Health, energy, and greenhouse-gas impacts of biomass combustion in household stoves

Kirk R. Smith
East-West Center, Honolulu, Hawaii 96848, USA

Poor biomass combustion in stoves entails three major environmental liabilities due in significant part to emissions of products of incomplete combustion (PICs). First, poor combustion contributes directly to low energy efficiency, with its attendant problems of onerous human labor requirements and pressure on biomass resources from harvesting. Second, some PICs are hazardous to health when breathed in the concentrations commonly found in homes using unvented biomass stoves. Third, a different set of PICs are strong direct or indirect greenhouse gases, potentially contributing to global warming. To evaluate the impacts in these three areas, it is valuable to construct carbon balances of alternative stove/fuel systems in what can be called ''triple carbon balance'' analysis (TCBA). Here TCBA is applied to traditional and improved woodstoves in developing countries and to one of the chief alternatives, kerosene. The tentative, counterintuitive result is that a switch to fossil fuels can sometimes be justified on all three environmental grounds.

1. Introduction

It has been said that wood is the fuel that heats you twice – once when you chop it and once again when you burn it. Like fossil fuels, however, biofuels also have the potential to heat you a third time as a result of enhanced greenhouse warming due to the gases released by combustion[1]. It has generally been assumed that this potential is only realized when the biomass being burned is harvested on a nonsustainable basis. With sustainable harvesting, it is argued, an equivalent amount of carbon is recaptured by the regrowing biomass as is released by combustion. Thus, the net greenhouse gas increment is zero.

Even when this is true with regard to the number of carbon atoms, it may not be with regard to their greenhouse equivalence. In particular, photosynthesis captures only carbon dioxide (CO_2) from the atmosphere, but actual biomass combustion emits other carbon-containing materials with atmospheric warming impacts [Levine, 1991].

These products of incomplete combustion (PICs) are also of concern because of their effects on human health. Measurements in village homes throughout the world have shown that health-impairing concentrations of PICs are often encountered where people use wood or other biomass for cooking or heating in poorly ventilated conditions [Smith, 1987].

These same PICs also represent lost energy and contribute to the low engineering efficiency with which meals are cooked in much of the developing world [Baldwin, 1987]. This, in turn, increases pressure on biomass resources, which, along with land clearing and other factors, has been associated with deforestation and accompanying environmental problems in some areas.

The apparent opportunity for decreasing forest-stressing biofuel demand as well as reducing health-threatening smoke exposures has lured many local, national, and international organizations, both government and private, into programs to disseminate improved biomass stoves in poor countries. Although there have been major successes such as the Chinese national improved stoves program [Smith, Gu, et al., 1993], which has reached more than one-half the nation's rural households, it is only in recent years that the percentage of success has been high [Barnes et al., 1994].

Recently, rising concerns about global warming from the buildup of CO_2, methane (CH_4), and other greenhouse gases in the atmosphere have focused attention on worldwide biomass combustion. Emitting 2100-4700 Tg carbon/year compared to 5700 Tg C/y from fossil fuels, biomass burning plays important roles in the global carbon cycle [Crutzen and Andreae, 1990]. Approaching 1000 Tg C/y, household biofuel, in turn, accounts for a significant fraction of overall biomass combustion [Meyers and Leach, 1989].

These parallel developments raise questions of the following sort:

- ''Would alterations in household biomass combustion, such as might be brought about by improved stoves or fuels, have significant implications for global warming?''

and

- ''Do actions leading to the reduction of the greenhouse-gas impacts of household combustion always reduce potential health impacts as well?''

In this paper, I attempt to demonstrate a type of analysis designed to quantitatively address these and related questions.

2. The Manila study

To explore these issues, it is essential to know the biomass stove emission factors for the various airborne species that have significant implications for energy, health, and global warming. Some of this information is already available, for in the 1980s a number of studies were undertaken to examine the energy efficiency and health implications of biomass stoves, both in developed and developing country situations [Smith, 1987]. Although a significant amount of greenhouse-gas research has gone into studies of biomass burning at large scale (forest fires, swidden agriculture, savannah burning, etc.), relatively little has focused on the type of small-scale combustion found in household stoves of developing countries [Levine, 1991].

With such a focus, a pilot cookstove study was undertaken in Manila. Monitored were emissions of more than 80 greenhouse-related and health-related gases (here, lumped together as total non-methane organic compounds, TNMOC) from traditional cookstoves burning wood, charcoal, kerosene, and liquefied petroleum gas (LPG), which together account for the bulk of all cooking activity in developing countries [Smith et al., 1992; Smith, Khalil, et al., 1993]. Involving only a few stove/fuel combinations in each category, it is not possible to draw statistically valid global conclusions from this pilot study. Nevertheless, the measurements are quite suggestive and serve to illustrate how more detailed studies of this type could be useful. Table 1 summarizes the results of the sampling and analyses in terms of emission factors and grams of pollutant per kilogram of fuel, for each of the major PICs.

Table 1. Emission factors, grams per kilogram dry fuel

Fuel	n	Carbon content	Stove efficiency	CO_2	CO	CH_4	TNMOC	RSP
LPG	2	0.87	0.7	3190	25	0.01	3	0.10
Kerosene	7	0.86	0.5	3050	39	0.90	14	3.00
Charcoal	6	0.80	0.3	2570	210	7.80	4	1.70
Wood	9	0.50	0.2	1620	99	9.00	12	2.00

n = Number of data points

TNMOC = total non-methane organic compounds

RSP = respirable suspended particulates: considered 75% carbon

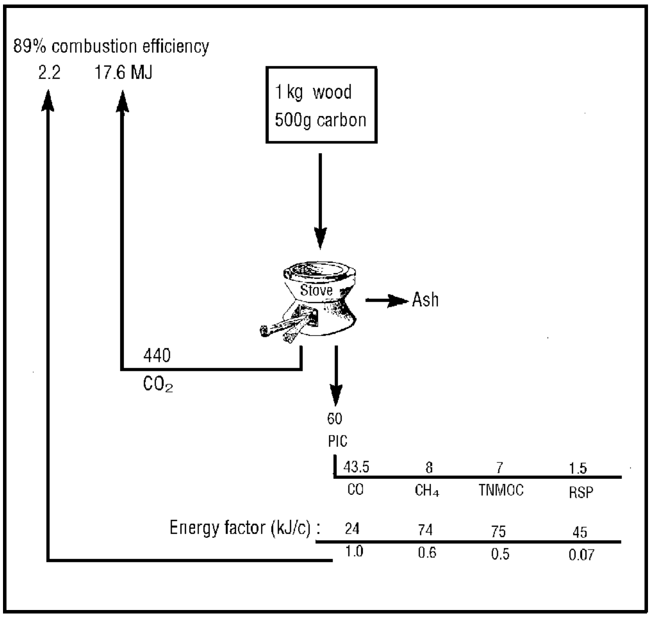

Fig. 1. Movement of fuel carbon through a traditional wood-fired cookstove as measured in the Philippines [Smith et al., 1992; Smith, Khalil, et al., 1993]. Sixty grams of carbon was not combusted completely (i.e., was released as PICs). Based on the available carbon energy in each PIC, if it had all been combusted completely, another 2.2 MJ would have been released as heat. The stove, therefore, has a combustion efficiency of about 89%. All the numbers refer to grams of carbon alone; i.e., the full mass of CO would be 28/12 (2.33) times larger.

3. Triple carbon balance evaluation

A profitable way to compare the three major effects (energy, health, and global warming) of biomass stoves is to determine how carbon flows through each by means of a ''triple carbon balance'' analysis (TCBA). Figures 1, 2 and 3 illustrate a TCBA derived for the composite wood-fired cookstove in the Manila study. TCBA follows the typical fate of the 500 g of carbon contained in 1.0 kg of wood burned in such a stove. About 88% of the carbon is emitted as CO_2 (weighing 1.6 kg), and the rest (60 g) is distributed as shown among several kinds of PICs, which together weigh about 126 g[2].

3.1. Energy

To put the PICs in an energy context, each constituent needs to be weighted by its energy content, i.e., the additional energy that could have been released if it had been burned all the way to CO_2. As shown in Figure 1, the result is that the PICs contain about 11% of the energy originally in the wood; i.e., the combustion efficiency is about 89%. Thus, compared with a stove of near 100% combustion efficiency, this stove requires about 13% more fuel (1/0.89 = 1.13).

This inefficiency is part of the reason that traditional stoves use more fuel than they seemingly should. The other major technical reason, of course, is low heat-transfer efficiency (the fraction of heat released from the fuel that is taken into the cooking utensil).

3.2. Health

As well as representing an energy loss, the 126 g of PICs represent the main health-damaging air pollutants from wood combustion. One way they can be aggregated and compared is by using the Relative Hazard Index (RHI), as shown in Figure 2. This is simply the amount of air it would take to sufficiently dilute each pollutant until it reaches the relevant health-based concentration standard [Smith, 1987]. With U.S. standards the total RHI of the PICs is about 120,000 cubic meters[3]. CO_2 is not much of a health hazard, as shown by the relatively small RHI, 1800 m^3. (Obviously, application of standards from dif-

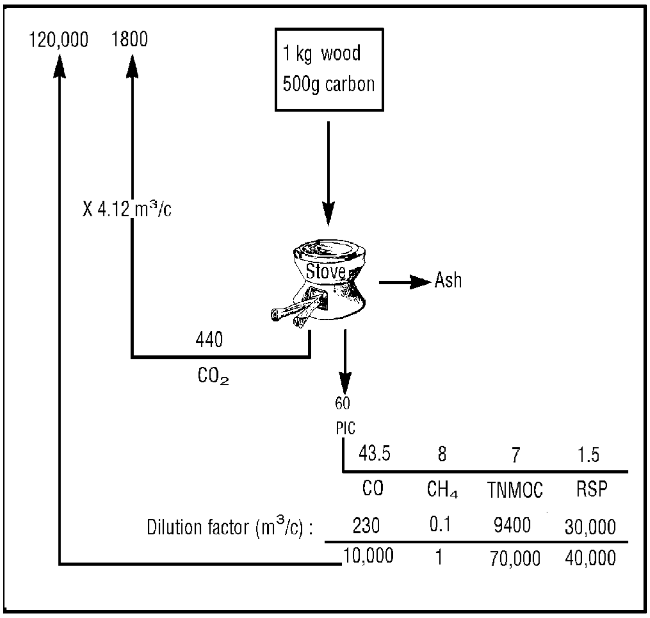

Fig. 2. Starting with the same fuel carbon flows as Figure 1, PICs are weighted not on the basis of energy, but on the basis of how many cubic meters of air would be necessary to dilute the emission to meet U.S. air pollution standards (Relative Hazard Index). Where there is only an occupational standard, an appropriate safety factor (10) has been used to establish a public standard. The dilution factors shown in the figure are on a per-carbon-atom basis [Smith and Thorneloe, 1992].

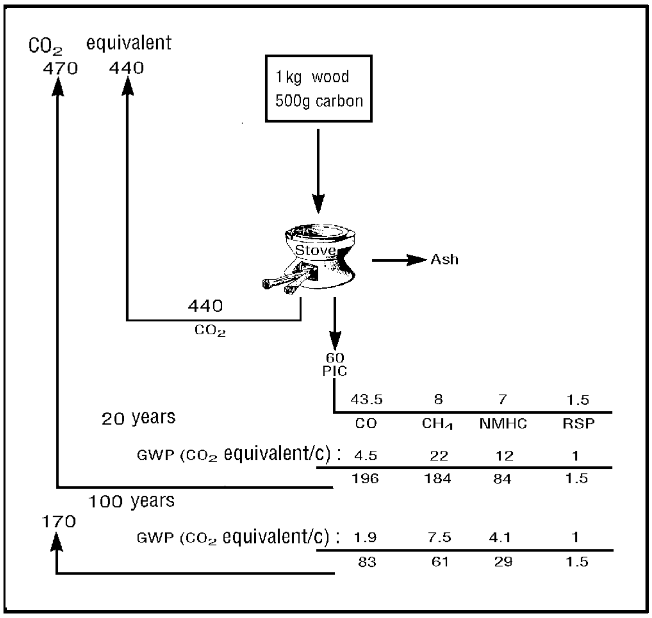

Fig. 3. The same carbon balance for the woodstove as in Figures 1 and 2. In this case, the PICs are weighted by the Global Warming Potentials (GWPs) appropriate for 20-year and 100-year time horizons [IPCC, 1990, 1992]. Since GWPs are cited in terms of non-methane hydrocarbons (NMHC), this term is shown here and in Figure 4 instead of TNMOC. NMHC generally seems to be within 10% of TNMOC for these stoves. Note that the PIC GWP is about equal to that of the CO_2 for a 20-year time horizon, but less for a 100-year horizon [Smith et al., 1992; Smith, Khalil, et al., 1993].

ferent countries would result in somewhat different relative weightings for the pollutants.)

Two of the PIC categories shown (TNMOC and RSP) are composites containing a vast array of, mostly, organic chemicals. Many of these individually are known to be health-threatening (e.g., benzene in TNMOC and polyaromatic hydrocarbons in RSP). Thus, if the RHIs included each separately, the total would be larger than that for the general categories.

3.3. Global warming

Figure 3 evaluates the same PICs in terms of their greenhouse-gas potential. To do this, it is necessary to apply some index so that the impacts of the different gases can be combined [Smith and Ahuja, 1990]. This is so because the gases have different heat-trapping abilities, lifetimes, and interactions with other gases in the atmosphere. Here, I have used the global warming potentials (GWPs) developed by the Intergovernmental Panel on Climate Change [IPCC, 1990; Hayes and Smith, 1993][4]. These are given as a ratio to CO_2 (either per molecule or per carbon atom), and thus can be interpreted as the degree to which the total warming of each compares to that of CO_2. Since the gases have different atmospheric lifetimes, the relative impact (GWP) depends on the chosen time horizon. Shown here are the results for time horizons of 20 and 100 years. In general, shorter time horizons make the non-CO_2 gases look more important relative to CO_2, since CO_2 is substantially longer lived.

The result is that depending on the time horizon chosen, the non-CO_2 greenhouse gases (i.e., the PICs) have a total global warming potential 20–110% as great as the CO_2 itself has. This implies that looking only at the CO_2 emissions of cookstoves may not give a good picture of their global warming implications. It also implies that improvements in combustion efficiency could result in much larger reductions in total GWP than would be indicated simply by changes in CO_2 emissions.

4. Global impacts

Using these preliminary data, it is instructive to note to what extent biomass stoves might appear to loom in the global picture for each perspective.

4.1. Energy

Although humans in some way utilize perhaps 40% of net global biomass production [Vitousek et al., 1986], as shown in Table 2, the proportion used directly for fuel only accounts for about one-seventh of direct human energy use. Even so, biofuel in the form of wood, crop residues, brush, and animal dung is today still the chief form of energy for the majority of humanity, just as it has been since the discovery of fire [Hall and Rosillo-Calle, 1991]. In developing countries, biofuels constitute about one-third of total energy use, and in rural areas of developing countries, some three-quarters. In the poorest developing countries, however, biomass fuels make up 80-90% of all energy use [Smith, 1987]. Based on the pilot study, therefore, the loss of energy represented by the PIC from biomass-fired cookstoves is roughly 1% of total human energy use and could approach 10% for some countries.

4.2. Health

In the case of health, human particulate exposures from biomass use could be responsible for something more than

Table 2. Global importance of PICs from biomass-fired cookstoves

Energy Biomass composes about 14% of all direct human energy use. It is about 33% of energy use in developing countries. It is about 75% of energy use in rural areas of developing countries. It is the most important fuel for the majority of humanity. Sources: Smith [1987]; Meyers and Leach [1989]; Hall and Rosillo-Calle [1991]
Health Cause of up to 50% of total human exposure to RSP Affects second-largest occupational group (cooks), after farm workers Known risk factor for most important killer of developing-country children (pneumonia) Source: Smith [1993]
Global warming Human biofuel consumption: 20–40% of all biomass combustion 1–5% of all CH_4 emissions 6–14% of all CO emissions 8–24% of all TNMOC emissions 1–3% of all human-generated global warming Sources: Smith, Khalil et al. [1993]; Ahuja [1990]

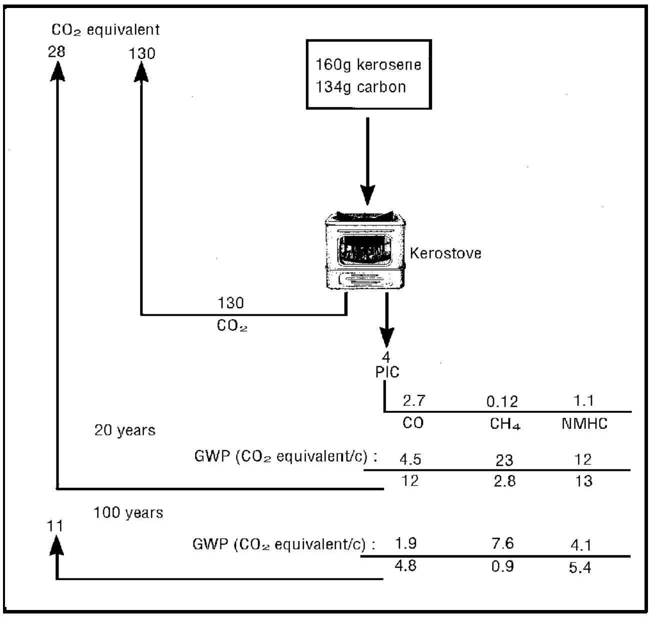

Fig. 4. Carbon flows and global-warming potentials for a simple wick-style kerosene cookstove cooking the same meal as cooked by the woodstove in Figures 1-3. Note that even at a 20-year horizon, the GWP of the PICs is less than one-quarter that of the CO_2. Note also how much less overall carbon is involved because the kerosene stove is more efficient and the fuel has more energy per carbon atom than does wood [Hayes and Smith, 1993].

one-half of total global exposure [Smith, 1993]. Most ot this occurs indoors in rural areas of developing countries, although there are significant exposures in cities and outdoors as well. Biomass stoves are undoubtedly responsible for a large fraction of global exposures to a range of other pollutants as well, e.g., CO, polyaromatic hydrocarbons, formaldehyde, and benzene.

It is important to note that the *emissions* from biomass fuels need not be high compared, for example, with those from coal-fired industrial and power facilities in order for the human *exposures* to be substantially greater. This is because a much larger proportion of pollution released in households reaches people, compared with that from centralized facilities [Smith, 1993]. The impact per unit emissions tends to be greater for distributed releases, and few things are more distributed than cooking, which occurs in every household, every day.

4.3. Global warming

Based on the few measurements taken in Manila, biomass stoves could account for fairly significant proportions of global emissions of the three greenhouse-gas categories CO, CH_4, and TNMOC (Table 2). For CO and CH_4, the percentages in Table 2 translate into contributions to overall global warming from biomass-fired cookstoves of 0.4–0.9% and 0.1–0.5%, respectively. These are in the same range estimated for all biomass stoves by Ahuja [1990], who also estimates that the overall contribution of biomass stoves to global warming is about 2%. In addition to the portion due to PICs, he estimates that stoves account for about one-eighth of net deforestation and, thus, about 1.5% of net human CO_2 additions to the atmosphere (1.1% of total warming).

5. Control measures

There are basically two approaches to reducing PIC emissions from biomass-fired cookstoves: use less fuel for the same task and/or reduce the fraction of carbon diverted into PICs. These can be accomplished by either changes in fuel and/or changes in the stove.

5.1. Fuel

One objective of household energy policy can be to encourage people to move up the energy ladder sooner to cleaner and more efficient fuels than they otherwise might. This can be done through fuel and stove pricing or other ways to make new stove/fuel combinations relatively more attractive. In most parts of the developing world, the first step beyond unprocessed biomass is charcoal or kerosene, followed by LPG. In some areas (e.g., Thailand), little kerosene is provided and the first step after charcoal is LPG. In China, it is often coal, followed by LPG. Movement up the ladder generally results in fewer health-damaging PIC emissions per meal [Smith, 1990].

With a switch from biomass to fossil fuels, however, a global warming penalty might first seem inevitable because fossil rather than contemporary carbon would be emitted. Because biomass combustion leads to a high amount of PICs with a significant GWP (Figure 3), the picture is substantially more complicated.

Based on the pilot study results, consider the kerosene stove carbon balance shown in Figure 4. The total GWP from cooking the same meal as with the woodstove in Figure 3 is less because of three factors: (1) there is more energy per carbon atom in kerosene than in wood; (2) the kerosene stove is much more energy-efficient; and (3) a smaller fraction of the fuel carbon in kerosene is diverted to PICs. From energy and health standpoints, therefore, kerosene looks much better.

The difference in GWP between Figures 3 and 4 is also large. This may not seem surprising, however, since Figure 3 represents the situation with no recycling of CO_2 (i.e., the wood is harvested in a completely non-renewable fashion). To determine the net greenhouse emissions in a completely renewable case, subtract 500 grams CO_2-equivalent from the total emissions in Figure 3. This leaves 410 g for a 20-year horizon, and 110 g for a 100-year horizon. Thus, surprisingly, even if the wood is harvested renewably (i.e., the carbon is completely recycled), the woodstove still produces substantially more 20-year GWP per meal than the stove burning fossil fuel. Real situations often lie between the extremes of complete renewability and non-renewability[5].

5.2. Stove

Improved biomass cookstoves that save fuel without changing the PIC :CO_2 ratio reduce all three types of impacts in rough proportion to the fuel savings. Introduction of a flue can greatly reduce health impacts through lowering human exposure, but does not, by itself, change the energy and greenhouse impacts.

To understand how changes in stove design and operation actually affect PIC emissions, however, it is important to recognize that overall stove efficiency (E_t) is a function of two internal efficiencies: combustion efficiency (E_c) (i.e., the amount of chemical energy in the fuel that is converted to heat) and heat-transfer efficiency (E_h) (i.e., the amount of the converted heat that enters the pot in a cooking stove or the room in a heating stove):

$$1)\ E_t = (E_u) \times (E_h)$$

In general, per-meal emissions of PICs and CO_2 are an inverse function of, overall efficiency in that, all else being equal, the less fuel used for a given cooking task, the less PICs will be released. Thus, it would seem that improvements in fuel efficiency would lead to lower emissions.

Changes in stove operation and design, however, often affect the two internal efficiencies in quite different ways. In particular, thermal transfer efficiency can be increased at the expense of combustion efficiency. Design and operation changes that improve overall fuel utilization, therefore, sometimes actually increase one internal efficiency at the expense of the other.

Although there are few data available for biomass cookstoves, Figure 5 illustrates this effect in a study of particulate and CO emissions of one traditional and two improved wood-fired metal cookstoves [Joshi et al., 1989]. Overall efficiency rose from 15% to 31% and 37% in the two improved stoves, greatly decreasing potential fuel demand for cooking. In the process, however, PIC emissions per meal actually increased by 8% because combustion efficiency dropped from 97% to 92%.

It might be thought that there is little net greenhouse-gas impact from changes in combustion efficiency. In other words, the fuel carbon that is not oxidized all the way to CO_2 will be released as PICs. The smaller the fraction of carbon released as CO_2, the more is released as PICs and vice versa.

In rough terms, this trade-off is true for carbon *mass* and number of carbon atoms. It may not be true for the net greenhouse impact, however, because these different molecules have different greenhouse impacts. Thus it is necessary to keep track not only of the total carbon emissions but also of their form.

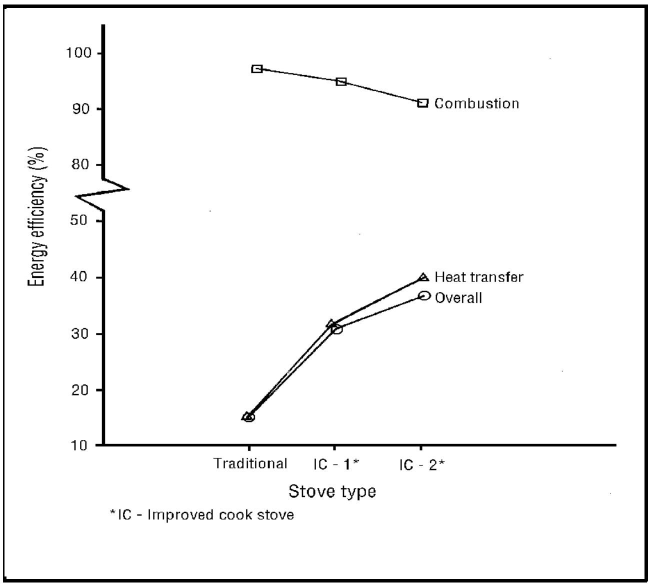

Fig. 5. The differences among overall and internal efficiencies in three metal wood-fired cookstoves without flues. Note that although both improved stoves achieve substantially more overall energy efficiency than the traditional stove, combustion efficiencies are less. Thus, IC-2 produces four times more PICs per unit energy delivered than the traditional stove (100–92)/(100–98). Although its energy use per meal is 2.5 times less (15/40), the overall result is that about 60% more PICs are produced per meal. The original investigators measured only CO and particulates [Joshi et al., 1989], thus the remaining PICs have been assumed to appear in the same ratios as measured in the Manila pilot study.

The PIC:CO_2 ratio can vary dramatically even at constant overall efficiency, depending on the relative contribution of heat transfer and combustion efficiencies. Carbon dioxide emissions are in general less dependent than PICs on combustion efficiency. For example, a shift from 90% to 80% combustion efficiency results in a near doubling of PICs but only about 10% less CO_2. (More dramatically, a change in combustion efficiency from 99% to 98% would result in less than a 1% loss of total efficiency but a near doubling of PICs.)

Since PIC emissions are a stronger function of combustion efficiency than they are of total efficiency, emissions can sometimes increase along with total efficiency. A popular means by which fuel utilization of traditional cookstoves has been raised, regrettably, is simply to reduce airflow by enclosing the fire, thereby greatly increasing the heat-transfer efficiency to the pot, but also lowering the combustion efficiency. The result, therefore, can be a net increase in fuel utilization and a consequent reduction in CO_2 emissions, but a rise in the PIC:CO_2 ratio or even an increase in absolute PIC emissions per cooking task.

The greenhouse-gas implications of stove emissions depend strongly not only on the PIC:CO_2 ratio, of course, but also on the particular mixture of PIC molecules. Each mixture will have a different greenhouse equivalence weighting, depending on the relative amounts of the dif-

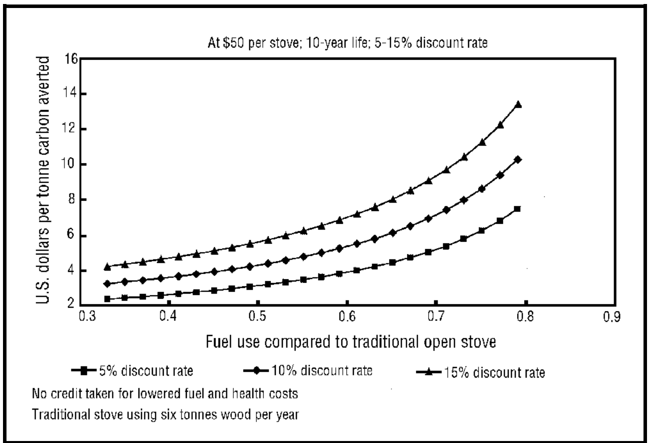

Fig. 6. The carbon reduction cost depends on five critical parameters: the fuel savings, cost, and lifetime of the stove; the degree to which the harvested wood is being replanted; and the discount rate applied to emissions averted in future years. The cost and lifetime are those found in an area of highland Guatemala, US$50 and 10 years. Results are then shown at three discount rates (5%, 10%, and 15%) and at a range of possible efficiencies for the improved compared to traditional stoves, which typically use about 6 tonnes of wood per year. The figure assumes that all the wood is harvested non-renewably, i.e., causing deforestation. (If half is being replanted, the carbon reduction costs would be twice those shown.) If data were available to incorporate GWP of PICs, the cost per equivalent carbon tonne would presumably have been even lower.

ferent constituents.

The radiatively active PIC molecules (such as methane) and the molecules that play a part in their atmospheric chemistry (such as carbon monoxide) have GWPs above 1.0, i.e., greater than that of CO_2. Indeed, it would seem that all organic molecules must have a GWP per carbon atom of at least 1.0 because once released they would relatively quickly be oxidized to CO_2, the rating of which by definition is 1.0. Only elemental carbon particles might have a GWP less than 1.0, if they are assumed not to be oxidized within a relevant time period. The average GWP of the PICs from woodstoves in Manila varied from 1.7 to 7.8, depending on time horizon.

Thus, efficiency improvements to the Manila woodstove that allowed combustion efficiency to drop in exchange for increased heat-transfer efficiency could actually lead to significant increases in PIC with their health and greenhouse impacts.

Decisions with regard to fuel and stove changes will, of course, depend on relative economics and other non-environmental issues. Nevertheless, the carbon flow framework made possible by the monitoring data would be a valuable grounding for these further analyses.

6. Conclusion

Improvements in household biomass-burning stoves potentially bring three kinds of benefits: 1) reduced fuel demand, with economic and time-saving benefits to the household and increased sustainability of the local natural resource base; 2) reduced human exposure to health-damaging air pollutants; and 3) reduced emissions of the greenhouse gases that are thought to increase the probability of global climate change.

These goals are not entirely compatible, unfortunately. Some stove design and operation changes may move toward one goal at the expense of moving away from another. This has been a problem in some improved stove designs (e.g., Figure 5). In general, however, increased fuel utilization leads simultaneously toward all three goals, a potentially powerful argument in favor of improved stove programs that work [Barnes et al., 1994].

6.1. The case

Figure 6 illustrates the kind of first-order argument that can be made. The vertical axis is the cost of reducing carbon emissions to the atmosphere, the principal measure of performance for greenhouse-reduction programs being examined worldwide. At 60–80% of fuel use in the traditional stove, costs are from US$4–15 per tonne of averted carbon, well within the range of many other international and national projects being considered for carbon emissions reduction.

Similar calculations could be done with the fuel and time savings accruing to households because of increased fuel utilization. Combining health, fuel, and greenhouse-gas benefits would likely result in quite good returns on stove investments.

As shown in this paper, more detailed analysis that includes examination of the non-CO_2 greenhouse gases (PICs) may change the simple curves in Figure 6 as well as the potential health benefits. Without more field data, however, it is uncertain in which direction[6].

6.2. Summary

Several tentative conclusions can be derived from the evidence presented in this paper:

1. Just because a biomass fuel cycle has a net zero carbon balance (i.e., is renewably harvested) does not guarantee net zero greenhouse impact.
2. To assure a near-zero greenhouse impact for biomass fuel cycles, it is necessary to add an additional criterion to renewability: high combustion efficiency (i.e., low PIC).
3. Where biomass is burned with poor combustion efficiency, movement up the energy ladder to fossil fuels can potentially result in lowered greenhouse emissions, even if the biomass is being harvested renewably.
4. Improving combustion efficiency is a worthwhile goal of biomass fuel policy with or without increases in overall fuel efficiency.

Before acting on these conclusions, more measurements are needed on a broad range of combustion devices using typical biomass and fossil fuels. ■

References

Ahuja, D.R., 1990. "Research needs for improving biofuel burning cookstove technologies." *Natural Resources Forum 14(2):* 125–34.

Baldwin, S., 1987. *Biomass Stoves.* Arlington, VA: Volunteers in Technical Assistance, with Princeton University.

Barnes, D.F., K. Openshaw, K.R. Smith, and R. van der Plas, 1994. "What makes people cook with improved biomass stoves?" World Bank Technical Paper #242, Washington, DC.

Crutzen, R.J., and M.O. Andreae, 1990. "Biomass burning in the tropics: impact on atmospheric chemistry and biochemical cycles." *Science 250: 1169-78.*

Hall, D.O., and F. Rosillo-Calle, 1991. "Biomass in developing countries." Report to the

Office of Technology Assessment, Washington, DC.

Hayes, P., and K.R. Smith, eds., 1993. *Global Greenhouse Regime: Who Pays?* London: Earthscan; and Tokyo: United Nations Univ.

IPCC (Intergovernmental Panel on Climate Change), 1990. *Climate Change: The IPCC Scientific Assessment,* Cambridge, UK: Univ. Press.

IPCC, 1992. *Supplement.* Cambridge, UK: Univ. Press.

Joshi, V., C. Venkararaman, and D.R. Ahuja, 1989. "Emissions from burning biofuels in metal cookstoves." *Environ. Management 13(6): 763–72.*

Levine, J.S. ed., 1991. *Global Biomass Burning.* Cambridge, MA: MIT Press.

Meyers, S., and G. Leach, 1989. "Biomass fuels in the developing countries: an overview." LBL-27222. Berkeley, CA: Lawrence Berkeley Laboratory.

Smith, K.R., 1987. *Biofuels, Air Pollution, and Health.* New York: Plenum.

Smith, K.R., 1990. "Indoor air quality and the pollution transition." *Indoor Air Ouality,* in ed. H. Kasuga. Berlin: Springer-Verlag, 448--56.

Smith, K.R., 1993. "Fuel combustion, air pollution exposure and health in developing countries." *Ann. Rev. of Energy and Environ. 18: 529–66.*

Smith, K.R., and D.R. Ahuja, 1990. "Toward a greenhouse equivalence index: the total exposure analogy." *Climatic Change 17: 1–7.*

Smith, K.R., S. Gu. H. Kun, and Qiu D., 1993. "100 million improved cookstoves: how was it done?" *World Development 21(6): 941–61.*

Smith, K.R., A. Khalil, R.A. Rasmussen, et al., 1993. "Greenhouse gases from biomass and fossil fuel stoves in developing countries: a Manila pilot study." *Chemosphere 26(1–4): 479-505.*

Smith, K.R., R.A. Rasmussen, F. Manegdeg, and M. Apte, 1992. "Greenhouse gases from small-scale combustion in developing countries," EPA-600-R-92-005. Washington, DC: Office of R&D.

Smith, K.R., and S.A. Thorneloe, 1992. "Household fuels in developing countries: global warming, health, and energy implications." In *USEPA Symposium on Greenhouse Gas Emissions,* Washington, DC, Paper 5-E.

Vitousek, P., P.R. Ehrlich, A.H. Ehrlich, and P.A. Matson, 1986. "Human appropriation of the products of photosynthesis." *Bioscience 36(6): 368--73.*

Notes

1. The energy involved at each step is quite different; for chopping, it is about 20 Kj/kg; for burning, 20 MJ/kg; and for warming, 20 GJ/kg.
2. Particulates were not measured in the pilot study, and so measurements from other studies were used in the figures (Smith, 1987, 1990; Joshi et al., 1989).
3. To put this in perspective, if a typical woodstove burning one kilogram per hour was in a kitchen having a 1 square meter window, a continuous wind of about 120 km/h through the window would be needed to dilute the smoke down to health-based standards.
4. These GWPs are not known with certainty, and changes can be expected as knowledge improves. Indeed, in its supplement, the IPCC (1992) suggested that the CH_4 GWP should be raised and the indirect effects (chemical interactions affecting other greenhouse gases) of the non-CO_2 gases were not well enough known to be used in policy discussions. For a 100-year horizon, the recommended total CH_4 GWP increases by a factor of 1.4, while those for CO and non-methane hydrocarbons (90+% of TNMOC) decrease by factors of 1.9 and 4.1, respectively. The report states, however, that "(t)he carbon cycle model used in these calculations probably underestimates both the direct and indirect GWP values for all non-CO_2 gases" (p. 21). Given this caveat and that the purpose here is principally illustrative, I have not modified the GWPs from those recommended originally by IPCC.
5. These comparisons are incomplete, however, because they exclude PIC contributions from elsewhere in the fuel cycles for these fuels. The releases at oilfields and refineries for kerosene are likely to be less than 10% of those at the stove. For locally harvested wood, they should be even lower, although there may be some wastage during harvesting, transport, and storage. For manufacture of another biomass-based fuel, at charcoal kilns, however, the contribution is likely to be quite large [Smith and Thorneloe, 1992].
6. Based on these enticing but preliminary findings, the East-West Center is embarking on a more extensive study of cooking and heating stoves. This is being undertaken jointly with colleagues in India and China, which together contain approximately two-thirds of all the biomass cookstoves in the world.

Acknowledgements

A number of people participated in the original Manila pilot study relied upon here; including S.A. Thorneloe, F. Manegdeg, M. Apte, R. Rasmussen, and M.A.K. Khalil. The research support of the U.S. Environmental Protection Agency is gratefully noted. Comments by Jim Zhang are appreciated as is the editorial assistance of Loraine Ikeda and Helen Takeuchi.

Contributions invited

Energy for Sustainable Development welcomes contributions from its readers.

Energy for Sustainable Development, now four issues old, is a venture in the field of journals on energy with a special focus on the problems of developing countries. It attempts a balanced treatment of renewable sources of energy, improvements in the efficiency of energy production and consumption, and energy planning, including the hardware and software (policy) required to translate interesting and useful new developments into action.

With such a multi-disciplinary approach, **Energy for Sustainable Development** addresses itself to both specialist workers in energy and related fields, and decision-makers. It endeavours to maintain high academic standards without losing sight of the relevance of its content to the problems of developing countries and to practical programmes of action. It tries to provide a forum for the exchange of information, including practical experience.

Material for publication as articles, letters, or reviews may be sent to the Editor:

Prof. K. Krishna Prasad, Technology University of Eindhoven, Den Dolech 2, P.O. Box 513, 5600 MB Eindhoven, The Netherlands Tel: +31 40 473168
Fax: +31 40 464151, e-mail: prasad@tn7.phys.tue.nl

All other categories of material may be sent to the Executive Editor:

S. Rajagopalan, 25/5, Borebank Road, Benson Town, Bangalore - 560 046, India. Tel: +91 80 554 3563
Fax: +91 80 554 8426, e-mail: raj@iei.uunet.in

For guidelines to authors on the preparation of the text and other material, see Page 2.