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Indoor air pollution in developing countries: recommendations for research†

Abstract Available studies indicate that indoor air pollution (IAP) from household cooking and space heating apparently causes substantial ill-health in developing countries where the majority of households rely on solid fuels (coal or biomass as wood, crop residues, and dung), but there are many remaining uncertainties. To pin down impacts in order to effectively target interventions, research is particularly needed in three areas: (1) *epidemiology*: case–control studies for tuberculosis (TB) and cardiovascular disease in women and randomized intervention trials for childhood acute respiratory diseases and adverse pregnancy outcomes; (2) *exposure assessment*: techniques and equipment for inexpensive exposure assessment at large scale, including national level surveys; (3) *interventions*: engineering and dissemination approaches for improved stoves, fuels, ventilation, and behavior that reliably and economically reduce exposure. There are also important potential synergisms between efforts to reduce greenhouse gas emissions and those to reduce health-damaging emissions from solid-fuel stoves. The substitution of biomass by coal being considered in some countries should be pursued with caution because of the known serious health effects of household coal use.

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The Problem

Although many people associate public exposures to air pollution primarily with urban outdoor settings, readers of this journal are well aware that indoor environments can also be contaminated, both from pollution penetrating from outside and from indoor sources. Perhaps less generally understood by the indoor air community, however, is that the largest exposures to health-damaging indoor pollution probably occur in the developing world, not in the households, schools, and offices of developed countries where most research and control efforts have focused to date. As a result, much of the health impacts from air pollution worldwide seems to occur among the poorest and most vulnerable populations, largely women and young children who are most exposed to the indoor pollution sources of importance in poor countries.

These high individual and population exposures are the result of a set of factors:

- About half the world's households use unprocessed solid fuels for cooking, ranging roughly from near zero in developed countries to more than 80% in China, India, and Sub-Saharan Africa (Holdren et al., 2000).
- In simple small-scale devices, such as household cookstoves, solid fuels have rather large emission rates of a number of important health-damaging airborne pollutants including respirable particulates, CO, dozens of PAHs and toxic hydrocarbons, and, depending on combustion and fuel characteristics, nitrogen and sulfur oxides.
- A large, although uncertain, fraction of such stoves are not vented, i.e. do not have flues or hoods to take the pollutants out of the living area.
- Even when vented to the outdoors, unprocessed solid fuels produce enough pollution to significantly affect local, 'neighborhood', pollution levels with implications for total exposures (Smith et al., 1994). As cookstoves are essentially used everyday at times when people are present, their exposure effectiveness (or intake fraction) is high, i.e. the percentage of their emissions that reach people's breathing zones, is much higher than for outdoor sources) (Smith, 2002; Bennett et al., 2002).
- The individual peak and mean exposures experienced in such settings are large by comparison with WHO guidelines and national standards.

- Because so many households are involved, the resulting global indoor population exposure is high, probably substantially exceeding total global outdoor exposures for several important pollutants, including respirable particulates (Smith, 1993).

Estimated impacts

Health effects, of course, derive from exposure and thus it can be expected that global ill-health from air pollution is dominated by indoor exposures in developing countries as well. The precise extent of impact, unfortunately, is not known yet, but enough information is available to make reasoned estimates for India, where more data are available than in most other developing countries (Smith, 2000).[1]

Strong evidence (from studies of outdoor air pollution, active and passive smoking, and multiple studies in solid-fuel-using households)

Acute respiratory infections (ARI), a class that includes infections from a range of viruses and bacteria, but with similar symptoms and risk factors. At one-eighth of the total burden, ARI is the largest single disease category for India, as well as for the world at large where it causes about one-twelfth of the total burden of disease.[2] Evidence from 13 studies in developing countries indicate a odds ratio range of 2–3,[3] i.e. young children living in solid-fuel using households have two to three times more risk of serious ARI than unexposed children after adjustment for potential confounders including socio-economic status (Smith et al., 2000a).

Chronic obstructive pulmonary disease (COPD), such as chronic bronchitis, in women accounts for about 1.5% of deaths in India, and 16% in China. Evaluation of eight studies in developing countries indicate an adjusted odds-ratio range of 2–4 for women cooking over biomass fires for many years (Bruce et al., 2000; Smith, 2000).

Lung cancer in women is a well-demonstrated outcome of cooking with open coal stoves in China, but there is little evidence of its connection to biomass fuel. Typical range of odds ratios for non-smoking women in 20+ Chinese studies is 3–5 (Smith and Liu, 1994). In addition, some coals produce large indoor exposures to arsenic and fluorine (Finkelman et al., 1999).

Moderate evidence (from studies of outdoor air pollution, smoking, lab animals, and at least three studies in biomass-using households)

Cataracts. An adjusted odds ratio of 1.3 for blindness in women was found in biomass-using homes in a large (89,000 household) Indian national survey corrected for a range of potentially confounding socio-economic factors (Mishra et al., 1999b). A Delhi clinical case–control study found similar risks 1.6 for cataract-caused blindness after adjustment (Mohan et al., 1989), while another case–control study in Nagpur, India, found an adjusted odds ratio of 2.4 (Zodpey and Ughade, 1999). Animal studies have found cataracts from woodsmoke (Rao et al., 1995).

Tuberculosis. Analysis of the same Indian national survey found a adjusted risk of 2.7 for solid-fuel using women (Mishra et al., 1999a), although based on self-reported tuberculosis (TB). A clinical study in Lucknow, India, found similar risks (2.5), although not adjusted for potential confounding (Gupta et al., 1997). A recent case–control study in Mexico City, however, that was both adjusted for potential confounders and had clinically confirmed TB found an odds ratio of 2.4 for people in households using wood for cooking (Perez-Padilla et al., 2001). Animal studies show declines of respiratory immune function with woodsmoke exposures (Thomas and Zelikoff, 1999).

Asthma attacks have been associated with passive and active smoking, indoor and outdoor pollution in developed countries, and in three studies in developing country biomass-using households (Azizi et al., 1995; Mohamed et al., 1995; Xu et al., 1996). Adjusted odds ratios range from 1.4 to 2.5, but as background rates currently seem to be low, the burden of disease in developing countries is not high by comparison with other diseases. The nature of the IAP/asthma interaction is not clear, but the potential for trigging of attacks through direct airway irritation and as facilitating factor for other allergens seems substantial.

Modification of the immune system with both increased incidence of attergic/atopic diseases and asthmatic tendency have been indicated in epidemiological studies of ETS. Tobacco smoke may influence primary allergen sensitization, secondary allergic responses, and the activation of non-specific inflammatory responses (Bascom, 1996). Other biomass smokes' could also influence the primary allergen sensitization and thus may cause permanent alterations in the immune system with changed life-time risk for diseases like asthma.

Adverse pregnancy outcomes (APO – stillbirth, low birthweight) and early infant death have been associated with outdoor air pollution and active and passive

[1]This abbreviated review of health effects is taken mainly from Smith (2000) and the associated supplementary materials found at http://www.pnas.org/cgi/content/full/97/24/13286/DCI. See also Smith et al. (2000a) and Bruce et al. (2000).

[2]Burden of disease is defined as lost healthy life years, which includes those lost to premature death and those lost to illness as weighted by a disability factor (severity). See Murray and Lopez (1996).

[3]All odds ratios reported here are statistically significant, i.e. the 95% confidence intervals do not include 1.0.

smoking in developed countries and in a few developing-country studies of households using solid fuels (Mavalankar et al., 1991; Boy et al., 2002). Preferential carbon monoxide absorption by hemoglobin provides a likely mechanism, although other pollutants may play roles as well. Low birthweight, of course, is a risk factor for a range of diseases in childhood and, probably in later life. Data are too sparse yet to determine odds ratios. Given the large direct and indirect (through low birthweight) burden of disease of this set of conditions, however, even a relatively low risk would translate into a large attributable burden.

In addition, there is evidence that early infant lung function may be reduced as a consequence of maternal smoking during pregnancy, with potential long-term effects. One study, for example, found significantly lower forced expiratory volume after controlling for infant size and other relevant confounders (Hanrahan et al., 1996).

Suggestive evidence (from studies of outdoor air pollution and smoking but no known studies yet done in biomass-using households)

Cardiovascular (heart) disease (CVD) is known to be related to outdoor air pollution and active and passive smoking in developed countries, but does not seem to have been yet studied in developing-country solid-fuel-using households.

Combining these risk estimates with the estimated pattern of exposures (solid-fuel use) and background health conditions in India, something like 500,000 premature deaths, which when added to the associated morbidity, produces some 6–7% of the national burden of disease, may be attributable to indoor air pollution (IAP).[4] Extrapolating to the rest of the world on the basis of regional use of solid fuels and regional population and health conditions, solid fuel use in developing countries might thus be responsible for nearly 4% of the global burden of disease and well-exceed 1 million premature deaths per year (WHO, 1997). If true, this would mean that the health impact of indoor pollution has been larger than the burden of all but two of the other major preventable risk factors that have been quantified, malnutrition (16%) and poor water/hygiene/sanitation (7%). It would have been larger in the early 1990s that the global burdens from illicit drugs, hypertension, outdoor air pollution, occupational hazards, alcohol, war, vehicle accidents, or homicide, and rivaling that of tobacco and unsafe sex (Murray and Lopez, 1996). Tragically, the latter two have been rising rapidly, but today IAP is still likely to rank fifth globally.[5]

Implications

In total, therefore, the studies summarized above point to a highly significant impact worldwide. It is an alarming but hazy picture because, from a strictly scientific standpoint, the quality and quantity of the available studies are unfortunately inadequate. The inadequacies can be divided into three categories.[5]

Risk studies

Consider, by comparison with the several dozen or so small studies relating IAP and disease in developing countries, the thousands of rigorous studies that have been carried out linking smoking with ill-health, or linking such major risk factors as hypertension and cholesterol with heart disease. Tens of billions of research dollars have been and are still being spent understanding these connections. Given the potential scale of impact and the particularly vulnerable nature of the populations affected by IAP (poor women and children in developing countries), therefore, it would seem appropriate to undertake a much more complete and scientifically sophisticated research program designed to reduce the most important uncertainties in the risk estimates (the quantitative connection between IAP exposure and various diseases).

Exposures

In addition to a lack of studies on the risks of exposures, there is a dearth of studies on the distribution and magnitude of exposure to IAP in developing countries itself. Such information is needed both to estimate the total burden of disease and to identify the regions and populations where interventions need to be focused. Compared with the thousands of studies on outdoor and indoor air pollution in developed-country urban settings, only a handful of studies (a few dozen) have been carried out in biomass-using households of the developing world, most of which are in rural areas. [By contrast, more than 100 such studies have been carried out in Chinese coal-burning households (Sinton et al., 1996).] Although striking because of the high exposures to major pollutants that have been demonstrated, the available studies have not been conducted in a fashion that allows the results to be confidentially extrapolated to large populations. Even for secondary indicators of IAP, e.g. distribution of fuel use, stove

[4]Burden calculated for women and children under 5 only (Smith, 2000). Revised estimates using formal meta-analyses and exposure modeling will be published in the WHO's World Health Report, 2002, and Smith et al., 2002 (forthcoming).

[5]Under WHO auspices, the global burdens of some 20 major risk factors is being calculated for the year 2000 conditions. Included are outdoor air pollution and indoor pollution from solid fuel use. See footnote 4.

type, ventilation conditions, etc., the data are poor in most countries.

Interventions

In spite of the clear need to conduct more research on risks and exposures, the current, if imperfect, knowledge of the health burden imposed by IAP in developing countries argues that action is warranted now. Unfortunately, however, there also is a severe lack of good information on the interventions that might be best applied to effectively reduce the risks. Better ventilation, better stoves, better fuels, and behavioral changes would seem to encompass the range of potential interventions, but remarkably little systematic work has been performed on any of these, considering again the potential scale of the problem and consequent potential benefit. Although, for example, there have been several hundred improved stove programs worldwide including the large Indian and Chinese efforts (Goldemberg et al., 2000), there has been no systematic and independent evaluation since 1990 and no effort ever to actually conduct measurements and surveys to assess their effectiveness in reducing IAP exposures as well as improve fuel efficiency.

Given the relative lack of research in each of these arenas, compared with their potential importance and the number of people affected, there are many dozens of studies needing to be carried out. Here, however, I briefly outline only what would appear to be the major and most pressing research needs under each category.

Risk research needs

Hundreds of urban developed-country epidemiological studies have been carried out in recent decades, allowing in some cases large-scale meta-analyses and reviews for important pollutants like small particulates (e.g. WHO, 1999; Kreweski et al., 2000; Samet et al., 2000). Extrapolating these relatively well-characterized results to the populations using solid fuels indoors is difficult, however, because of different pollutant mixtures, health conditions, age-distributions, exposure patterns and so on, as well as the scarcity of actual exposure measurements.[6] There is clearly need to find ways to make these extrapolations with more confidence (McMichael and Smith, 1999).

In addition, however, there are needs to conduct additional research directly within the communities of interest. Given what is known about the relative importance of the major air-pollution-related diseases in developing countries, the risks from existing studies, and the relative difficulties of measuring effects in studies of reasonable duration, the following kinds of studies would seem to have the highest priority. Here under each category, the diseases are listed with the highest priorities first:

- *Case–control studies of TB, APO, and CVD*. Such studies should be performed carefully to assure that socio-economic factors, such as income, education, housing, nutrition, and access to medical care, do not confound the results. In other words, as poverty is associated with both biomass-fuel use and the prevalence of these diseases, the effect of fuel quality must be distinguished from the relationship solely because of poverty. There are means to do this in the design of the studies, methods of choosing controls, and the way the data are analyzed, but they add to the resources and sophistication required. They also need to be carried out with clinically confirmed health impacts, i.e. the disease condition should be confirmed using standard international clinical criteria by trained health personnel with a subsample verified by medical staff. Exposures to air pollution must be performed carefully, particularly in TB and CVD studies where current disease status may be a function of many years past exposure.

  Acute lower respiratory infection (ALRI) might also be given priority because of its huge impact on lost life years globally, but a number of such observational studies have already been performed (Smith et al., 2000a). Most used indirect binary indicators of exposure (fuel used, stove used, whether child was carried on mother's back, etc.) and thus were not able to examine exposure–response relationships. One study in Kenya, however, was able to measure pollution levels and find, exposure–response relationships (Ezzati and Kammen, 2001a). More improvements could come from further studies that actually monitor indoor pollution levels and pin effects to particular pollutants. In addition, as only one case-fatality study seems to have been carried out (Johnson and Aderele, 1992) it would be valuable to design studies to see if IAP has an impact on ALRI severity as well as incidence. As noted below, given the state of current knowledge, randomized trials for ALRI should have higher priority, however.

  Tuberculosis has the highest priority for additional observational studies because of its importance for developing-country women in the middle productive (and child rearing) years, because it is on the rise in many parts of the world because of the HIV epidemic, and because drug-resistant strains are becoming more prevalent. In addition, from a political standpoint, confirmation of a connection between IAP and TB would likely make LDC IAP much more of a priority for environmental, health,

[6]See the discussion in the supplementary material to Smith (2000) found at http://www.pnas.org/cgi/content/full/97/24/13286/DC1.

research, and development agencies in the developed countries because TB is a worldwide epidemic, unlike ALRI.

- Randomized intervention trials for ARI and APO. The 'gold standard' of risk studies is the randomized double-blind intervention trial. This is considered the best way to actually demonstrate causality, i.e. to show that a statistical association is because of one factor physically causing the disease outcome and not a result of some third factor causing both. Such intervention trials, for example, are nearly universally required before a new drug is approved for use. They are randomized because the choice of which person to receive the drug and which to receive the placebo is made randomly. They are double-blind if neither the researcher administering the medication nor the patient knows whether they are receiving the drug or the placebo. In this way, there is less chance for bias to be introduced by the behavior or attitude of the participants.

  Randomized intervention trials would bring the evidence for the relationship of IAP with ARI and APO much closer to the standards of causality expected in the public health community. Such trials could be carried out by randomizing households for introduction of improved stoves or fuels, for example, and then following the intervention and control households to see if the ARI and APO rates diverged. It is difficult, however, to envision a double-blind study (placebo stoves?). Nevertheless, researcher and participant bias can be reduced by careful design and implementation of such studies.

  Such intervention trials are not practical for TB, COPD, lung cancer, and CVD because of the long latency periods involved – a change in exposures today would not be manifested in changed disease rates for years, even decades. Changes in ARI and APO rates, on the other hand, should be discernable within a few months.

  It is important to note, however, that acceptance of causation and the need for action has not depended on such randomized trials in the case of most environmental pollutants of issue today.[7] Indeed, it is rare for such trials to be possible for logistical and ethical reasons. How would one randomize cities for ambient air pollution interventions, for example? Ironically given the relative inattention given to indoor compared with outdoor pollution, because it is possible to randomize at the household level IAP studies may be among the first to move closer to the gold standard for proving causation for important air pollutants.

  Such studies would go a long way in making the argument about causality to health ministries and international agencies that support them, who usually have very limited resources to deal with a number of large health problems. They have the results of rigorous studies focused on other means of dealing with these same diseases [e.g. antibiotics and vitamin-A for ARI; Directly Observable Therapy Shortcourse (DOTS) treatment for TB]. At present, as the effectiveness and cost of such measures has been much better established, IAP interventions garner little attraction. On the other hand, the currently available interventions are clearly imperfect and will not serve to entirely control the diseases. Thus, unlike, for example, such diseases as measles against which vaccination is essentially a magic bullet, there is still need to find additional weapons.

  Among the chief priorities for research on outdoor particles is determining the specific characteristics of particles (size and composition) that make them most damaging to health (NRC, 1998). As wood smoke is often a major and occasionally a dominating source of outdoor pollution in some developed-country communities, it may be possible to more closely link the vast epidemiological results from outdoor studies to the third world indoor settings by examining whether the exposure–response relationships vary with wood smoke compared with other, more common, outdoor particle types.

Research on exposures

Such research is needed along the entire spectrum of exposure indicators, from indirect indicators such as fuel use and house type through to area and personal measurements and biomarkers.

- There is need for better and more comprehensive household energy surveys in rural and peri-urban areas in order to better understand the current and changing patterns of fuel use over time. Although used by nearly half the households in the world, biomass fuel use is not well tracked by current national or international surveys, largely because only a small fraction is purchased through formal markets. The International Energy Agency (IEA), for example, only started listing biomass fuels in its annual compendia in the late 1990s and has had the resources to do so only in the most aggregated form (IEA, 1998). Better understanding of the factors associated with household fuel choices is also needed for designing effective interventions (see below).
- There is need to develop monitoring instruments designed to address pollution, stove efficiency, and other technical parameters under developing-country conditions. There has been tremendous progress in fast, small, portable, smart, and rugged monitoring

[7] The most well characterized risk factor in the world today, tobacco smoking, also has had its causality established without randomized trials.

equipment for pollution and combustion monitoring in developed countries, but essentially no effort to develop such equipment for developing countries. There is need to develop relatively low-cost devices that would facilitate research and monitoring in a much wider set of households than are now covered. Given the weak existing database, the relatively high concentrations, and limited resources available, such devices need not have the high accuracy and precision expected in developed-country settings in order to contribute valuable information.

- Smoke from wood, crop residues, and dung, like that from the most well-studied biomass, tobacco, contains dozens of health-damaging pollutants (Smith, 1987). As was chosen for the warnings on cigarette packs, however, probably the two best indicators of health hazard for these other biomass smokes are also particles ('tar') and CO, which should probably thus be the initial foci for instrument development.[8] Adapting the widespread and cheap 'smoke' and CO devices sold by the tens of millions as alarms for developed-country households would seem to be a promising approach for developing devices for monitoring pollution levels in developing-country household.

- New instruments are needed for several time constants:
  - Cheap devices that can be left for a week to determine mean concentrations. Such equipment is needed because significant daily variations have been found in such households complicating evaluation of the benefits of interventions without longer term exposure measures.
  - 24-h levels, particularly for personal exposure monitoring. Reliable and inexpensive devices to monitor time-activity patterns are also needed.
  - Continuous monitoring to catch peaks, which can be extreme during cooking, particularly when fuel is added to the fire. There is evidence that for some endpoints peaks may be more predictive of effects than means (Ezzati *et al*., 2000).
- Although exposures to benzene, 1.3-butadiene, toluene, styrene, formaldehyde, benzo-α-pyrene and other compounds are often thought to be mainly associated with industrial, urban, and transport settings, there are significant levels in biomass smoke as well (Zhang and Smith, 1996). Biomarkers for these chemicals, as well as for those unique to biomass smoke, would thus be valuable adjuncts to exposure assessment.
- The low combustion efficiency of solid fuels in simple devices leads to significant diversion of fuel carbon to products of incomplete combustion (PIC; typically 5–20%; Smith *et al*., 2000b). Such PIC include not only the major health-damaging pollutants, but also a range of greenhouse gases. Most important among the latter is methane, which has some 20 times more global warming capacity per carbon atom than carbon dioxide. Needed therefore are reliable portable field monitoring devices designed to measure combustion efficiency and methane not only to check on the performance of stoves but also to determine the global warming potential of alternative stoves and fuels. This evidence would be valuable as part of arguments to garner international support for clean stoves and fuels (see below).
- Develop exposure atlases for particular regions or nations detailing regions of highest exposure and best potential for exposure reduction. This might involve:
  - Collecting and organizing information on fuel-use patterns, rural and urban, and identifying gaps in order to implement needed additional data gathering.
  - Collecting similar information on household conditions relevant to exposures; including those related to ventilation and, potentially, systematic time-activity surveys.
  - Coordinating with agencies taking data on outdoor pollution levels.
  - Develop models for predicting indoor concentrations based on these secondary data.
  - Validating the estimates by conducting IAQ measurements in an appropriate sample of households.
- Work to add a few of the most relevant questions related to IAQ to national census questionnaires or other regional, national, and international surveys, as has been performed in India and by the WHO.
- Consider promoting environmental indicators for access to clean household air equivalent to the commonly used international indicators for access to clean water and access sanitation (WHO, 2000). Possibilities include:
  - Access to clean fuels, which might be defined as the existence of a stove for using liquid and gaseous fuels combined with local availability of appropriate fuels below defined sulfur levels.
  - Access to ventilation, which might be defined as existence of chimneys, hoods, or outside cooking facilities.

Research on interventions

As with most of the important poverty-related environmental health risks, IAP tends to reduce with development. History has shown that people, given resources and access, will move to vented combustion and clean fuels by choice and markets will develop to meet the demand. The art and science of public health, however, is in finding ways to make people healthy before they become wealthy. We do this not only

[8] Particles in all biomass smokes, including those from tobacco, are generally in the respirable range of particle sizes (most less than a micron or two in diameter).

because it is right and moral, but because development itself is accelerated through a healthy population and workforce. We know how to do it effectively in many arenas, for example with vaccines, nutrition supplements, maternal education, primary health care, family planning, and improved water/sanitation, although there are still too many failures in political will in doing so. It is not so clear, however, that the available interventions for reducing IAP can be efficiently, effectively, and widely disseminated in populations still poor. This remains a tremendous research and implementation challenge at several levels. Here there is only room to discuss a few of the avenues of needed research.

Wood spaceheating stoves in many developed countries are now regulated by environmental agencies to meet emission standards. In response, clever designs involving such features as reliable secondary combustion or catalytic converters have enabled manufacturers to greatly reduce emissions as well as increase efficiency. Such stoves, however, all have flues and even the cleanest would not be considered suitable for venting indoors. Furthermore, by developing-country standards, they are extremely costly, $500 and up. Finally, of course, they are rarely designed for cooking. There is thus a great engineering challenge to bridge the cost gap between these devices and what is needed in the developing world. There would seem to be basically two approaches to designing biomass-burning cookstoves costing at most a few tens of dollars that reliably achieve sufficiently low indoor emissions from unprocessed biomass fuels:

- Stoves that achieve extremely reliable and high combustion efficiency such that emissions can be safely released into the living environment. To date, although relatively little R&D and systematic comparison has been conducted, only stoves relying on combustion with air forced by a small electrical fan seem likely to meet this criterion (Hall and Larson, 1997).
- Stove systems that remove the smoke from the living environment through flues or hoods/chimneys. Deceptively simple in concept, designing reliable and acceptable low-cost systems has turned out to be quite difficult. One reason is that in many cases, because of the added airflow from the natural draft induced by the flue, fuel efficiency is lowered, reducing the attractiveness to users.

One reason for the limited success of the improved stove programs in many parts of the world is that they often attempt to rely entirely on local materials, such as mud and sand. In reality, however, the local populations already probably have the best possible stoves using these resources. For significant improvement, there is probably usually a need to move to more durable materials such as ceramic and metal as well as providing the skills development needed to work with them. This has cost implications, but there is also good evidence from different part of the world that even quite poor people will be willing to help pay for truly improved and durable stoves that are significant additions to their assets.

The factors leading to adoption of any device operating at the household level extend well beyond the technical and economic to the social, cultural, and perceptual. As with implementation of improved water/sanitation, therefore, surveys, marketing, education, advertising, and other avenues directed at assessing and influencing behavior will also play important roles. In addition, of course, there are major differences in food availability and cooking practices around the developing world. The bad news is thus that there is unlikely to be any magic stove that will solve the IAP problem everywhere. The good news, however, is that there are likely to be large population niches for solutions at several levels of cost and technology.

There is research needed not only on the technologies and their acceptance at the household level, but also on the policy tools needed to promote exposure-reducing changes in household fuels and stoves.

- How to include education and training for improved kitchen hygiene as part of the primary health care package, healthy child package, water and sanitation package, maternal and child health package, etc.
- How to develop cofunding for exposure-reduction efforts among developing sectors (health, energy, housing, environment) in the worst affected regions.
- Conduct research on ways that different sectors can implement programs with exposure reduction potential, for example, fuel pricing in the energy sector.
- Review successes and failures of current and past programs to design and disseminate improved stoves with lower emissions and/or chimneys in order to distill lessons learned. Such reviews should include well-designed stratified random sampling of households with improved stoves for fuel efficiency and emissions/exposures. Of particular relevance in this regard would be a detailed review of the large-scale programs in India and China, which together have disseminated some 200 million stoves in 20 years but have been the subject of little or no independent evaluation since the early 1990s (Barnes *et al.*, 1993; Smith *et al.*, 1993).
- Intensified research to design and disseminate truly smokeless stoves with extended lifetimes (cost-effectiveness greatly depends on lifetime). To do this:
  - Focus on intermediate technology utilizing local artisans knowledgeable in the use of high-quality ceramics, metals, and other materials to make durable devices with the close tolerances required for long-lasting energy savings and smoke removal.

  - Schedule stove programs so that high exposure areas are addressed first.
  - Evaluate the impact of chimneys on overall exposure in densely populated areas where a significant amount of 'neighborhood' pollution can be created from household stoves, with or without chimneys/flues.
- Conduct systematic program of research to evaluate the effectiveness of various policy measures to encourage households to move up the 'energy ladder' to cleaner fuels faster than they would otherwise. This effort could include:
  - Enhanced availability and supply reliability of high-quality fuels (LPG and kerosene) in all areas, but first in areas with largest exposure.
  - Examination of economic and other policy tools to provide incentives to households to move up ladder, including coupons, stove and/or fuel subsidies, etc.
- Research on biomass-based clean household fuels that have the double advantage of being renewable when harvested and liquid or gaseous when burned. Such fuels thus have the potential double benefit of being greenhouse-gas neutral and health-promoting. Such research is needed not only on the technical parameters of such systems, but also on the financial, managerial, and other aspects of implementation in rural areas. The technology is currently available for biological conversion through anerobic digestion to biogas where sufficient animal dung or other appropriate biomass is available. Not well developed, but promising, are technologies for chemical gasification to producer gas at the village scale, which then can be distributed to households for cooking. The latter approach must be considered carefully, however, because producer gas typically contains dangerous CO levels.
- Research on the international policy implications of promoting household technologies that both reduce health impacts locally and help achieve greenhouse-gas reduction goals globally (Wang and Smith, 1999; Smith et al., 2000c).
- Finally, to make the case for IAP-reduction to national and international agencies, there is need to conduct rigorous economic analyses to demonstrate the cost-effectiveness of such measures in achieving health benefits, such as extending healthy life-years, and reducing the risk of climate change, such as carbon dioxide-equivalent emissions (Ezzati and Kammen, 2001b; Hughes et al., 2001).

Coal replacement for household biomass fuels

In a well-meaning effort to reduce the pressure on forests and other biomass resources by household fuel demands, it has been proposed in several countries of Asia and Africa to promote the substitution of coal as a household fuel. Although such a plan has some potential benefits, great caution should be exercised because of the health risk involved. Recent research in China and South Africa and older studies in the UK and elsewhere demonstrate quite clearly that household coal use can lead to dramatic health problems. For one example, China has among the highest lung cancer rates in the world for non-smoking women probably because of the extensive use of household coal.

Although it is possible to wash and process raw coal into cleaner-burning forms, it is not clear that sufficiently clean burning can be achieved at a cost competitive with the already well established cleaner fossil fuels, kerosene and LPG. In addition, even the cleanest forms of processed coal were eventually banned in many parts of the UK and elsewhere as too polluting for household use, particularly because of the 'neighborhood' pollution that often developed.

Thus, it is strongly urged that a thorough review, including new primary research if needed, be conducted well before embarking on such a program of coal substitution for the households of developing countries.

Conclusion

Although a program of risk, exposure, and intervention studies as outlined above would not be inexpensive by some measures, it is likely to be highly cost-effective as a means to address the large exposures now being experienced widely in developing countries. For comparison, it could be undertaken for far less (a few tens of millions of dollars) than what is commonly spent on air pollution controls for only one new coal-fired power plant of moderate size anywhere in the world. The potential impact on human exposures, by contrast, could be orders of magnitude higher.

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