# Estimating the burden of disease attributable to indoor air pollution from household use of solid fuels in South Africa in 2000

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*Objectives***.** To estimate the burden of respiratory ill health in South African children and adults in 2000 from exposure to indoor air pollution associated with household use of solid fuels.

*Design.* World Health Organization comparative risk assessment (CRA) methodology was followed. The South African Census 2001 was used to derive the proportion of households using solid fuels for cooking and heating by population group. Exposure estimates were adjusted by a ventilation factor taking into account the general level of ventilation in the households. Population-attributable fractions were calculated and applied to revised burden of disease estimates for each population group. Monte Carlo simulation-modelling techniques were used for uncertainty analysis.

*Setting.* South Africa.

*Subjects.* Black African, coloured, white and Indian children under 5 years of age and adults aged 30 years and older.

*Outcome measures.* Mortality and disability-adjusted life years (DALYs) from acute lower respiratory infections in children under 5 years, and chronic obstructive pulmonary disease and lung cancer in adults 30 years and older.

*Results.* An estimated 20% of South African households were exposed to indoor smoke from solid fuels, with marked variation by population group. This exposure was estimated to have caused 2 489 deaths (95% uncertainty interval 1 672 - 3 324) or 0.5% (95% uncertainty interval 0.3 - 0.6%) of all deaths in South Africa in 2000. The loss of healthy life years comprised a slightly smaller proportion of the total: 60 934 DALYs (95% uncertainty interval 41 170 - 81 246) or 0.4% of all DALYs (95% uncertainty interval 0.3 - 0.5%) in South Africa in 2000. Almost 99% of this burden occurred in the black African population.

*Conclusions.* The most important interventions to reduce this impact include access to cleaner household fuels, improved stoves, and better ventilation.

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Although attention to air pollutant emissions is dominated by outdoor sources, human exposure is a function of the level of pollution in places where people spend most of their time.[1-4] Human exposure to air pollution is therefore dominated by the indoor environment. Most research into indoor air pollution has focused on sources that are particularly relevant in developed countries, such as environmental tobacco smoke, volatile organic compounds from furnishings, and radon from soil.[5,6] This article focuses on the use of solid fuels for cooking and heating, which is probably the largest traditional source of indoor air pollution globally – nearly half the world continues to cook with solid fuels such as dung, wood, coal and agricultural residues. This includes more than 75% of the people in India and China and 50 - 75% of those in certain regions of South America and Africa. In China, it is estimated that indoor air pollution from solid fuel use is responsible for about 420 000 premature deaths annually, which is more than the 300 000 attributed to urban outdoor air pollution in the country.[7]

In South Africa, nationally representative data on household energy are available from two sources; viz the Demographic and Health Survey of 1998 (SADHS 1998),[8] and the national Census of 2001.[9,10] Both data sources indicate that the distribution of households by main energy source used for cooking or heating differs markedly by population group and province. (The population group classification is used in this article to demonstrate differences in the risk factor profile and the subsequent burden. Data are based on self-reported categories according to the population group categories used by Statistics South Africa. Such mentioning of differences allows for a more accurate estimate of the overall burden and may assist in higher effectiveness of future interventions. The authors do not subscribe to this classification for any other purpose.) Although 70% of South African households used electricity for lighting, only half used electricity for cooking and heating in 2001.[9] About one-third of households in the country used solid fuels (wood, coal and dung) for cooking and heating, and 95% of these households were black African.[9,10] A further 1 in 5 households used paraffin

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(kerosene), and a very small proportion (less than 3%) used gas for cooking and heating. In 2001 almost 60% of households in Limpopo, a predominantly rural province, used wood as the main source of energy for cooking (almost 3 times the national average), while in the more developed province of Gauteng less than 1% of households used wood for cooking.

Poorly designed and manufactured stoves and fireplaces burning solid fuels, as well as agricultural fires, emit significant quantities of health-damaging pollutants and carcinogenic compounds including respirable particles, carbon monoxide, nitrogen and sulphur oxides, benzene, formaldehyde, 1,3-butadiene, and polyaromatic compounds such as benzo(α)pyrene.[11,12] Household coal smoke has now been declared a class 1 carcinogen[13] and woodsmoke is also mutagenic and possibly carcinogenic, but less so than coal smoke.[11] Limited ventilation is common in many developing countries and this increases exposure, particularly for women and young children who spend much of their time indoors. Biomass smoke is also an important part of outdoor air pollution in developing countries, but no studies seem to have been done to separate out its impacts from those of other pollutants.[11] This is discussed in the urban outdoor air pollution assessment, a separate article in this supplement.[14]

In animal studies, exposure to woodsmoke results in significant impacts on the respiratory immune system and at high doses can produce long-term or permanent lesions in lung tissues.[11] Exposure to indoor air pollution has been associated with a number of health outcomes in humans, including chronic obstructive pulmonary disease (COPD), lung cancer, nasopharyngeal cancer, tuberculosis, cataracts, asthma, adverse birth outcomes and, of particular concern, acute lower respiratory infections (ALRIs) such as pneumonia among children younger than 5.[11,15,16] Worldwide, ALRIs are the single leading cause of death among children less than 5 years old,[17] and are among the top 4 killers of South African children under 5 years of age.[18,19]

In South Africa most published research has focused on the association between indoor air pollution and ALRIs in children. Although epidemiological studies of the health effects of indoor air pollution exposure are limited, several have highlighted cause for concern. As early as 1982, Kossove[20] found that of 132 infants with severe lower respiratory tract disease treated in an outpatient clinic, 70% were exposed to daily levels of smoke from cooking and heating. In comparison, only 33% of the 18 infants free of respiratory illness were exposed to smoke (odds ratio (OR) > 4).[20] Similarly, a failure to use electricity for cooking and heating (OR 2.5[21] and 3.5[22] respectively), as well as living in areas that are exposed to high levels of both indoor and outdoor air pollution,[23] were found to be associated with acute respiratory infections in children. Another study among poor communities living in the Eastern Cape showed a possible association between high levels of recurring respiratory symptoms among children and high levels of indoor air pollution (with levels of CO, $SO_2$ and $NO_2$ up to 12 times those of international guidelines).[24]

One of the most comprehensive South African studies, the Vaal Triangle Air Pollution Study (VAPS), highlighted, among others, high levels of air pollution in coal-burning urban areas as well as the risk to upper and lower respiratory health associated with exposure.[25,26] Among rural children the VAPS study also highlighted a significantly elevated risk of developing acute respiratory infection (OR > 5) among those in wood- and coal-burning homes.[27] In a recent re-analysis of SADHS 1998 data, exposure to cooking and heating smoke from polluting fuels (paraffin included) was significantly associated with under-5 mortality after controlling for mother's age at birth, water source, asset index and household density.[28]

A study of indoor air quality among paraffin-burning urban households revealed that 42% exceeded 1 hour guidelines for $SO_2$, 30% for CO, and 9% for $NO_2$.[29] Baseline monitoring of particulate matter with diameters less than 10 microns ($PM_{10}$) in the more rural North West province showed that 68% of wood- and cow dung-burning households exceeded the United States Environmental Protection Agency (24-hour) guideline for $PM_{10}$, in some instances by a factor of 20.[30]

Although South African epidemiological indoor air pollution studies are few, they are relatively consistent with the international evidence. With the exception of the study by Wesley and Loening,[31] all of those published showed positive associations between indoor air pollution and child ALRIs. The majority of studies reported ORs between 1.88 and 3.5, comparable with other studies in developing countries (ORs 2 - 3).[32] The aim of this study was to estimate the burden of disease attributed to indoor air pollution from household use of solid fuels in South Africa in 2000 by population group.

## Methods

Using World Health Organization (WHO) comparative risk assessment (CRA) methodology,[1,33] the disease burden attributable to this particular risk factor was estimated by comparing the current local health status with a theoretical minimum counterfactual with the lowest possible risk. The attributable fraction of disease burden in the population is determined by the prevalence of exposure to the risk factor in the population and the relative risk (RR) of disease occurrence given exposure.

Using an approach consistent with that used in most epidemiological studies in developing countries and in the WHO global assessment,[6,34] the local population was divided into categories of people exposed or not exposed to indoor smoke from solid fuels on the basis of the energy source used for cooking and heating. These two end-uses were combined, because in the global study it was not possible to distinguish between exposures from cooking and heating, although Smith *et al.*[6] maintain that these exposures can differ considerably because of different conversion technologies.

The theoretical minimum for this risk factor is no use of solid fuels for the production of household energy, and this has been achieved in many populations. Hence household solid fuel use was estimated at population group level using binary classifications of exposure to household fuel use (exposed to solid fuels if using wood, coal or dung; or not exposed if using electricity, gas or paraffin for cooking or heating) based on Census 2001 data.[10] Owing to marked differences in fuel use in the four different population groups, the analysis was carried out separately for each.

In order to account for differences in other factors such as type of housing which may affect levels of indoor air pollution, the exposure variable was adjusted by a ventilation factor:

*Household-equivalent solid fuel exposed population = (population using solid fuel) x (ventilation factor).*

The ventilation factor or coefficient reflects the share of people being exposed after taking into account the ventilation in the household. Solid fuel use outdoors results in complete ventilation and a ventilation coefficient of 0, while a poorly ventilated household would have a coefficient of 1. There is no national improved stove programme and although stoves are used daily for cooking, when the weather is mild cooking is often done outdoors, decreasing exposure. Based on expert opinion and taking into account that due to the mild climate, heating is only necessary for about 3 months of the year, we used an estimate of 0.6 (range 0.4 - 0.8 to allow for seasonal variation) as the ventilation factor.

Smith and colleagues[6] carried out a comprehensive review of the epidemiological evidence available for each disease endpoint in order to select the health outcomes caused by exposure to indoor smoke from the use of solid fuels. Three health outcomes had strong evidence of a causal relationship: ALRIs in children under 5 years, and COPD and lung cancer (from the use of coal) in adults of 30 years and older. Available data indicate that men are at lower risk than women because of lower exposures. Relative risk estimates are presented in Table I together with ICD-9[35] codes for related health outcomes.

Outcomes potentially associated with solid fuels but not quantified because of a lack of sufficient evidence on causality included cardiovascular disease, cataracts, tuberculosis, asthma, perinatal effects including low birth weight, and lung cancer from biomass. It is assumed that the nature and level of indoor air pollution caused by solid fuel use is similar across developing countries and the estimates of RRs and confidence intervals (CIs) for the related health outcomes from the meta-analyses of the available literature[6] presented in Table I are used in this study. It has been suggested that chronic bronchitis, tuberculosis, asthma and emphysema originating from infections or predisposing factors may increase the probability of developing lung cancer in later life.[36] The meta-analyses were therefore restricted to studies that controlled for the confounding effects of chronic respiratory disease and smoking.[6]

Customised MS Excel spreadsheets based on templates used in the WHO study (A Prüss-Üstün, WHO – personal communication, 2005) were used to calculate the attributable burden using the attributable fraction formula below:

$$PAF = \frac{P\,(RR-1)}{P\,(RR-1)+1}$$

where $P$ is the prevalence of exposure and $RR$ is the relative risk of disease in the exposed versus unexposed group. Population-attributable fractions (PAFs) were then applied to revised South African burden of disease estimates for 2000 for each population group,[37] deaths, years of life lost (YLLs), years of life lived with disability (YLDs) and disability-adjusted life years (DALYs) for the relevant disease categories to calculate attributable burden. The total attributable burden for South Africa in 2000 was obtained by adding the burden attributed to indoor smoke for the four population groups.

Smoking is an important risk factor for the diseases associated with indoor smoke from solid fuels, specifically lung cancer and COPD. However, information on the joint effects of smoking and solid fuel use is scarce. In order to avoid possible overestimation of the burden of disease attributable to indoor smoke, PAFs for lung cancer and COPD caused by exposure to indoor smoke were applied to disease burden remaining after removal of the burden attributable to tobacco (with an adjustment for occupational exposure). The burden attributable to smoking was obtained from the related article in this supplement.[38] It was estimated that, overall, about 21% of lung cancer deaths in males and 32% in females, and 31% of COPD deaths in males and 49% in females, were not attributable to tobacco. We acknowledge that this approach is highly conservative as attributable risks do not add up to 100% and some of the effect attributable to tobacco may also be attributable to indoor smoke from household use of solid fuel.

Monte Carlo simulation-modelling techniques were used to present uncertainty ranges around point estimates that reflect all the main sources of uncertainty in the calculations. The @RISK software version 4.5 for Excel[39] was used, which allows multiple recalculations of a spreadsheet, each time choosing a value from distributions defined for input variables. For the ventilation coefficient a uniform probability distribution was specified across the range 0.4 - 0.8. For the RR input variables we specified a normal distribution, with the natural logarithm of the published RR estimates as the entered means of the distribution and the standard errors of these RR estimates derived from the published 95% CIs (Table I). For each of the output variables (namely attributable burden as a percentage of total burden in South Africa, 2000), 95% uncertainty intervals were calculated bounded by the 2.5th and 97.5th percentiles of the 2000 iteration values generated.

**Table I. Relative risk estimates**

| Health outcome | ICD-9 code[35] | Age-sex group (years) | Lower estimate | Relative risk | Upper estimate | Evidence base |
|---|---|---|---|---|---|---|
| Acute lower respiratory infections | 466, 480-487 | Children < 5 | 1.9 | 2.3 | 2.7 | Strong |
| COPD | 490-492, 495-496, 416 | Women ≥ 30 | 2.3 | 3.2 | 4.8 | Strong |
| | | Men ≥ 30 | 1.0 | 1.8 | 3.2 | Moderate* |
| Lung cancer, coal only | 162, 166 | Women ≥ 30 | 1.09 | 1.94 | 3.47 | Strong |
| | | Men ≥ 30 | 0.97 | 1.51 | 2.46 | Moderate* |

Source: Smith *et al.*, 2004.[6]
*Few studies providing evidence of the impact on men are available.
Lung cancer = trachea/bronchi/lung cancer; COPD = chronic obstructive pulmonary disease.

## Results

Estimated exposure to indoor air pollution from household use of solid fuels is presented in Table II by population group. Separate estimates of exposure resulting from use of coal are also presented. Overall, 33% of South African households used solid fuels for cooking or heating, with marked population group differences ranging from 41% of black African households to only 1 - 2% of Indian and white households. After taking ventilation into account, exposure to solid fuels was estimated at 24% in the black African, followed by 9% in the coloured and about 1% in both the Indian and white population groups (Table II).

The PAFs for children under 5 years and adults of 30 years and older are shown in Table III. Overall in South Africa in 2000, about 24% of the burden from ALRIs in children under 5 years was attributable to indoor air pollution from household use of solid fuels. For COPD, female PAFs were more than double those in males. Indoor air pollution from household use of solid fuels was estimated to cause 2 489 deaths (95% uncertainty interval 1 672 - 3 324) or 0.5% (95% uncertainty interval 0.3 - 0.6%) of all deaths in South Africa in 2000. As most indoor smoke-related respiratory disease events occurred in very young children or in middle or old age, the loss of healthy life years comprised a slightly smaller proportion of the total: 60 934 DALYs (95% uncertainty interval 41 170 - 81 246) or 0.4% of all DALYs (95% uncertainty interval 0.3 - 0.5%) in South Africa in 2000 (Table III).

Age-standardised attributable mortality rates by population group are presented in Fig. 1. Large population group differences were observed, with the highest rates seen in black African males and females, followed by coloured males and females. Very low rates were observed in the Indian and white population groups. With exposure assumed to be the same for all household members, but adult women at an increased risk compared with adult men, in the black African groups age-standardised attributable mortality rates in females were, as expected, higher than in males. However, in the coloured group the rates in males were higher than in females. Almost all deaths (98%) and DALYs (99%) attributable to this risk factor occurred in the black African population group (data not shown).

The national average contribution of ALRIs in children under 5 years, and COPD and lung cancer in adults aged 30 years and older, to the total attributable burden is shown in Fig. 2. The burden of disease attributed to the use of household solid fuels is dominated by the burden caused by ALRIs in children under 5 years of age, which accounts for almost 80% of the total attributable burden. COPD accounts for almost all the remainder, with lung cancer burden a relatively minor contributor.

**Table II. Exposure to indoor air pollution from household use of solid fuels by population group,* South Africa, 2000**

| | Population group | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Household solid fuel use (%) | | | | | Exposure† adjusted by ventilation factor (%) | | | | |
| Fuel type | Black African | Coloured | White | Asian/Indian | South Africa | Black African | Coloured | White | Asian/Indian | South Africa |
| Solid fuel use | 41 | 15 | 2 | 1 | 33 | 24 | 9 | 1 | 1 | 20 |
| Biomass | 32 | 14 | 2 | 1 | 26 | 19 | 8 | 1 | 0 | 16 |
| Coal | 9 | 1 | 0 | 0 | 7 | 5 | 1 | 0 | 0 | 4 |

Source: Census 2001.[10]
*Population group of household head.
†Exposure to solid fuels = % households using solid fuels for cooking or heating after taking into account the ventilation in the households (ventilation coefficient 0.6).

**Table III. Burden attributable to indoor air pollution from household use of solid fuels, South Africa, 2000**

| Outcome | Male PAF (%) | Male Deaths | Male DALYs | Female PAF (%) | Female Deaths | Female DALYs | Person PAF (%) | Person Deaths | Person DALYs |
|---|---|---|---|---|---|---|---|---|---|
| Acute lower respiratory infections | 23.6 | 732 | 25 052 | 23.8 | 696 | 23 527 | 23.7 | 1 428 | 48 579 |
| Chronic obstructive pulmonary disease | 13.1 | 304 | 2 957 | 31.1 | 721 | 8 920 | 23.2 | 1 024 | 11 877 |
| Lung cancer | 1.8 | 16 | 197 | 3.3 | 21 | 281 | 2.4 | 37 | 479 |
| **Total** | | **1 052** | **28 206** | | **1 437** | **32 728** | | **2 489** | **60 934** |
| 95% uncertainty interval | | 607 - 1 564 | 18 495 - 38 781 | | 980 - 1 894 | 22 346 - 43 196 | | 1 672 - 3 324 | 41 170 - 81 246 |
| **% of total burden** | | **0.4%** | **0.3%** | | **0.6%** | **0.4%** | | **0.5%** | **0.4%** |
| 95% uncertainty interval | | 0.2 - 0.6% | 0.2 - 0.5% | | 0.4 - 0.8% | 0.3 - 0.6% | | 0.3 - 0.6% | 0.3 - 0.5% |

PAF = population-attributable fraction; DALYs = disability-adjusted life years.

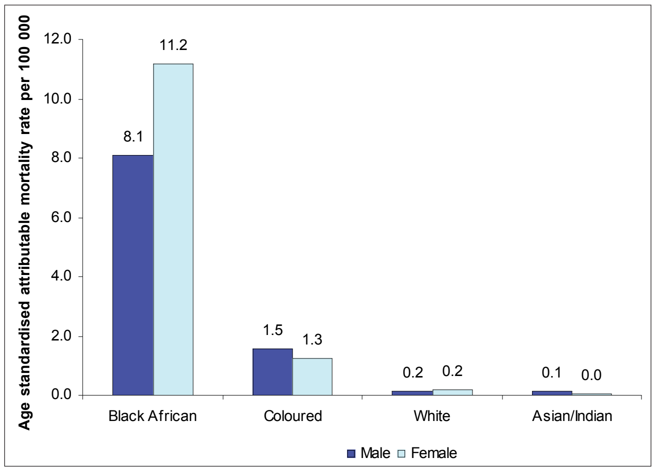


*Fig. 1. Age-standardised indoor air pollution attributable mortality rates by population group and sex, South Africa, 2000.*

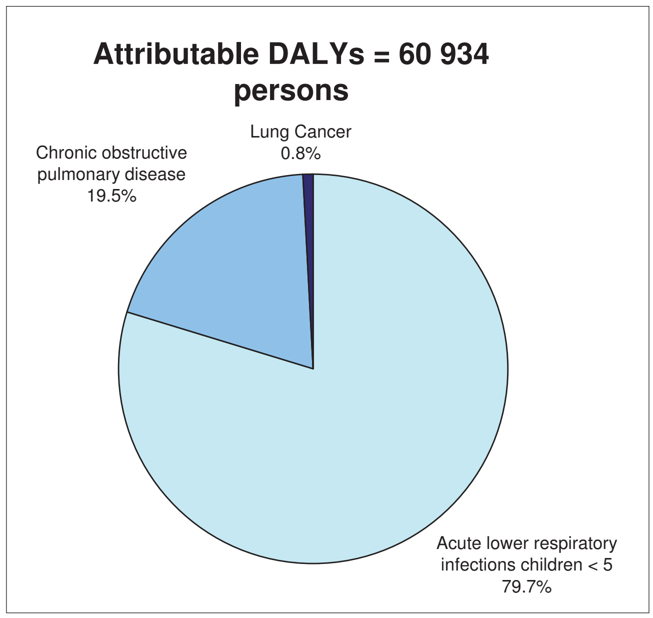


*Fig. 2. Burden of disease attributable to indoor air pollution from household use of solid fuels, South Africa, 2000.*

## Discussion

Globally, more than 1.6 million deaths and over 38.5 million DALYs (or about 3% of the global burden of disease) were attributable to indoor air pollution from household use of solid fuels in 2000. This risk factor appears to be of less serious public health importance in South Africa than the rest of sub-Saharan Africa. This is partly due to the lower exposure and better ventilation assumed in this study. In the global assessment, estimates for the African region were based on extrapolations from fuel use surveys and all African countries were assigned a ventilation coefficient of 1. WHO country-specific estimates for South Africa in 2002 estimated the percentage of the population using solid fuels at 18%, much lower than for other African countries, and 0.1% of DALYs were attributable to indoor air pollution from solid fuel use.[40] In this local assessment, after taking ventilation into account, exposure to solid fuels was estimated at 20% overall (Table II), and indoor air pollution from household use of solid fuels caused 0.4% of all DALYs (95% uncertainty interval: 0.3 - 0.5%) in South Africa in 2000.

It is likely that our estimate is an understatement of the burden as a result of several factors. Firstly, there is multiple fuel use and a degree of 'fuel switching' in poor households which may use up to 5 fuels for cooking and heating. Hence, even if households reported 'clean fuel' as their main energy source for cooking, they may often have complemented this with other fuels, based largely on affordability. One study[41] found that after being paid, people used paraffin for cooking and as the month progressed and funds diminished, they slid down the energy ladder to relying on wood (cheaper) and then cow dung (free) as the fuel source.

Considering the exposure as a binary classification would also result in an underestimation of the burden. In reality, exposure to indoor air pollution from the use of solid fuels results in a wide range of exposures, which vary according to fuel type and quality as well as stove and housing characteristics (ventilation and size), cooking and heating methods, time spent within the household, close proximity to the pollution source and the season. Exposure would therefore best be characterised as a continuous outcome, or at least better characterised by multiple categories.

The burden of lung cancer and COPD attributed to indoor smoke may also be an underestimate, as a conservative approach was used to adjust for the effects that may be attributable to indoor smoke from household use of solid fuel without the effect of tobacco. Furthermore, exposure to indoor pollution from solid fuel use and tobacco smoking may act synergistically on lung cancer and COPD; this would be particularly important in the black African population, where almost 99% of the burden occurs, and smoking is also an important risk factor among males.

There is also growing evidence that other important health outcomes such as tuberculosis (of special concern because it is also closely related to the HIV/AIDS epidemic), ischaemic heart disease and asthma, which are among the leading causes of death in the country, may also be associated with exposure to indoor smoke from solid fuels. However, these outcomes were not included in this analysis as the evidence was considered insufficient at this stage,[6] which may also result in an underestimate of the true burden attributable to this risk factor. The association between these priority diseases and indoor smoke needs further investigation in our local setting.

It was also assumed that children aged 6 - 14 years and adults aged 15 - 29 years were not exposed to this risk factor, although there is probably some exposure in these groups. Furthermore, although the related chronic diseases would not yet manifest in the 15 - 29-year age group, the development of these diseases at older ages is a consequence of exposure in the younger age groups. As levels are unknown in these age groups they could not be quantified, possibly also leading to an underestimate.

This analysis considered only the disease burden attributable to indoor smoke from solid fuels. However, this risk factor may work jointly or synergistically with others (such as undernutrition or HIV) to increase incidence and effects of diseases such as ALRI. Some risks related to indoor smoke may be mediated through undernutrition while, equally, some risks for undernutrition may be mediated through indoor smoke-related ALRI. HIV-positive children living in conditions of high exposure to indoor air pollution may be particularly vulnerable to consequent respiratory ill health effects. However, the extent to which this may occur is difficult to measure and has not been assessed.

Due to lack of local epidemiological data, results of the meta-analysis by Smith and colleagues[6] were used as the source of the RR estimates. This is not ideal as extrapolating results of epidemiological studies from one region to another does not take into account the potentially interactive risk factors such as malnutrition or HIV, which were not addressed in all of the meta-analyses[6] and would result in an unquantified uncertainty in our results. It would be important to collect more epidemiological data on the risks of indoor air pollution in the current South African setting.

The use of solid fuels also impacts negatively on household economies due to the time spent harvesting, storing and preparing these fuels. This deducts time that can be spent on other tasks including child care, education, domestic hygiene, commercial activities and rest and relaxation, particularly for women, thereby impacting negatively on health and well-being. It should be noted that other fuels carry health risks too. For example, households using paraffin and gas for cooking and heating may also be exposed to pollution, largely related to stove quality, and are also at risk of fire injuries and childhood poisonings associated with the use of paraffin. Access to electricity is therefore key to good health, breaking the cycle of poverty, and to promoting sustainable development. However, there are health risks involved in providing electricity to households as well, including occupational hazards from coal mining, air pollution from power plants, and nuclear plant accidents.[6]

## Conclusions and recommendations

Indoor smoke is ranked 15 overall in terms of DALYs compared with 17 risk factors assessed in South Africa, ranking lower than unsafe water, sanitation and hygiene but higher than lead exposure and urban outdoor air pollution. Indoor smoke from solid fuels is an important risk factor in children, with more than 1.1 million children under 5 years of age exposed to this risk. In children under 5 years, indoor smoke ranked 7th overall, accounting for 1.2% of all healthy life years lost in this group. As this burden is preventable and amenable to interventions, it is important to identify appropriate exposure reduction interventions.

Four intervention categories have been identified for their potential to reduce the impact of indoor air pollution on child acute respiratory infection: cleaner burning fuels, improved cooking stoves, housing design, and behavioural change.[42-44] An improved biomass stove is the most cost-effective intervention for sub-Saharan Africa.[44] In a randomised controlled trial on the effects of indoor smoke on the risk of pneumonia in children, the introduction of a well-operating chimney stove reduced exposure to indoor smoke by about half. As a result the risk of serious bacterial pneumonia in children, the most life-threatening form, was reduced by about 40%.[45] In the same trial, the chimney stove reduced blood pressure in women, the first quantitative evidence of an effect on a major cardiovascular risk factor.[46] Evidence exists in the South African context of the potential for intervention in relation to cleaner-burning fuels, for example electricity,[47] liquid petroleum gas[24] and low-smoke coal;[48] improved cook stoves;[49] as well as behavioural change, such as the reverse ignition process or 'scotch method' for coal[50] (the heavier material, i.e. coal, is placed at the bottom, followed by the paper and wood which are ignited on top of it – in other words the fire burns down, leading to lower emissions and better fuel efficiency) and the promotion of outdoor burning in poor rural areas.[30] It is important to note, however, that while interventions may show promise in terms of air pollution reduction, the sustainability of interventions in resource-poor contexts has been questioned. Nonetheless, efforts should continue to promote indoor air pollution reduction in populations that are most vulnerable to the health effects. Intervention technologies ranging from as simple as adding a chimney to a modernised bio-energy programme can only be viable with co-ordinated support from the government and/or commercial sector.[7]

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**References**


1. World Health Organization. Quantifying selected major risks to health. In: *World Health Report 2002*. Geneva: WHO, 2002: 47-97.
2. Bruce N, Perez-Padilla R, Albalak R. Indoor air pollution in developing countries: a major environmental and public health challenge. *Bull World Health Organ* 2000; 78: 1078-1092.
3. Smith KR, Samet JM, Romieu I, Bruce N. Indoor air pollution in developing countries and ALRI in children. *Thorax* 2000; 55: 518-532.
4. Smith KR. Inaugural article: national burden of disease in India from indoor air pollution. *Proc Natl Acad Sci USA* 2000; 97: 13286-13293.
5. Spengler JD, Samet JM, McCarthy JF. *Indoor Air Quality Handbook*. New York: McGraw-Hill, 2001.
6. Smith KR, Mehta S, Maeusezahl-Feuz M. Indoor air pollution from household use of solid fuels. In: Ezzati M, Lopez AD, Rodgers A, Murray CJL, eds. *Comparative Quantification of Health Risks, Global and Regional Burden of Disease Attributable to Selected Major Risk Factors. Geneva:* World Health Organization, 2004: 1436-1493.
7. Zhang J, Smith KR. Household air pollution from coal and biomass fuels in China: Measurements, health impacts, and interventions. *Environ Health Perspect 2007*. http://www.ehponline.org/members/2007/9479/9479.pdf (last accessed 4 April 2007).
8. Department of Health, Medical Research Council and Macro International. *South African Demographic and Health Survey 1998*. Full report. Pretoria: DOH, 2002.
9. Census 2001. Census in brief. Statistics South Africa. Pretoria: Statistics South Africa, 2003. www.statssa.gov.za
10. Statistics South Africa. Census 2001: Metadata. Pretoria: Statistics South Africa, 2004. http://www.statssa.gov.za/census01/html/C2001metadata.asp (last accessed 31 January 2007).
11. Naeher LP, Brauer M, Lipsett M, *et al*. Woodsmoke health effects: A review. *Inhalation Toxicology* 2007; 19: 67-106.
12. Smith KR. *Biofuels, Air Pollution, and Health: A Global Review*. New York: Plenum, 1987.
13. Straif K, Baan R, Grosse Y, Secretan B, El Ghissassi F, Cogliano V, on behalf of the WHO IARC Monograph Working Group. Carcinogenicity of household solid fuel combustion and of high-temperature frying. *Lancet Oncology* 2006; 7: 977-978.
14. Norman R, Cairncross E, Witi J, Bradshaw D. Estimating the burden of urban outdoor air pollution in South Africa 2000. *S Afr Med J* 2007; 97: 782-790 (this issue).
15. Bruce N, Perez-Padilla R, Albalak R. Indoor air pollution in developing countries: a major environmental and public health challenge. *Bull World Health Organ* 2000; 78: 1078-1092.
16. Smith KR, Samet JM, Romieu I, Bruce N. Indoor air pollution in developing countries and acute lower respiratory infection in children. *Thorax* 2000; 55: 518-532.
17. Murray CJL, Lopez AD. Global mortality, disability, and the contribution of risk factors: Global Burden of Disease Study. *Lancet* 1997; 349: 1436-1442.
18. von Schirnding YER, Yach D, Klein M. Acute respiratory infections as an important cause of deaths in South Africa. *S Afr Med J* 1991; 80: 79-82.
19. Bradshaw D, Bourne D, Nannan N. What are the leading causes of death among South African children? MRC Policy Brief. Cape Town: Medical Research Council; 2003. http://www.mrc.ac.za/bod/reports.htm (last accessed 30 January 2007).
20. Kossove D. Smoke filled rooms and lower respiratory disease in infants. *S Afr Med J* 1982; 62: 622-624.
21. von Schirnding YER, Yach D, Blignaut R, Mathews C. Environmental determinants of acute respiratory symptoms and dirrhoea in young coloured children living in urban and peri-urban areas of South Africa. *S Afr Med J* 1991; 79: 457-461.
22. Dudley L, Hussey G, Huskissen J, Kessow G. Vitamin A status, other risk factors and acute respiratory infection morbidity in children. *S Afr Med J* 1997; 87: 65-70.
23. Zwi S, Davies JCA, Becklake MR, Goldman HI, Reinach SG, Kallenbach JM. Respiratory health status of children in the eastern Transvaal highveld. *S Afr Med J* 1990; 78: 647-653.
24. Sanyal DK, Maduna ME. Possible relationship between indoor air pollution and respiratory illness in an Eastern Cape community. *South African Journal of Science* 2000; 96: 94-96.
25. Terblanche AP, Opperman L, Nel CM, Nyikos H. Exposure to air pollution from transitional household fuels in a South African population. *J Expo Anal Environ Epidemiol* 1993; 3: 15-22.
26. Terblanche AP, Opperman L, Nel CM, Reinach SG, Tosen G, Cadman A. Preliminary results of exposure measurements and health effects of the Vaal Triangle Air Pollution Health Study. *S Afr Med J* 1992; 81: 550-556.
27. Nel R, Terblanche P, Danford I, Opperman LBP, Pols A. Domestic fuel exposure as a risk factor for development of upper respiratory illnesses and lower respiratory illnesses in rural and urban communities. Proceedings of Clean Air Challenges Conference, Dikhololo Game Lodge, Brits, 11 - 12 November 1993: paper 7, pp. 1-5.
28. Wichmann J, Voyi KVV. Influence of cooking and heating fuel use on 1 - 59-month-old mortality in South Africa. *Matern Child Health J* 2006; 10: 553-561.
29. Bailie RS, Pilotto LS, Ehrlich RI, Mbuli S, Truter R, Terblanche P. Poor urban environments: use of paraffin and other fuels as sources of indoor air pollution. *J Epidemiol Community Health* 1999; 53: 585-586.
30. Barnes B, Mathee A, Bruce N, Thomas L. Protecting children from indoor burning through outdoor burning in rural South Africa. *Boiling Point* 2006; 52: 11-13.
31. Wesley AG, Loening WEK. Assessment and 2-year follow-up of some factors associated with severity of respiratory infections in early childhood. *S Afr Med J* 1996; 86: 365-368.
32. Smith KR. Indoor air pollution in developing countries: recommendations for research. *Indoor Air* 2002; 12: 198-207.
33. Ezzati M, Lopez A, Rodgers A, Vander Hoorn S, Murray C. Selected major risk factors and global and regional burden of disease. *Lancet* 2002; 360: 1347-1360.
34. Desai MA, Mehta S, Smith KR. *Indoor Smoke from Solid Fuels: Assessing the Environmental Burden of Disease at National and Local Levels*. Geneva: World Health Organization, 2004. (WHO Environmental Burden of Disease Series, No. 4).
35. World Health Organization. *International Classification of Diseases. Manual of the International Statistical Classification of Diseases, Injuries, and Causes of Death, Based on the Recommendations of the Ninth Revision Conference in 1975*. Geneva: WHO, 1977.
36. Luo RX, Wu B, Yi YN, Huang ZW, Lin RT. Indoor burning coal air pollution and lung cancer – a case-control study in Fuzhou, China. *Lung Cancer* 1996, 14: S113–119.

37. Norman R, Bradshaw D, Schneider M, Pieterse D, Groenewald P. *Revised Burden of Disease Estimates for the Comparative Risk Factor Assessment. South Africa 2000*. Methodological Notes. Cape Town: Medical Research Council, 2006. http://www.mrc.ac.za/bod/bod.htm (last accessed 7 July 2006).
38. Groenewald P, Vos T, Norman R, *et al*. Estimating the burden due to smoking in South Africa. *S Afr Med J* 2007; 97: 674-681 (this issue).
39. Palisade Corporation. @RISK software version 4.5 for Excel. New York: Palisade Corporation, 2002.
40. World Health Organization. *Indoor Air Pollution: National Burden of Disease Estimates*. Geneva: WHO, 2007. http://www.who.int/indoorair/publications/indoor_air_national_burden_estimate_revised.pdf (last accessed 31 May 2007).
41. Barnes BR, Mathee A. *The Identification of Behavioural Intervention Opportunities to Reduce Child Exposure to Indoor Air Pollution in Rural South Africa*. Johannesburg: Medical Research Council of South Africa, 2002. http://www.mrc.ac.za/healthdevelop/IAPphase1report.pdf (last accessed 31 January 2007).
42. Ballard-Tremeer G, Mathee A. *Review of Interventions to Reduce Exposure of Women and Young Children to Indoor Air Pollution in Developing Countries.* Washington, DC: WHO/ USAID Global Consultation, 2000.
43. von Schirnding Y, Bruce N, Smith KR, Ballard-Tremeer G, Ezzati M, Lvovsky K. *Addressing the Impact of Household Energy and Indoor Air Pollution on the Health of the Poor.* Geneva: World Health Organization, 2002.
44. Bruce N, Rehfuess E, Mehta S, Hutton G, Smith K. Indoor air pollution. In: Jamison DT, Breman JG, Measham AR, *et al*., eds. *Disease Control Priorities in Developing Countries*. 2nd ed. Washington, DC: Oxford University Press and The World Bank, 2006.
45. Smith KR, Bruce N, Weber MW, *et al*. Impact of a chimney wood stove on risk of pneumonia in children aged less than 18 months in rural Guatemala: Results from a randomized, controlled trial. International Society for Environmental Epidemiology (ISEE/ISEA) 2006, Paris, France. Symposium Abstracts. Epidemiology 2006; 17(6): Suppl, S45.
46. McCracken JP, Díaz A, Smith KR, Mittleman MA, Schwartz J. Chimney stove intervention to reduce longterm woodsmoke exposure lowers blood pressure among Guatemalan women. *Environ Health Perspect* 2007. http://www.ehponline.org/members/2007/9888/9888.pdf (last accessed 4 April 2007).
47. Röllin HB, Mathee A, Bruce N, Levin J, von Schirnding YER. Comparison of indoor air quality in electrified and un-electrified dwellings in rural South African villages. *Indoor Air* 2004; 14: 208-216.
48. Engelbrecht JP, Swanepoel L, Chow JC, Watson JG, Egami RT. PM2.5 and PM10 concentrations from the Qalabotjha low-smoke fuels macro-scale experiment in South Africa. *Environ Monit Assess* 2001; 69: 1-15.
49. Ballard-Tremeer G, Jawurek HH. Comparison of five rural, wood-burning cooking devices: efficiencies and emission. *Biomass and Bioenergy* 1996; 11: 419-430.
50. Surridge AD, Kgobane KB, Chauke GR. Strategy to combat the negative impacts of domestic coal combustion: Basa Njengo Magogo. *Clean Air Journal* 2005; 14: 13-16.