0.0713
Acacia-ivm	15100	355	35.45	3.041	3.365	0.0543
Acacia-ivc	15100	308.2	18.05	0.7814	2.882	0.0468
Acacia-3R	15100	502.8	23.67	3.439	3.532	0.0652
Root-tm	15480	792.5	22.74	5.317	7.415	0.2225
Root-imet	15480	492	21.16	0.992	3.335	0.135
Root-ivm	15480	560.6	24.89	1.267	6.151	0.1466
Must-tm	16530	635.2	31.99	3.698	4.141	0.0239
Must-imet	16530	376.9	15.6	1.071	3.527	0.0452
Must-ivm	16530	479	42.17	11.17	12.49	0.082
Must-ivc	16530	371.2	18.1	1.567	8.803	0.0579
Rice-tm	13030	862.2	38.14	4.221	7.354	0.1723
Rice-ivm	13030	692.1	71.11	2.985	5.658	0.1387
Dung-tm	11760	929	44.85	5.156	17.02	0.2786
Dung-ivm	11760	905.6	25.77	2.764	25.07	0.2713
Dung-ivc	11760	694.9	21.01	2.378	21.05	0.2086
Dung-Hara	11760	1010	63.66	18.21	24.08	0.3028

GWC is expressed in relation to some denominator of interest. Depending on the question being asked, for example, it may be useful to examine GWC per unit fuel mass, per unit fuel energy, or per unit delivered energy to the pot. Here we focus on the latter because it gives the most relevant information about the potential impact on GHG emissions of policy measures to promote substitution among different fuels and stoves.

The GWP of a GHG is not easily determined for it depends on difficult-to-measure parameters, such as its atmospheric lifetime, as well as assumptions about future atmospheric conditions, such as the concentration of other gases and free radicals, which may affect the lifetime or radiative forcing of the GHG in question (27). These factors are important not only for the gas in question, but also for CO<sub>2</sub>,

**TABLE 5** Global warming potentials used in this analysis (on a mole basis, i.e. per carbon or nitrogen atom) (26, 27)

Gas	0 years =			
	instantaneous	20 years	100 years	500 years
CO <sub>2</sub>	1.0	1.0	1.0	1.0
CH <sub>4</sub>	21	22.6	7.6	3.2
N <sub>2</sub> O	210	290	300	200
CO	0–1.0 <sup>a</sup>	4.5	1.9	1.3
NMHC <sup>b</sup>	0–1.0 <sup>a</sup>	12	4.1	2.3

<sup>a</sup>At the instant of release, there is no radiative forcing. 1.0 indicates the impact of eventual oxidation to CO<sub>2</sub>.

<sup>b</sup>Nonmethane hydrocarbon molecular weight assumed to be 18, as is common for such calculations (26).

because GWP is defined as the ratio of the radiative forcing of the non-CO<sub>2</sub> GHG to that of CO<sub>2</sub>. Thus, there is not universal agreement about the exact values for GWPs, which are also being modified as knowledge advances.

Early in the 1990s, the GWP concept itself was questioned in some quarters because, among other problems, it was believed that GWPs depended too strongly on the future emission scenario for all relevant gases. This concern has reduced substantially, however, both because there is more recognition of a need to have an overall index for policy, even if imperfect, and because GWPs have been found to depend less on emission scenarios than previously believed (31). Economic indices have sometimes been proposed as a substitute (e.g. 32, 33), but have not been widely applied.

The GWP of CO<sub>2</sub> is, by definition, 1.0 for all time horizons. Those for methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are reasonably well established (34) and, in comparison to those for CO and NMHC, accepted not to be subject to wide uncertainty ranges. They are listed in Table 4. Some research has indicated that with more realistic carbon cycle models, the GWP values for CH<sub>4</sub> and N<sub>2</sub>O may actually be understated (35), although more recent research has tended to verify values for CH<sub>4</sub> (36).

Those for the other PICs of concern here (CO, NMHC), however, are not nearly as well specified because they operate principally by affecting the level of OH radicals in the atmosphere, which in turn affect the lifetime of methane. In the first set of IPCC reports (26), they were given the values reported in Table 5. In the second set, no values were listed because the uncertainties were believed to be too large to do so (27). One uncertainty, for example, is that local conditions affects PIC's impacts, making global modeling difficult. More recent research, however, has tended to verify that the values listed in IPCC(1990) are probably reasonable, although still in the middle of significant ranges in uncertainty. Daniel &

Solomon (37), for illustration, estimate that the range of CO GWP are 20 year: 2.8–14, 100 year: 1.6–4.4. Note that the values in Table 4 lie at the lower portions of these ranges.

In this study, we use 20-year GWPs for the analysis because we wish to compare investment options for reducing emissions. A 20-year GWP is roughly equivalent to a discount rate of 4–5%, which is about the lowest that can be justified for social investments (24). Application of longer time horizons would arguably penalize near generations for the benefit of later ones. Given the severe development problems that exist today in poor countries such as India, such sacrifice does not seem warranted. It should be noted, however, that the international negotiations surrounding the Kyoto Protocol currently use 100-year time horizons for GWPs, although this choice is subject to revision as needed (24a).

### Basic and Full Global Warming Potentials

To take into account the difference in uncertainty associated with the GHGs, we define two types of GWC.

$$\text{GWC}_{\text{basic}} = \sum_j \text{GHG}_j * \text{GWP}_j, \quad 3.$$

where  $j$  refers only to the basic (well established) set of GHGs ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ), and

$$\text{GWC}_{\text{full}} = \sum_k \text{GHG}_k * \text{GWP}_k, \quad 4.$$

where  $k$  refers to all five gases.

### Renewable and Nonrenewable Global Warming Potentials

With renewable harvesting of biomass,  $\text{CO}_2$  emissions are completely recycled and thus there is no net increase in GWC from  $\text{CO}_2$ . For PICs, renewable harvesting only affects GWC by eliminating the portion of the GWP of each gas owing to its eventual conversion to  $\text{CO}_2$  in the atmosphere. In nonrenewable harvesting, however, all the carbon in biomass is a net addition to the atmosphere, as for fossil fuels.

The impact on GWPs for renewable harvesting is to subtract 1.0 from the value of each entry in Table 4 (except for the instantaneous GWPs).  $\text{N}_2\text{O}$  remains the same, however, because nitrogen is not recycled in the same way as carbon. Note that subtracting 1.0 always completely eliminates  $\text{CO}_2$  emissions from the calculation.

Here we assume that crop residues, dung, and biogas always derive from renewable harvesting and that LPG and kerosene are always nonrenewable. Thus, only wood and root have different GWPs according to how they are harvested. For these fuels, therefore, there is a difference between GWC (renewable) and GWC (nonrenewable).

## GWCS OF FUEL/STOVE COMBINATIONS

Figure 3 shows the ranking of GWC (nonrenewable) with both basic and full sets of GHG. Note that all the wood and root fuels have substantially higher GWC (nonrenewable) per standard meal than any of the fossil fuels tested. This is because of the low combustion and thermal efficiencies of biomass stoves, even improved ones, compared with stoves burning liquid or gaseous fuels.

Figure 4 shows the same calculations using GHG (renewable). From a GWC-basic perspective, eight of the wood/root stoves do better than the fossil fuels, three are comparable, and one is worse. From a GWC-full perspective, fossil fuels are better than all wood/root fuels, however, even those renewably harvested. Fossil fuels even do better in GWC-full than the always-renewable agricultural wastes (crop residues and dung). Two of the agricultural waste stoves do better with GWC-basic and two others are comparable. The other six do worse even with GWC-basic.

Interestingly, however, the biogas stove is by far the best of all, with only some 10% of LPG GWC and more than a factor of 100 less than the most GWC-intensive solid biomass fuel/stove combinations. One surprising result, however, is that LPG is only slightly superior to kerosene. It would seem substantially easier to premix gas with combustion air, thus leading to higher combustion efficiency.

Although it is not the purpose of this review to provide detailed evaluation of individual stove types, it is useful to note the relatively poor overall performance of the improved vented mud stove (ivm). With both crop residues and both wood species tested, ivm was the worst performer among all stoves. The reason can be gleaned from Table 2, which shows that with all these fuels, the superior heat-transfer efficiency of the ivm stoves compared with the traditional mud stove was overwhelmed by decreased nominal combustion efficiency (NCE), resulting in high GWC per delivered energy even though fuel use was generally lower. This counter-intuitive result, i.e. that improvements in stoves that result in higher fuel efficiency can still lead to greater emissions per unit delivered energy, is consistent with previous studies (38).

Figure 5 (see color insert) summarizes the results of GWC calculations aggregated by fuel and divided according to type of analysis (renewable/nonrenewable, basic/full). It shows the contribution by each GHG as well as the totals per MJ energy delivered. We have weighted the emissions according to how much of each fuel is used in each stove type in India (Table 1). Although a powerful GHG, N<sub>2</sub>O emissions from these fuels are small and thus contribute a minor part to all GWCS.

Note the strong performance of kerosene and LPG when the full set of GHG is used and that even in the renewable case, wood has only a relatively modest advantage over fossil fuels, using the basic GHG set (26 g carbon as CO<sub>2</sub> per MJ delivered compared with 39 g for kerosene and 34 g for LPG). Indeed, the figure indicates that the national wood supply produces more GWC<sub>basic</sub> per MJ delivered

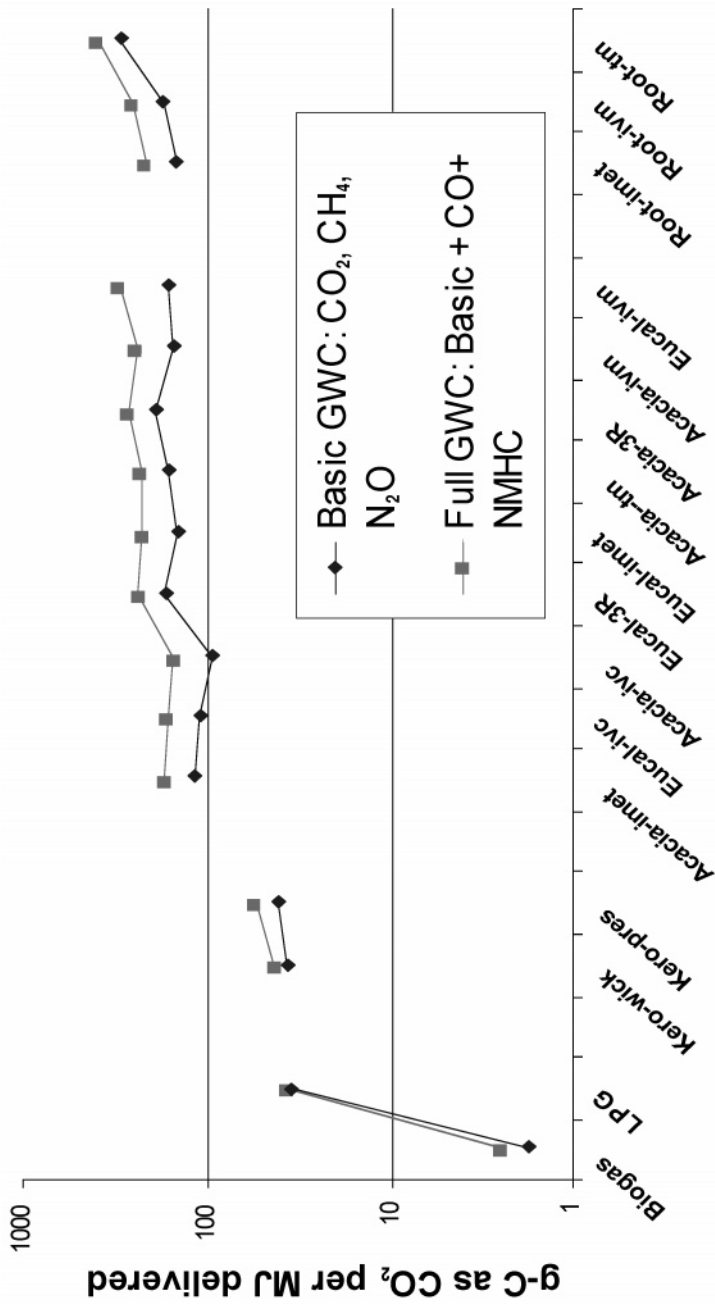


Figure 3 GWC-nonrenewable: biogas, LPG, kerosene, wood, and root.



than kerosene if only 10% is harvested non-renewably. Although the actual percentage of non-renewable wood fuel harvesting in India is unknown, it is likely to be substantially higher (16). The strikingly superior potential performance of biogas has only 2 g per MJ delivered.

## POLICY IMPLICATIONS

The findings noted above illuminate a number of possible policy approaches for reducing GHG emissions in conjunction with other goals. Here are some examples:

1. Encourage expanded dissemination of biogas digesters to reduce the direct use of dung as fuel. Compared with direct combustion of dung in India, as shown in Figure 5, biogas stoves produce only 1% of the GWC for the same delivered energy. If the meals cooked on the 53.5 million tons (MT) of dung used annually in household stoves (Table 1) had been cooked with biogas, there would have been an annual savings of some 20 MT of carbon as CO<sub>2</sub>-equivalent, or about 10% of the total GWC (CO<sub>2</sub> and CH<sub>4</sub>) from fossil fuels in the nation in the early 1990s (39). According to the most recent census (1991), more than 15% of India's 150 million households used dung as their main fuel, indicating a total potential savings per stove of about 1.1 ton carbon as CO<sub>2</sub>-equivalent per year. The present value of these savings is \$3.0 billion at the commonly applied value of \$20/ton carbon and an amortization period of 8 years (40). This comes to about \$150 per household, which should be added to the local benefits of biogas digesters in the form of relatively high-quality fuel for lighting and other uses, much less indoor air pollution, good quality fertilizer, and potentially, sanitation. For comparison, the typical current cost of a household biogas plant is about \$200, 25% of which is subsidized by the Indian government's nonconventional energy ministry (16).
2. Focus development of improved stoves on those that not only save fuel and reduce indoor air pollution, but also achieve lower GWC. For example, across all fuels, the improved vented ceramic stoves in Figure 3 generally do much better than the improved vented mud stoves. The difference is about 50 g per MJ for crop residues and wood, which at 1000 meals per year, 5 MJ per meal, and an amortization period of 4 years, indicates a potential present value of about \$20 per stove, several times more than the current difference in their costs. In addition, the improved vented ceramic stoves achieve significantly greater fuel economy, some 30% more for wood and 70% more for crop residues compared with the improved vented mud stove. The ceramic combustion chamber also provides longer lifetimes and lower maintenance costs. To date, however, partly because its first cost is less, the improved vented mud stove has been promoted to a much greater extent in India, probably accounting for more than 90%

of all improved vented stoves. It may well be a false economy, however.

3. The most counter-intuitive implication of this analysis is that it is possible to recommend fossil fuels as a GHG control measures in households. This is perhaps not surprising for stoves using wood that is not harvested renewably, given that wood has about one-third less energy per carbon atom and that wood stoves are substantially less efficient. In this case, the wood carbon is essentially being mined, just like the petroleum from which kerosene and LPG are made. What is surprising is that for all renewable biomass fuels,  $GWC_{full}$  are above those for the fossil fuels. Even for  $GWC_{basic}$ , many biomass/stove combinations perform less well than kerosene and LPG. Given the current pattern of stove use in India, crop residues and dung, although renewable, produce greater  $GWC_{basic}$  than their potential fossil substitutes. Renewable wood is apparently about even with the fossil fuels, but because, nationally, a (unknown) portion is not harvested renewably, the wood supply system as a whole does more poorly. In addition, the petroleum-based liquid and gaseous fuels produce substantially less health-damaging pollution than any of the solid biomass fuels in any stove tested although a large part of the smoke mixture may be vented outdoors with properly operating improved vented stoves. Unfortunately, however, in urban areas and the many villages with closely spaced households, such venting does not completely eliminate human exposures because of the "neighborhood pollution" effect (41).
4. The only sure way to reduce air pollution exposures in all situations over the long term is to move up the energy ladder to cleaner burning liquids and gases (or electricity). The primary source of these fuels is not important from the household combustion standpoint, only that they be liquid or gaseous so that they can be premixed with the air supply to achieve high combustion efficiency in simple small-scale devices. Thus, the excellent performance of biogas in this GWC analysis is indicative of how other upgraded fuels, such as producer gas and alcohols, made from renewable biomass might fare. It should help reinvigorate efforts to develop such fuels using renewable resources such as crop residues that currently are inefficiently utilized and produce significant health damage as well as GHGs.

## CONCLUSIONS

For a complete analysis, the GWC of the rest of the fuel cycles should be included as well. The fossil fuels, for example, will have GHG releases at the oil well, refinery, and transport stages of the fuel cycle (42). Biogas will lose some of its apparent lead because of  $CH_4$  leaks from the digester and pipelines, although preliminary measurements indicate that these are relatively small (43). Although

not discussed here, a fuel-cycle evaluation of charcoal's GWC would be quite different than one including only the stove because of the inefficient operation of most charcoal kilns (44). In addition, there are implications of not using some fuels. Some uncollected dung, for example, may undergo anaerobic decomposition in agricultural areas with significant GWC in the form of  $\text{CH}_4$  (45).

Furthermore, although the measurements making up the database were taken in simulated field conditions, they do not completely duplicate actual household stove operations. For example, they likely understate efficiency (overstate GHG emissions) for the liquid and gaseous fuels because they do not account for the much greater controllability of such fuels. For example, once cooking is finished, such stoves can be instantly turned off; thus, few emissions occur outside times when service is not needed. This is not true for solid fuels, which cannot be turned off quickly and emit even after (and sometimes before) services are needed. In addition, studies have shown that emissions of particles and CO from household solid fuel combustion are highly nonuniform, peaking, for example, immediately after fuel is added (46–48). It is not clear whether the simulated cooking cycle used to provide uniformity to the emission factor and efficiency measurements adequately includes such peaks. Similarly, variations in operating parameters are known to change emission factors for small-scale, solid-fuel combustion (49, 50), and little is known about this effect or the distribution of operating practices in developing-country settings.

Although additional work is surely warranted, being based on a database both far more consistent and reflective of actual practice than previous ones, the analyses here tend to confirm some of the preliminary counter-intuitive conclusions of the original Manila pilot study, i.e. in some circumstances a switch from solid biomass fuels, even if renewably harvested, to kerosene or LPG can be recommended for the purpose of reducing GHG emissions. The remarkable performance of biogas occurs because it is the only fuel tested here that is favored with both the high thermal and combustion efficiency of gaseous fuel along with the carbon-recycling advantages of renewability. As such, it foreshadows the large potential for liquid and gaseous fuels made from biomass to substantially reduce the GWC and health-damaging emissions from household use of unprocessed biomass.

Four specific conclusions can be drawn:

1. Even if renewably harvested, biomass fuel cycles are often not GHG neutral because of their substantial production of PIC.
2. To be nearly GHG neutral, not only must biomass fuel cycles be based on renewable harvesting, they must also have close to 100% combustion efficiency, which, it seems, few do in their current configurations in India.
3. In the processed form of biogas, however, biomass seems to offer the opportunity of providing a renewable source of household energy with extremely low GWC because of its double blessing of being gaseous when burned and renewable when harvested.
4. Technologies to upgrade renewably harvested biomass to liquid and

gaseous fuels may also have extremely low GWCs, depending on the processing emissions.

The overall message is that the current household fuel situation in India and other developing countries offers potentially quite attractive opportunities for true win-win interventions that achieve important global benefits in the form of cost-effective GHG reductions while providing even greater local benefits in the form of higher quality fuels and healthier environments. In particular, infusions of international resources into development of household energy systems could provide the needed extra push. Currently, however, there are few if any international mechanisms through which such small-scale devices could be promoted in a way that both sets of benefits accrue.

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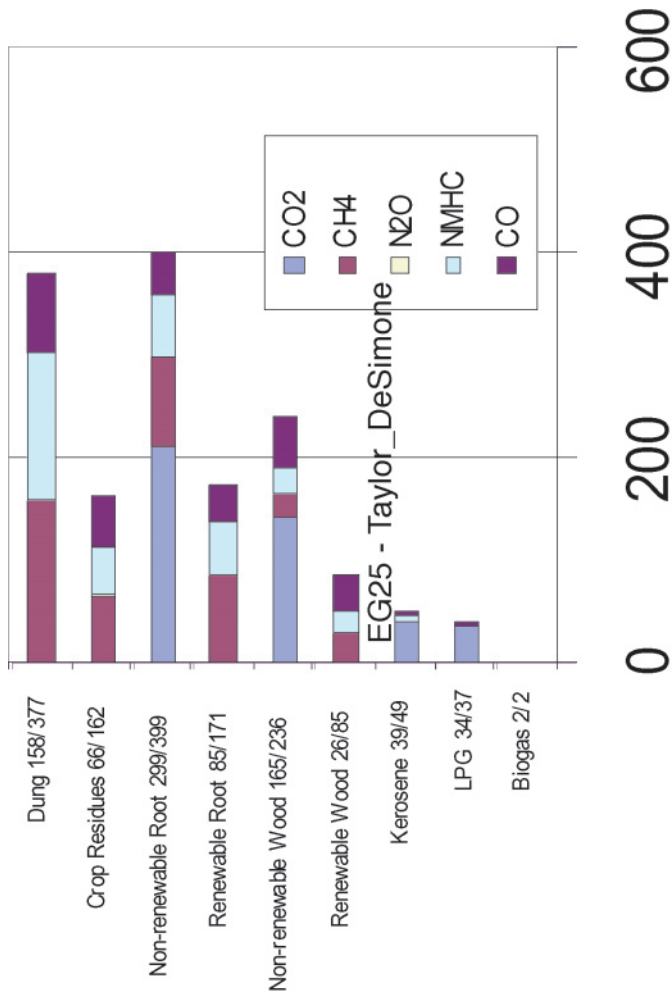
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## Grams Carbon as CO2 per MJ Delivered

Figure 5 GWCs for household fuels in India (basic/full GWCs)

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