Considerations in Intervention Design to Reduce Indoor Air Pollution from Cooking with Biomass

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A Master's project submitted to the School of Environmental Studies

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June, 2008

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Introduction

> The fire-mediated relationship between humans and the Earth is complex. It comes directly through control over ignition and indirectly through manipulation of the available fuels. A still greater range of indirect effects derives from fire's power as a catalyst, an enabling device for hunting, foraging, farming, pastoralism, heat engines, and fire-dependent technologies from ceramics to metallurgy to fire-tempered spears and stones. Thus fire is at once *cause,* consequence, and catalyst. Its universality makes it a convenient index for virtually all human relations with the Earth.
>
> Fire origin myths almost universally identify the acquisition of fire as the means of passage from life among the beasts into special status as a human being. In ecological terms that mythology contains more than a kernel of truth. Revealingly the etymology of the English word "focus" derives from the Latin focus, meaning '"hearth." Controlled combustion remains, literally, the focus of human life. Accordingly wholesale anthropogenic modification of the biosphere did not begin with the industrial revolution or with the Neolithic revolution but with the hominid revolution announced with Promethean splendor by the capture of fire. (Pyne, 1994)

This excerpt from Stephen Pyne's historical analysis of anthropogenic fire captures three fundamental concepts. The first is the inextricability of fire from human life as it has been conceived since the species first learned to control the former at least 800,000 years ago (Goren-Inbar *et al*., 2004). [1] The second, which stems from the first, is the multitude of uses that fire has for humans as an "enabling device" (Pyne, 1994). While the above list ranges from primitive to more modern functions, its contemporary widespread use for cooking, heating, lighting, transportation and industrial activity maintains its place as both a central and diverse tool in human society. The third and final notion worth highlighting is the ensuing "modification of the biosphere" by human life that arguably originates from the time of the aforementioned acquisition of fire control. The environmental impacts of humanity present an ever-growing threat to the

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[1] Recent findings suggest that the origins of human fire control may in fact date as far back as 1.5 million years ago. (Rincon, 2004)

ecological balance that has characterized the planet to date. It is imperative to recognize a correlation between these impacts and such an essential facet of human existence as fire if irreversible damage is to be mediated through changed practices.

Global use of solid fuels

Fire is used around the world for cooking, heating and lighting. The process of burning, or combustion, that produces heat and light requires a chemical reaction between a fuel and an oxidizing element, usually oxygen from the ambient air. The World Health Organization (WHO) estimates that approximately 3 billion people rely primarily on solid fuels (Bruce *et al*., 2002), namely wood, dung, agricultural residues, charcoal and coal, towards this end (Larson and Rosen, 2002). The former three belong to the family of living or recently dead biological material known as biomass while the latter two are substances that have been transformed from biomass by geological processes. Nearly one-tenth of total human energy needs are accounted for by biomass use, of which wood-based fuels alone represent almost two-thirds of household consumption (Smith, 2006a). The use of these fuels occurs primarily in low-income countries where in the poorest, and predominantly rural, areas of Asia and Sub-Saharan Africa they account for as much as 90% of rural households' energy needs (Bruce *et al.,* 2002). Since the mid-20th century, most high-income countries have transitioned to electricity, oil and natural gas for many of their energy needs. (Ramanakumar *et al*., 2006) There is clearly strong regional variation in the use of solid fuels (Bruce *et al*., 2006). Evidence suggests that the population reliant on biomass for energy in many of these low-income countries is increasing (Bruce *et al*., 2000) and is projected to continue to do so over the next 20 years (IEA, 2002). This paper will focus on low-income countries exclusively, as they represent such a disproportionately large share of global use and their socio-economic conditions differ so greatly from their higher-income counterparts that factors determining fuel choices in each display little congruency for analysis.

Indoor Air Pollution (IAP)

The complete combustion of biomass fuels under ideal conditions produces mainly carbon dioxide and water as emission products, along with inorganic ash, and is thus fairly clean (Smith, 2006a). In low-income countries, however, these conditions are rarely realized. The open fires and traditional cookstoves that dominate cooking, heating and at times lighting practices in those countries generate incomplete combustion (Smith *et al*., 2000). This in turn produces a myriad of chemical compounds other than carbon dioxide that may be emitted into the air. The most pervasive of these are the gaseous compounds- carbon monoxide (CO), nitrogen oxides (NOx), sulphur dioxide, (Ballard-Tremeer and Jawurek, 1996) as well as a host of volatile organic compounds (VOC), semivolatile organic compounds (SVOC) and smoke which is an aerosol comprised of fine carbon-based particles[2](Zhang and Smith, 2003).[3] Given the complex chemical nature of the air-borne emission products (Schei *et al.,* 2004), the mixture at any one time is variable and is determined by the source, materials combusted, combustion conditions, and the time lapsed since it was generated. Following common practice in some of the literature, this text will use the terms ‘smoke’, ‘emissions’ and ‘pollutants’ interchangeably to refer to these chemical mixtures, be they gaseous or aerosol, produced

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[2] Hereafter referred to as particulate matter (PM)

[3] Examples of VOCs are benezene, toluene and formaldehyde and SVOCs include phthalate plasticizers and pesticides.

by combustion (Smith, 1987).

Health Impact

While the presence of smoke indoors may be unpleasant by virtue of itself, exposure to the aforementioned emissions has also been associated with numerous proven and postulated health problems.[4] Frequent reporting of cough and eye irritation by traditional fuel users (WHO, 2002) is complemented by a growing set of small scale studies striving to establish causal relationships. Some of the smoke-related pollutants have been found to harm the defense mechanisms that protect against infectious organisms (Smith *et al.*, 2000). In addition many of these have been shown to adversely affect the respiratory functions of the body, and the findings have allowed the conclusion of a causal link between exposure and an increased risk of acute lower respiratory infection (ALRI)[5] (Ezzati and Kammen, 2001; Bruce *et al*., 2002). Furthermore the pollutants may exacerbate the severity of respiratory infections through inflammation of the lung airways and alveoli (Smith *et al*., 2000). Of particular concern are the small particles (PM 2.5)[6] produced in high concentrations by traditional fuels that have been found to penetrate most deeply into the respiratory system (Brunekreef and Holgate, 2002). Adult women who have spent many years cooking over unvented stoves suffer high rates of chronic obstructive pulmonary diseases (COPD) (Smith, 2006a). The World

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[4] See Smith *et al*. (2000); Bruce *et al*. (2000; 2002) and WHO (2002) for a more detailed account of detected health impacts of the emissions in question.

[5] See Ezzati (2000) for a complete explanation of acute respiratory infections.

[6] Until recently most research focused on particulate matter with a median diameter of less than 10 μm, but there is now widespread recognition that particles smaller than 2.5 μm are able to penetrate moret deeply into the lungs and thus may be even more important in the ability to generate detrimental health effects (WHO, 2000).

Health Organization has deemed the evidence for a causal link between indoor air pollution exposure and both ALRI and COPD to be strong (WHO, 2002). Further, CO exposure is a proven factor influencing low birthweight of infants and may increase *in utero* risks resulting in excess infancy disease risk (Mishra *et al.*, 2004). Use of biomass as fuel has also been associated with increased risk of tuberculosis and vision problems such as cataracts and blindness (Mishra *et al.*, 1999a,b); Pokhrel *et al.*, 2005). Other diseases for which expected correlations have been suggested are heart disease and asthma (Mishra, 2003). While biomass fuel is a designated probable human carcinogen, smoke from coal combustion is proven to be so (Straif *et al.*, 2006). [7]

Burden of Disease

Acute respiratory infection (ARI), most frequently in the form of pneumonia, is the most common cause of illness in children under five, causing 3-5 million deaths a year (Smith *et al*., 2000). The susceptibility of children is magnified by the immaturity of their respiratory defense mechanisms (Smith *et al*., 2000). The result is an inflated amount of disability-adjusted life years (DALYs)[8] lost, estimated at 2.7% of the global total (Bruce *et al*., 2006). Preceded only by heart disease, cancer and cerebrovascular disease, ARI is one of the leading causes of death in the world. ALRI, a predominant form of ARI, in children under five causes more than half of all deaths and 83% of

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[7] Bruce *et al.* (2000) list several limitations on the evidence for health effects including "a general paucity of studies for many conditions, a lack of pollution/exposure determinations, the observational character of all studies, and the failure of too many studies to deal adequately with confounding". Despite this reality, current literature deems the evidence for ALRI and COPD to be suggestive of causality and for the other abovementioned conditions to be 'compelling' and worthy of further research.

[8] See WHO (2002) for further explanation of Disability Adjusted Life Years (DALYs).

DALYs lost by virtue of solid fuel use (Bruce *et al.,* 2006). Solid fuel use has been associated with 800,000 to 2.4 million premature deaths a year (Smith, 2006a) and ranks tenth globally among health risks that incite potentially preventable lost life years (Zhang and Smith, 2003). In lower-income countries, solid fuel use is the fourth greatest risk factor after malnutrition, unsafe sex, and lack of water and sanitation, second only to the latter among all environmental risk factors (Zhang and Smith, 2003). In these areas, over half the deaths from COPD among women and both 30% of mortality and 40% of morbidity resulting from ALRI are attributed to solid fuel use (Bruce *et al.,* 2006). Many countries have set outdoor air quality standards for the pollutants outlined above, testifying to the hazard they present to human health (Smith *et al.*, 2000). There are, however, no internationally recognized standards for pollutant concentrations indoors, inciting inquiry into estimates of total population exposure in developing countries.[9] Under the premise that for many people more time is spent indoors than outdoors, Smith and his colleagues (2000) assert that "the total global dose equivalent (amount actually inhaled) for indoor pollution could be an order of magnitude greater than from ambient pollution". They conclude that it is likely that ARI "disease outcome represents the largest class of health impacts from air pollution exposure worldwide" (2000).[10] Such a pervasive health risk begs to be addressed as a major public health issue (Bruce *et al.,* 2000).

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[9] A more in depth discussion of emissions below will present IAQ guidelines and examples of national standards in contrast to those characterizing solid fuel use.

[10] See WHO (2002) for a detailed explanation on the concept of Global Burden of Disease.

Determinants of Exposure

While the studies referenced above suffer from a "lack of detailed and systematic pollution exposure determination" (Bruce *et al*., 2002), there is enough general knowledge about the predominant determinants of exposure to pollutants to assume a role played by certain factors. Highlighting these determinants is a necessary prerequisite for establishing interventions that could reduce exposure. Exposure is essentially the pollutant concentration within a defined breathing environment during an established period of time (Bruce *et al*., 2000). Ramanakumar *et al.* (2007) provide a non-exhaustive list of determining factors in IAP exposure, namely the "type of fuel, source of fuel, physical characteristics and layout of the dwelling, presence of other air contaminants, location of heating or cooking appliance, use patterns of the appliances, ventilation conditions, season and time of day". Important additional factors are the amount of time spent in the contaminated environment and the convergence of this with the time-activity pattern of the appliance use (Smith *et al.,* 2000). As Smith *et al.* (2000) articulate, "[t]he composition of the smoke varies with even minor changes in fuel quality, cooking stove configuration, or combustion characteristics", indicating variety in the nature of the emissions and therefore in the impact of the emissions as well. It can also be extrapolated that the variety induced by 'even minor changes' indicates potential for improvements with alterations in those factors. An important component of exposure determination that will be discussed at greater length below, is the uneven distribution of exposure for certain demographics. The close relationship between socioeconomic conditions and solid fuel use referenced above highlights the greater exposure of poor populations (Bruce *et al.,* 2006). Further, women's dominant role in food preparation and child rearing means that both gender and age are significant determinants in ultimate exposure and disease risk (Pandey *et al.,* 1989). As women and children spend more of their day in proximity to the pollutants, their time-activity patterns subject them to higher overall exposures (Zhang and Smith, 2003).[11] These phenomena are central to understanding not just how, but who is at greatest risk of exposure, a primary factor to be considered when attempting to alleviate the problem.

Purpose of paper

The ever-growing research on the health effects of indoor air pollution from solid fuels is being complemented in turn by a drive to reduce exposure on a large scale. This effort has been in the form of interventions undertaken at the community level, as well as by government and non-governmental organizations. These interventions vary greatly in nature, from the factors they alter, and the people they affect, to how they are implemented and their ensuing success. Further, beyond the initial intervention design, there arises with each a myriad of issues and considerations that are central to the final outcome of the project. While the literature is replete with the results of these experiences, each is presented within an isolated and narrow scope. There is a paucity of any type of work that integrates all of these findings and presents all the necessary considerations that should precede future interventions. As the WHO warns "[c]urrent evidence on the effectiveness of different interventions is insufficient for providing clear guidance to decision-makers on suitable strategies to reduce the health effects caused by

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[11] See WHO (2006) Air Quality Guidelines for information about the greater susceptibility of the undeveloped lungs and immune systems of young children to the harmful effects of pollutants.

indoor air pollution" (WHO, 2008). In turn the organization has embarked upon, and is in the preliminary stages of, a Programme on Indoor Air Pollution to present an inventory of intervention experiences. This paper strives to produce such a catalogue in the hopes of filling the aforementioned dearth. It presents a systematic treatment of an admittedly broad topic with the hopes of capturing the relevant components in a holistic manner. An amalgamation of a fractured literature will seek a more methodical approach for policy-makers to evaluate the viability of an intervention within its proposed context.

The first section of the paper will correlate for the reader the above-described exposure determinants with the various interventions that have been both applied and postulated for implementation. In other words, based on the factors that dictate exposure, the possible changes to these factors that are suggested to reduce exposure will be presented and discussed. Broadly, these will be the sources of the pollutants, namely the fuel type and combustion devices; the environment in which the pollutants are produced, specifically the housing design and ventilation of the space; and finally user characteristics that can be modified by various behavioural adjustments. All of these elements and options will be defined and the implications of their implementation with respect to emissions levels will be described to the extent that they are known.

The second section of the paper will systematically highlight and discuss the factors arising throughout the literature that may affect the success and viability of an intervention. Many of these have hitherto been ignored, given little consideration, or not been deemed as important as experience elucidates them to be. Those categories of factors that will be outlined are: other uses of the energy sources; climate; costs and income generation; access, availability and the reliability of supply; infrastructure and education; gender and susceptible demographics and finally, preferences and perceptions. Insight into how these factors can ultimately determine household energy choices will be presented based on past programme experiences and anecdotal evidence from user testimonials reported in the literature. Some concluding remarks will look forward to improved intervention design and implementation premised on thorough consideration of all these factors.

Chapter 1- Interventions

The wide-range of factors that determine a person's exposure to pollutants dictates in turn that the possible interventions to reduce this exposure span a similar gamut. Aptly put by Kirk Smith in his book on bio-fuels, air pollution and health, this subject encompasses:

> a set of problems that do not fit neatly into traditional disciplines of inquiry. These problems could be classified as health problems, or problems of economic development, intra-familial equity, the environment, energy, or housing, to name a few of the most obvious. Just as the causes are not simple, neither are the solutions, which must address a range of social and technical questions if they are to be feasible and effective (Smith, 1987).

This statement provides a preface to the implicitly interdisciplinary and deeply intertwined nature of the issue of indoor air pollution. Addressing any one element of the so-called set of problems inherently begs discussion of others. It thus goes without saying that a paper attempting to present all said elements in a clear manner faces an organizational challenge.

As outlined in the introduction, current research on indoor air pollution exposure is neither exhaustive nor comprehensively documented, but intervention design over the last 30 years has been rooted in those primary factors that have been increasingly better understood and, in turn, conclusively associated with pollutant exposure.[12] The literature generally categorizes these factors into three overarching groups (Bruce *et al*., 2006). The first set is most commonly comprised of 'source' factors and encompasses fuel types

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[12] See Smith *et al.* for a technical discussion of the physical factors affecting indoor concentrations, namely outside concentrations, fuel-stove emission factors (fuel type, fueling rate and combustion conditions), room volume, effective air exchange rate, and conditions of the room, air and fire that induce mixing (1983).

and combustion devices. The second, labeled 'environmental', describes features of the physical space in which the combustion takes place, namely the size and layout of the location, ventilation conditions, and other sources of pollutants such as building materials. The third and final category is referred to as 'behavioural', and comprises at once cooking practices, and the time-activity patterns of both the appliance use and fuel burning, as well as the people who may be exposed. This last includes childcare practices based on the patterns of room usage. Bruce *et al.* (2006) provide a useful table of common interventions divided into these three categories.

For the purpose of this paper, discussion of the interventions will be kept to general descriptions and relatively superficial reporting of quantitative effects on emission levels and exposure to pollutants. While this component certainly represents important considerations in gauging intervention suitability, it is far beyond the scope of this paper to assess the wide variety of research and testing methods used within the field. As Albalak *et al.* (1999) further note, "[m]ost studies on domestic biomass fuel combustion are not entirely compatible with one another since they deal with different cooking fuels, different sampling durations and techniques, and a different size fraction of pollution". This is of particular relevance to fuel and stove emissions. There is much disagreement amongst researchers as to the most reliable and representative measurement techniques, as well as the health implications of changes in emission levels.[13] Moreover, the advent of more precise measurement technologies over time has rendered the comparison of findings from different studies an often-inexact endeavour (Smith, 1987). Such an

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[13] See Ezzati (2000) for a more detailed account of the challenges in exposure assessment and the quantitative uncertainties that ensue.

undertaking could warrant its own research paper and will thus be omitted from this text. It should therefore be noted that given the magnitude of available research on the topic and the array of ensuing findings, this paper does not boast a complete treatment of every pertinent result regarding fuel and combustion device emissions. Instead this work will be based on consensus findings that indicate whether experience with a given intervention has shown increased or decreased emission levels and pollutant concentrations. It is hoped that by including such results, this attempt to provide a comprehensive guide to interventions will neither suffer from ambiguities nor contain decision-altering gaps in information. Furthermore, it must be emphasized that given the lack of quantitative evidence associated with the pollutant reductions achieved by most interventions in the environment and behaviour categories, there is no conclusive algorithm by which a 'best' intervention can be derived. Intervention design to reduce pollutant exposure from cooking is an inexact science at best and this cross-disciplinary literature review claims only to provide a comprehensive set of qualitative guidelines to facilitate this endeavour.[14]

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[14] Observational investigations in human populations frequently need to address the issue of confounding, the situation in which the effects of two or more variables are difficult to separate from one another. As the cited articles are academic peer-reviewed papers, this report will adopt the assumption that confounding was addressed at the time of the study and will thus not be discussed here.

Source factors

Fuels

A widely accepted theory of household energy use is generally termed ‘the energy ladder’ (*Appendix* 1) and describes an observed move from so-called ‘dirty’ fuels (high emissions) to ‘clean’ fuels (low emissions) as income increases (WHO, 2002). The shortcomings of this theory will be addressed later on in this paper but pertinent at this stage is the premise of a reduction in emissions that has been consistently proven as one goes ‘up’ the ladder. A review of 29 studies that compared emissions of cooking fuels showed there was very little disagreement between findings about the legitimacy of this assertion (*Appendix* 2). There are four fuel categories that are most commonly used and were those most often studied. At the bottom of the ladder with the highest emissions one finds unprocessed biomass, followed by coal, kerosene and liquid petroleum gas (LPG). At the top of the ladder is electricity which, although widely used in high-income countries, has not been sufficiently used in the areas in question to boast the extent of literature related to the other fuels, although it is known to emit little in terms of individual household use compared to the aforementioned fuels. Thus, this paper will have a disproportionate concentration on the former four while addressing the latter when pertinent information is available. More recently two other categories of fuel have gained some attention. The first of these are known as renewables, such as solar energy and ethanol, but given how new their technological development and the fact that their diffusion to date has not been sufficient to allow for any large-scale research of their effectiveness, they will not be included in this paper.[15] The second are upgraded biofuels, namely charcoal and biogas, and these have been, albeit to a limited extent, utilized in some low-income countries. As there is currently less experience with upgraded fuels than with the aforementioned fuels on the energy ladder there is less conclusive information on their emission levels. What data are available will be presented in order to give some concept of where these alternatives fall within the ladder paradigm.

The pollutants most often measured are carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx), sulfur oxides (SOx), methane (CH_4), formaldehyde (HCHO), polycyclic aromatic hydrocarbons (PAH), most commonly benzo[a]pyrene (B[a]P), and particulate matter (PM). This last is subject to a certain lack of clarity, being measured in different studies as either total suspended particulates (TSP), suspended particulate matter (SPM), or respirable suspended particulate matter (RSP).[16] The most important distinction between these pertain to the sizes of the particles measured, qualifying only those particles smaller than 10 μm as respirable and thus hazardous to human health. For simplicity's sake this paper will refer to PM concentrations using the quantities provided in all three above mentioned categories without differentiation and will only distinguish between particle sizes measured.

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[15] For more information on solar cookers and other renewable technologies please see: Al-Saad and Jubran, 1991; Anozie *et al.*, 2007; Carmody and Sarkar, 1997; Goldemberg and Coelho, 2004; Goldemberg *et al.,* 2004a and b; Karekezi, 2002; Kaygusuz and Ahmet, 2003; Keong, 2005; Mohamad *et al.*, 1998; Nahar, 2003; Pohekar *et al.*, 2005; Purohit *et al.,* 2002.

[16] See Smith (1987) for a detailed treatment of the distinctions between each term and their quantitative significance.

While a number of negative health effects of each pollutant have been established, it is a separate and far more contentious task to postulate a hierarchy of hazard amongst them. Thus, favouring one intervention that reduces a given pollutant over a second one that reduces a different pollutant is beyond the expertise of this paper. A predominant trend in the literature cited in this paper is to focus on PM concentrations when striving for reductions in indoor air pollution from cooking and this discussion of fuel and combustion device emissions will follow that approach. While this still precludes any conclusive assertion about the 'healthiness' of one fuel over another, it does allow a comparison of emissions of one pollutant that is decisively associated with great health risks (Bruce *et al.,* 2002). Other pollutants will only be reported when insufficient data on PM is available[17], in order to give some indication of the impact of a technical change on emissions. This will hopefully beget as reliable a deduction of intervention effectiveness as a paper of this scope could envisage.

i. Biomass

Biomass is the fuel most commonly used in low-income countries for cooking. Given this prevalence it will be used in the discussions of fuel as the baseline from which all changes would be made. The term biomass encompasses all non-fossil organic matter in solid form. The solid varieties typically used in low-income countries are wood, agricultural residues or animal dung. Which of these three is used varies greatly by region and depends in large part on availability (Smith, 1987). There is also a vast diversity within the first two of these categories. Tree species and the wood that they

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[17] CO has frequently been used as a proxy for particulates and will be reported as CO when this is the case (Bruce *et al.,* 2004).

produce vary not only across, but also within regions, as does the part of the tree used, be it wood, bark, branches or leaves. Further some populations rely on brush and plant residues other than trees when this last is not in abundance. Likewise, agricultural residue types will differ based on the predominance of varying crops across seasons and locations. Despite the assortment within this category, this paper will not distinguish beyond the three aforementioned types of biomass. This is based on the assumption that future interventions will be seeking to initiate more drastic changes in emission levels than alterations in wood type or crop residues could produce (Smith, 1987).

Table 2 (*Appendix* 2) shows the concentrations of PM observed by a series of reviewed articles for all 3 types of biomass. When these are compared with a United States Environmental Protection Agency (US EPA) standard of 24-hour concentrations of 65 μm/m^3 for $PM_{2.5}$ and 150 μm/m^3 for PM_{10} (Bruce *et al.,* 2000)[18], the discrepancy is sizeable. All reported measurements exceed the corresponding US EPA standard; those for $PM_{2.5}$ range from 528 μm/m^3 (Naeher *et al.,* 2001) to 27200 μm/m^3 (McCracken and Smith, 1998) while those for PM_{10} span from 173 μm/m^3 (Dasgupta *et al.,* 2006) to 3690 μm/m^3 (Albalak *et al.,* 1999). Moreover, Smith found that 90-95% of TSP from biomass combustion were less than 3.2 μm in diameter (1987) while Raiyani *et al.* (1993) attributed 96% of TSP from dung and 86% from wood to those sized less than 9 μm. Given these figures, even findings reported only as TSP or SPM in the table represent respirable quantities above the designated standard. Between the three prevalent forms

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[18] Similar guidelines have been set by other bodies including WHO ambient air quality standards of 100-150 μm/m^3 for PM10 (Smith *et al.,* 1983) and South Africa air quality guidelines of 180 μm/m^3 (Engelbrecht *et al.,* 2002).

of biomass cooking fuel, dung is found to have the highest PM emissions, followed by agricultural waste and then wood with the lowest emissions measured, although some studies have found wood to have higher emissions than agricultural residues or alternately the latter to be a higher emitter than dung. When compared with LPG, wood emitted three (3) times more TSP while cattle dung combustion produced amounts six (6) times greater (Raiyani *et al.,* 1993). Similarly Smith (1987) reported dung TSP emissions over three (3) times higher than those from wood and TSP emissions from agricultural residues almost six (6) times greater than the latter. Raiyani *et al.* (1993) reported comparable findings to a number of other studies. This amalgamation of findings leaves little question as to the level of emissions to which people using biomass for cooking fuel are exposed. It is thus that one focus of smoke reduction efforts looks to alternative fuel as a viable option. The following sections will detail the quantitative effects, to the extent that they are available in the literature, on pollutant concentrations that have been reported when a switch to 'cleaner' fuels is made.

ii. Coal

The second step on the energy ladder after biomass, coal is a combustible fossil fuel in a solid rock form. Already a popular fuel in low- and middle-income countries such as China and South Africa, its consumption is expected to grow over the coming decades (EIA, 2001). Coal combustion has also been associated with many health problems (Smith, 2002). Indoor household coal burning is considered an important risk factor for respiratory illness (Lan *et al*., 2002). Coal is composed predominantly of carbon but varies with respect to its other contents.[19] It may contain differing degrees of other elements including oxygen, hydrogen, nitrogen and sulfur, and 'smoky' and 'smokeless' varieties are some of the more common differences encountered (Lan *et al.*, 2002). It follows that the quality, and in turn emission types and levels, of the coal vary depending on the composition (Mestl *et al.,* 2007). As it falls outside the focus of this paper, details of said differences will be omitted, reporting coal emissions as a homogeneous group (as it is typically presented in the literature). Table 3 (*Appendix* 2) displays a series of findings that complement both the health hazard asserted above and the tenet of the energy ladder. Authors that contrasted biomass and coal emissions (Kandpal *et al.,* 1995a,b; Mestl *et al.*, 2007; and Raiyani *et al.,* 1993) all reported decreased PM values from coal compared to biomass. TSP concentrations were almost three (3) times less than those for dung (Kandpal *et al.,* 1995a,b; Raiyani *et al.,* 1993) and 25% less than wood (Raiyani *et al.,* 1993). Comparable ratios (15-25%) were observed by these authors for decreases in $PM_{2.5}$ and PM_{10}. Nonetheless, all authors except Engelbrecht *et al.* (2002*)* reported quantities far above the EPA standards (Kandpal *et al.,* 1995a,b; Mestl *et al.*, 2007; Raiyani *et al.,* 1993; and Smith, 1993). Thus from a public health perspective an intervention advocating a switch to coal from biomass would still contend with pollutant exposure at levels likely to be damaging to health. In light of recent promotion in Asia and Africa for the substitution of coal for biomass as a cooking fuel, Smith (2002) warns, "great caution should be exercised because of the health risk involved"[20]. Zhang

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[19] See Coal Association of Canada online for a more detailed description of coal types and their elemental composition.(http://www.coal.ca)

[20] See Zhang and Smith (2005) for a review of the health impact of coal use in China.

and Smith (2007) briefly discuss clean coal options, but given the dearth of literature and experience with this technology in low-income country conditions, their quantitative benefits cannot be reported here.

iii. Briquettes/Honeycombs

There is also some mention in the literature of altering the forms, without modifying the state, of solid fuels to decrease their emissions or improve their practicability for household use. Sarmah *et al.* (2002) discuss the unsuitability of loose biomass burning in many traditional biomass stoves and suggest that biomass briquettes made through 'proper technology' are a worthwhile alternative that warrants research and development. Briquetting is a process that compresses matter into a higher density entity (Bhattacharya *et al.,* 2002a). A similar process utilizes a honeycomb shape towards the same end (Zhang and Smith, 2005). This compact form theoretically produces more efficient and cleaner combustion. Reductions in pollutant emissions have been found, although comparative results are not widely available. Edwards *et al.* (2004) report an 85% reduction in TSP concentrations in a switch from unprocessed coal to coal briquettes. Isobe *et al.* (2005) found reductions in SO_2 concentrations with the use of coal-biomass briquettes but the correlation between this result and TSP has not been established. This technology is clearly not in widespread use to date and thus will not receive the same attention as others, but where pertinent its application or challenges to such will be outlined.

iv. Kerosene (Paraffin)

A flammable hydrocarbon liquid (distilled petroleum), kerosene, or paraffin (as it is called in many parts of the world), is widely used as a cooking fuel in countries like India and attempts have been made to spread its use to areas such as sub-Saharan Africa. Placed as the first step of 'clean' fuels on the energy ladder it has been shown to produce significantly less emissions than its solid fuel counterparts. Rollin *et al.* (2004) found a 75% reduction in RSP concentrations between homes using solid fuels and those using kerosene. While Kandpal *et al.* (1995b) found values of 425 $\mu m/m^3$ for SPM at a squatting position and 810 $\mu m/m^3$ for SPM at a standing position, these values include background air pollutant levels and the authors qualify the contribution of this quantity from kerosene emissions as only 'a little'. Comparatively these amounts are 75% less than those found by the same authors for dung (Kandpal *et al.*, 1995a). Balanakrishna *et al.* (2002) observed a 90% decrease in RSP from 1307 $\mu m/m^3$ for wood to 132 $\mu m/m^3$ for kerosene. Raiyani *et al.* (1993) measured a mean TSP concentration of 504 $\mu m/m^3$ with PM_{10} at approximately 441 $\mu m/m^3$ and $PM_{2.5}$ at approximately 193 $\mu m/m^3$. These values represent reductions of 5, 3 and 2 times the concentrations for dung, wood and coal respectively. The improvements in PM concentrations from solid fuels to kerosene are thus well established and the consequential reductions in health risks can be deduced. As with coal, however, this does not imply an elimination of health risks. Smith (1987) summarizes a number of health effects ranging from asthma to heart and lung degradation that have a postulated association with kerosene exposure. More research would be needed to conclude the quantitative improvement on health from this fuel switch.

v. Liquid Petroleum Gas (LPG)

LPG is a liquid mixture of hydrocarbon gases (predominantly propane and butane) that at present is used predominately in urban areas of low- and middle-income countries. While not the final rung on the energy ladder, LPG is touted in the literature as the fuel that offers one of the most “effective strateg[ies] to reduce particulate exposure” (Brauer *et al.* 1996). From a quantitative perspective it is easy to see why. Table 4 (*Appendix* 2) depicts the measured indoor concentrations from LPG along with the reduction ratio compared to other fuels. TSP reductions were between 6 and 19 times the quantities found for dung or agricultural residues and 6 times that for wood (Balanakrishna *et al.,* 2002; Kandpal *et al.,* 1995b; Lodhi and Zain-al-Abdin, 1999; Raiyani *et al.,* 1993). PM_{10} concentrations were respectively 3, 6 and 18 times less than biomass in general, dung and wood in particular (Brauer *et al.,* 1996; Kanagawa and Nakata, 2007; Raiyani *et al.,* 1993). Finally concentrations of $PM_{2.5}$ were between 8-9 times less than those from biomass and 11 times less than that from dung (Brauer *et al.,* 1996; Naeher *et al.,* 2000; Raiyani *et al.,* 1993). Moreover, Kandpal *et al.* (1995b) also measured concentrations 5-7 times lower than those for coal and 4-5 times that for kerosene. These findings not only underline one of the basic principles of the energy ladder theory but also display the considerable gap in concentration levels between the lower fuels on the ladder and LPG. Not only does it emit considerably less than the traditional biomass fuels, but it even offers important reductions from the concentrations of its ‘cleaner’ fossil fuel counterparts (coal, kerosene). Most authors conclude LPG PM emissions levels to be ‘substantially lower’ than their ladder precedents and Brauer *et al.* (1996) qualified them as similar to outdoor concentrations. The implied health benefits of this scale of pollutant reduction have catalyzed a great interest in LPG on the intervention front.

vi. Electricity

Rounding out the classic energy ladder is the source now found pervasively in high-income countries. Electricity is considered a high-grade option that is preferred for its cleanliness. Rollin *et al.* (2004) found "overwhelming evidence" of significant RSP concentration reductions between electrified and un-electrified villages in South Africa. These authors also highlight the lack of comparable data in the literature. Due to its high cost to date it is rare that electricity acts as the primary cooking fuel in low and middle-income countries, and even more unusual in the rural areas. Thus, examples of rural electrified villages in which pollutant concentrations have been measured are scarce. Its cleanliness and potential to improve indoor air quality are rarely contested, however, and rural electrification is an ultimate goal of most development programmes (Bruce *et al.,* 2006). Further, it offers a unique opportunity to aid common cooking tasks with specific appliances such as rice cookers and electric kettles (Tyler, 1996). It is, however, widely conceded amongst researchers and policy-makers alike that this will only be realised within a long-term time frame (Bruce *et al.,* 2006).

vii. Biofuels

a. Charcoal

One of the more feasible interventions to reduce IAP at the level of fuel is that of charcoal and many programmes have devoted efforts towards its popularization (Hassrick, 1982; Sherman *et al.,* 1983). Charcoal is produced when biomass is heated under particular physical conditions. This process typically removes many of the particulates and hydrocarbons at the manufacturing stage and thus PM emissions when charcoal is used as a cooking fuel are generally less than traditional biomass. Smith (1987) describes it as a cleaner fuel than biomass with lower TSP emitted at the household level. Kandpal *et al.* (1995a) found SPM concentrations were 4 times less for charcoal (410 $\mu m/m^3$ and 790 $\mu m/m^3$ for squatting and standing positions respectively) than dung and 55-65% less than wood. Ezzati (2000) also reports a large reduction in PM_{10} concentrations (92-96%) through a switch from wood to charcoal. Further, Ezzati *et al.* (2000) found 54% reductions in SPM when wood was replaced with charcoal in their respective traditional combustion conditions. With respect to health effects, Ezzati and Kammen (2002) found 45% reductions in ALRI cases and 65% reductions in ARI cases when households switched from wood to charcoal. There is some concern, however, that while TSP emissions are lower, those of CO are actually higher, increasing the risk of acute poisonings (Ballard-Tremeer and Mathee, 2000). Nonetheless, of those fuels outside the typical energy ladder, charcoal is that which has been most widely used and is generally ascribed the greatest viability for short-term interventions.

b. Biogas

Despite not yet having penetrated the mainstream of energy alternatives, the concept of biogas is one that has been implemented experimentally in low- and middle-income countries for 30 years (Karekezi, 2002; Reddy, 2004). Specifically, projects have been developed that use anaerobic fermentation of dung (or at times other forms of biomass) to produce energy (biogas) that may be used for cooking or other energy needs. It is considered to be one of the cleanest states in which to use biomass for energy and presents in turn the least health risk of this family of fuels (Pohekar *et al.,* 2005). Kandpal *et al.* (1995b) reported SPM concentrations of 105 and 250 in the squatting and standing positions respectively from biogas use and both positions were 90% less than dung. Hamberg (1989) found that SO_2 levels from biogas were four times lower than those for coal and agricultural residues. Biogas technology has been proven viable through many experiences in the field (Karekezi, 2002) and has been continuously promoted by researchers (Pokharel and Chandrashekar, 1995).

Uncertainties in emission measurements

Before continuing, it is important to note two closely connected issues that may affect the otherwise straightforward interpretation of reported emission levels and their potential health impact. Measurements taken to assess indoor pollutant concentrations are subject to the timeframe in which they were collected. As cooking is an activity that occurs for discrete periods at different points in the day, there are implicitly very large differences between peak values obtained during the cooking process and those determined as an average over 24 hours. The literature boasts no systematic treatment of this discrepancy and in turn there are no conclusive deductions about which timeframe is more pertinent to addressing health concerns (Park and Lee, 2003). Moreover, Saksena *et al.* (2007) warn that studies reporting low 24-hour averages could in fact be masking high acute exposure during cooking times. This is evidenced in Table 2 (*Appendix* 2), in which values are given as mean concentrations and thus those fuels that have higher peak emissions are not scrutinized as such. Another example is evidenced in the findings of Park and Lee (2003) who reported 37 $\mu m/m^3$ and 58 $\mu m/m^3$ 24-hour $PM_{2.5}$ concentrations for the two stoves examined but peak levels up to 4740 $\mu m/m^3$ and 8170 $\mu m/m^3$ respectively. The highest peak levels of $PM_{2.5}$ in this study were 39 times higher than the 24-hour averages (Park and Lee, 2003). This discrepancy must be addressed to ensure that interventions are not being falsely credited with reducing harmful exposure. A better juxtaposition of health research on the relative impacts of each measurement type and the indoor air pollution literature would be necessary towards this end. Edwards *et al.* (2004)

articulate the second and interrelated issue when they state, “although it is possible to assess the relative emissions of these fuel and stove combinations, the relationships to personal exposure and health effects are less clear”. Likewise Bruce *et al.* (1998; 2000; 2006) emphasize the importance of “estimating the potential health gains that might result from reducing exposures by different amounts”. While Park and Lee (2003) assert that a daily increase of 20 μm/m^3 in PM exposure increases the mortality rate by 1% , such postulations are generally absent in favour of echoes of the above calls for greater inquiry. The obvious consequence is that interventions must, at this point in time, be based on a degree of uncertainty with respect to relative changes in health burden based on altered emission quantities. With this understanding of the limitations of the measurements provided in this section, we may proceed to an outline of the combustion devices, hereafter also referred to as stoves, used to produce the energy in question.

Combustion devices

Until recently, one of the most commonly identified reasons for discrepancies between fuel emissions measured in studies and those experienced at the household level is that much of the research was carried out in laboratory settings and did not account for the drastic effect of imperfect combustion conditions on emission levels. The controlled environments in which the experiments took place did not necessarily accurately represent the primitive devices in which combustion was taking place in the field (WHO, 2002). Thus, while the quantities reported in the previous section for traditional biomass burning in open fires can be interpreted with relative confidence, those for all other fuels used in stoves are subject to the varying condition and quality of the devices themselves. While this does not undermine the trend of reduced emissions up the energy ladder, as the consistency of these findings makes any such severe error rather unlikely, it does call for an analysis of the combustion devices available and the effects of the range of technology on pollutant emissions. Raiyani *et al.* (1993) state that “emission factors for biomass vary dramatically with combustion conditions”, while Park and Lee (2003) assert that “[s]everal studies showed that particulate matter produced from the biomass combustion environments was strongly associated with the combustion facilities”. As biomass is the baseline fuel assessed in this paper, the discussion of combustion devices will focus on options for its use. While some variation exists amongst the devices used for other fuels, they will not be addressed here. For more information on these see Lucky and Hossain (2001) for natural gas, kerosene and electricity, Smith (1987) for kerosene, Raiyani *et al.* (1993) for LPG, kerosene and coal, and Edwards *et al.* (2004) for coal. Further, this section does not discuss every stove type available, as such a list extends into the hundreds, but outlines the general categories of devices and the standard changes that distinguish the improved alternatives most commonly implemented.[21]

There are four principal features by which stoves may be categorized. The first feature is the material from which the stoves are made, which may be sub-divided into the three types: an open fire pit dug into the ground; the high mass type such as cement, mud and clay (Bhattacharya *et al.,* 2002b; Aggarwal and Chandel, 2004; Ahmed *et al.*, 2005); and the low mass alternatives, specifically metal and ceramic (Bhattacharya *et al.,* 2002b; Aggarwal and Chandel, 2004). While a change in material is associated with the

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[21] The following authors offer detailed lists of available stoves and their performances: FAO, 1993; Joseph *et al.*, 1980 and Kumar, 1985.

emission levels produced, this is generally a function of the design feature of the fourth stove category discussed below.

The second feature is the number of pot holes built into the stove which typically vary between one and two, or of course none in the case of the open fire, which can accommodate different quantities of pots depending on its size. This is also a secondary feature of improved designs and is not in and of itself a characteristic on which improvements are based.[22] Further, there were no studies found that measured emission differences based solely on building materials or pot hole quantity thus these will both only be discussed within the context of the fourth category below.

The third category of stove differentiation is that of efficiency. A stove's total efficiency dictates how much of the energy in the fuel is converted into heat used for cooking (Edwards *et al.,* 2004). The total efficiency of a combustion device is a combination of how much energy from the fuel is converted to heat- *combustion efficiency*- and what percentage of this heat produced actually reaches the cooking vessel- *heat transfer efficiency* (Smith, 1987). Until recently, stove improvement programmes focused primarily on improving stove efficiency towards an end of overall wood saving for households. The more efficient a stove, the less wood would be required to fuel any given cooking task. Not only would households save resources for other expenditures but total wood or biomass from a region would also be available for other uses (Edwards *et al.,* 2004). Many studies of improved stoves programmes over the last 30 years have

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[22] The table on stove PM concentrations, however, does indicate the building materials and number of pot holes for those stoves where they were specified so see Table 5 (Appendix 6) for crudely surmised correlations between these and emissions.

reported increased efficiencies with the switch (Ballard-Tremeer and Jawurek, 1996; Edwards *et al.*, 2004; Lucky and Hossain, 2001). For example, Masera *et al.* (2000) reported wood savings of 40% when the 3-stone fire was replaced with an improved alternative. It may also be worth noting that efficiencies tend to increase as one ascends the energy ladder so that coal, kerosene, LPG, briquettes and biogas were all found to have higher efficiencies than biomass, thus requiring less fuel to complete any given task (Anozie *et al.,* 2007; Pohekar *et al.,* 2005; Raiyani *et al.,* 1993; Sarmah *et al.*, 2002).

What is surprising, given that efficiency appears to increase with the cleanliness of the technology, is that when the improved biomass stoves were tested for PM emissions, their increased efficiency was more often than not correlated with an increase in pollutants emitted (Ballard-Tremeer and Jawurek, 1996; Edwards *et al.,* 2004). This can be explained by a common practice for efficiency to be achieved at the cost of a reduction in the completeness of combustion, by introducing enclosed fireboxes or airflow reductions, thus increasing pollutant emissions (Ballard-Tremeer and Jawurek, 1996; Budds *et al.,* 2001). As the damaging health effects of the emissions became better established over the last 20 years, researchers began to call for biomass stoves that were designed to reduce smoke emissions along with an increase in efficiency (Ballard-Tremeer and Jawurek, 1996; Raiyani *et al.*, 1993).

In line with this redirection of focus, the fourth classification of stoves emerged based on the design of the combustion chamber. Within this category there is a great deal of variation and positioning any one stove into one design type is an arbitrary task at best. There are nonetheless four overarching combustion chamber features that can be used to distinguish between stoves. The first is open chamber combustion and refers specifically to a traditional 3-stone fire in the ground. A flat surface often made of clay is placed over the fire and rested on the stones and is used in some places as a cooking surface (Masera *et al.* (2000) found this was particularly prevalent for tortilla making in Mexico). While Smith (1987) asserts that these can be quite efficient, their high emission of pollutants was established in the previous section. The second design is that of partly open chamber combustion and involves a modification from the traditional fire to a shallow pit, a U-shaped hole in a block of clay or brick, or raising the fire onto a grate (Bruce *et al.*, 2000; Smith, 1987). Ballard-Tremeer and Jawurek (1996) found that just these basic improvements could decrease TSP concentrations by 30% from open fire levels.

The third and fourth alternatives are enclosed chambers with and without flues or hoods respectively. Unlike the open or partly open options where at least one side of the fire is open to the room, the combustion in these devices is enclosed on all four sides. A flue is a chimney-like component that vents smoke directly from this enclosed combustion chamber to outside the cooking area, while a hood is a large structure that is positioned above the stove and connects to a chimney, also redirecting the smoke outside (Bruce *et al.,* 2006; Ramanakrishna *et al.,* 1989). Some of the better-known versions of this technology are the *Plancha*, made of cement blocks forming an enclosed chamber, a metal plate for a cooking surface (Albalak *et al.,* 2001) and a flue and the *Lorena,* a clay and sand box-like stove with a flue (Ahmed *et al.*, 2005), both of which are used in Central America. There are also many low mass versions made of metal or ceramic that are being advocated as replacements for these high mass options. Table 5 (*Appendix* 2) shows changes in PM concentrations from traditional to improved technologies. It is clear that the majority of improved stoves reduced indoor PM concentrations in these studies (all except Ballard-Tremeer and Jawurek, 1996). Reductions in TSP concentrations ranged from approximately 10-85% and the lowest $PM_{2.5}$ concentrations on improved devices were 37 $\mu m/m^3$ (Park and Lee, 2003), compared to the highest levels on the traditional open fire of 5310 $\mu m/m^3$ (Naeher *et al.,* 2000). Ramanakrishna *et al.* (1989) also found that TSP was reduced by a factor of 2 when hoods were used.

There is nonetheless a complicated relationship between flues or hoods and emission levels which is a product of the complex dynamic between efficiency and emissions. Smith (1987) explains that "all being equal, the use of less fuel will mean less emissions". As explained above however, this requires a stove design that does not derive efficiency by reducing the completeness of combustion. Thus while some stoves saw increased emissions accompany increases in efficiency, properly designed and maintained stoves should achieve the opposite. Flues, however, have been found to increase airflow, which reduces efficiency by increasing the total amount of fuel consumed. When this is the case, emissions may be expected to increase accordingly if other provisions to curb them aren't made. Bruce *et al.* (2006) state that the extent of the improvement in pollutant exposure from the addition of hoods and flues has been minimal in some parts of the world, and has been known in fact to increase with the implementation of these improved technologies. Both Edwards *et al.* (2004) and Smith (2002) report that the presence of flues dramatically decreased fuel efficiency and this in turn increased emission levels of TSP.

What may also occur is that indoor concentrations are lowered significantly, as the flues vent the pollutants into the vicinity outside the house, but this, in turn, can increase ambient concentrations. There is therefore a trade-off between acute exposure of those indoors at the time of cooking, and chronic exposure of all neighbourhood inhabitants if ambient levels are drastically increased. The above-noted issue of maintenance of the flue in order to maintain high efficiency will be further addressed in Chapter Two.

Smith (2002) asserts that “there has been no systematic and independent evaluation [of stove programmes] 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”. When this deficiency is juxtaposed with the variety of results that individual studies and programmes have experienced (Ramanakrishna *et al.*, 1989), it is difficult to assert any all-encompassing conclusions. Further, Schei *et al.* (2004) describe that while the pollution reducing effect of improved stoves is large, the mean level of $PM_{3.5}$ in the improved stove group is still twice the EPA accepted level, thus once again raising the need to evaluate what level of reduction lends worth to an intervention.

Many authors maintain nonetheless that where improved technologies with flues or hoods have been successfully adopted, they have offered the most substantial reductions in IAP amongst available and viable options (Aggarwal and Chandel, 2004; Albalak *et al.,* 2001; Lan *et al.,* 2002; Ramanakrishna *et al.*, 1989). Bruce *et al.* (2004) conclude that their results “indicate that improved stoves do reduce exposure for the majority of users despite variations in stove use [and] condition…” and Lan *et al.* (2002) found long term reductions in lung cancer incidence after stove improvements were implemented. It is thus that stove improvement has been the most fervently explored intervention but one that, as Chapter Two will elucidate, necessitates careful consideration before being implemented in order to achieve substantial and sustained reductions in IAP.

Environmental factors

Ventilation

The discussion above on flues and hoods, and their role in providing improved ventilation of pollutants, leads into the second class of intervention targets labeled 'environmental factors'. While this nomenclature reflects the inclusion of those factors related to the location of the combustion, these are all ultimately important because of their affect on ventilation. Smith (1987) asserts that pollutant concentration at any time will depend on ventilation which determines the air exchange rate and how well building air is mixed. He states that simple ventilation changes can have a large impact on air exchange rates and indoor concentrations. In many cases particulate levels have been significantly reduced with the provision of adequate ventilation (Aggarwal and Chandel, 2004; Park and Lee, 2003). Ramanakrishna *et al.* (1989) determined that older houses with limited ventilation had higher pollutant concentrations. Dasgupta *et al*. (2006) found that indoor pollutant concentration levels plunged in the afternoons when kitchens were aired out and that generally differences in structural arrangements and ventilation behaviour generated large differences in overall concentrations. A study by Akunne *et al.* (2006) confirmed the importance of ventilation in the health risk associated with solid fuel use and the significance of ventilation improvements towards the end of reducing the burden of disease.

The main factors that have been associated with the ventilation of domestic cooking are the number of openings such as windows and doors; the housing design including room size and layout; the building materials of the house and finally the cooking location itself. The role played by openings in the house is derived from the strong effect on the ventilation rate of "pressure, wind and temperature differences acting against the resistance of airflow through walls, windows, doors, cracks and other openings in the building" (Smith, 1987). Saksena *et al.* (2007) attributed their findings of low pollutant concentrations to coastal breezes in the area and the kitchen characteristics that allowed their penetration into the houses. Dasgupta *et al.* (2006) also observed that mean PM_{10} concentrations were reduced by 32 μm/m^3 simply by opening kitchen doors and windows after the midday meal due to the strong effect this behaviour had on ventilation. These findings point to the importance of both the presence of windows and doors as well as their use as openings to enhance ventilation.

The significance of kitchen configuration and housing design (specifically the size and layout of the room in which the cooking takes place and the house in general) as determinants of PM exposure, have been subject to varying results (Saksena *et al.*, 2007). Some studies, however, have found compelling associations. Bruce *et al.* (2004) concluded that physical characteristics of the cooking location such as more eaves spaces and greater kitchen volume had a negative relationship with pollutant levels. Likewise, Albalak *et al.* (2001) determined that the volume of the kitchen showed a highly significant negative association with $PM_{3.5}$ concentrations and established a 1% decrease in concentrations for every unit increase in volume. Saksena *et al.* (2007) found that houses with lower ceiling heights were more likely to have severe ventilation problems. Lan *et al.* (2002) observed a reduction in lung cancer incidence in houses that had 3 or more rooms. This last result, however, was only significant for males, as it has a much greater effect on 24-hour concentrations throughout the living area than peak emissions in the kitchen to which it is primarily females that are exposed. Besides doors and windows, houses can also be designed with other openings that increase ventilation. It was found that closing a $2m^2$ hole in the kitchen ceiling decreased the air exchange rate by a factor of 14 and in turn increased the cook's PM exposure by eight, however it has also been postulated that openings located in the wrong places can increase exposure so these must be carefully positioned (see Smith (1987) for a technical explanation of air exchange rates and opening placement).

The materials used in the construction of a house have been repeatedly found to be associated with indoor pollutant concentrations. Mud walls and thatched roofs were found to have highly significant effects on ventilation (Dasgupta *et al.,* 2006). Mud roofed houses had higher TSP than tile-roofed and thatched houses (Ramanakrishna *et al.*, 1989) and thatched roofs generally had lower NO_2 concentrations than their iron counterparts (Boleij *et al.,* 1989). Thatched roofs lowered the PM_{10} by 100 $\mu m/m^3$ compared to other materials such as mud (Dasgupta *et al.* 2006), while mud walls require periodic re-coating, creating an effective seal that hinders ventilation and increases PM_{10} concentrations by 253 $\mu m/m^3$ compared to non-mud options (Dasgupta *et al.,* 2006).[23] Thus while altering building materials used may not offer a viable solution to IAP for established houses, it may be an important factor to consider in future development plans for housing construction in low-income countries.

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[23] Mishra *et al.* (1999a) observed a lower prevalence of blindness in higher quality housing (containing at least a certain amount of bricks, tiles, cement or concrete) than that found in lower quality alternatives such as mud or thatch, but a direct correlation between this and ventilation is not established.

As biomass stoves do not rely on a connection to an exterior power source, their placement is relatively flexible. One commonly suggested remedy for IAP is to move the cooking location from within the living space to outdoors. Where an outdoor area is not available, even a separate room or a partially open cooking area such as a verandah has been shown to reduce pollutant concentrations. Ramanakrishna *et al.* (1989) found that CO levels were significantly higher in indoor kitchens than protected and outdoor ones, while Saksena *et al.* (2007) reported that moving from indoors to an open kitchen lowers PM_{10} concentrations indoors by almost the same magnitude as switching from firewood to kerosene. Dasgupta *et al.* (2006) observed that PM_{10} concentrations indoors were reduced by 47 $\mu m/m^3$ with a move to a detached kitchen and by 64 $\mu m/m^3$ when shifted to an open air space. While Balanakrishna *et al.* (2002) found that concentrations of RSP in the cooking area were 1578 $\mu m/m^3$ when cooking took place indoors, this number dropped to 884 $\mu m/m^3$ when moved outdoors. Even more compelling is that the concentrations for the living area drop to 970 $\mu m/m^3$ when the kitchen is partitioned off and to 199 $\mu m/m^3$ when cooking is moved outdoors (Balanakrishna *et al.,* 2002). Thus there are seven-fold reductions in the concentrations to which household members other than cooks are exposed when the cooking is moved outdoors and 33% reductions simply by erecting a partition between the cooking and living spaces. Albalak *et al.* (1999) observed a similar increase by a factor of 9 between outdoor cooking PM_{10} concentrations of 430 $\mu m/m^3$ and 3690 $\mu m/m^3$ when indoors. From a health perspective, results from Akunne *et al.* (2007) showed that the fraction of ARI attributable to smoke from biomass solid fuel in children under 5 years of age can be reduced by at least 50% when households are encouraged to cook outdoors, while the prevalence of blindness was lower in people whose kitchens were separate from their living spaces (Mishra *et al.*, 1999a). Boadi and Kuitunen (2005) found respiratory health symptoms in 62% of households that cooked in the living area, compared to 33% where separate kitchens were used and 19% where cooking was done outdoors.

Although there are only a few studies that have looked at the specific impact of ventilation on pollutant concentrations, the relatively uniform results indicate that interventions to improve ventilation may offer an effective alternative or be a complementary effort to modifying household energy technology.

Behavioural factors

As was the case with ventilation, there is very limited objective information available on interventions based on user behaviour (WHO, 2002). As previously mentioned this means in turn that there is little in the way of established quantitative impacts of these interventions. A report from WHO (2002) contends that these are unlikely to generate exposure reductions of the same magnitude as technical interventions but nonetheless highlights their potential as important supporting measures. Thus a review of interventions related to behaviour will be rather narrow in content. Those that will be underlined are primarily associated with the user's interactions with fuel, combustion device and ventilation. Many of the ventilation options discussed above are premised on the cook's use of the ventilating mechanisms. Dasgupta *et al.*'s (2006) discussion of windows and doors highlights the need for these to be opened during and after cooking has taken place. Moreover, the above section on cooking location also places the onus on the cook to reposition the stove outside during meal preparation. Other adjustments to cooking practices are thought to engender large differences in overall concentrations (Dasgupta *et al.*, 2006). Bruce *et al.* (2006) advocate reducing exposure through a number of operating modifications including drying wood before its use, cutting wood into smaller pieces and using pot lids to conserve heat, while the WHO (2002) also suggests the implementation of partially pre-cooked food such as parboiled rice to reduce cooking time and thus pollutant emissions. Use of pot lids, for example, has been shown to reduce emission levels by up to 50% and reduced fuel use by a factor of three (Ballard-Tremeer and Mathee, 2000). Further, Ezzati *et al.* (2000) underline that the large range of emissions observed within stove types illustrates how the manner in which a stove is used may be as important a determinant of emissions as stove type itself. Some conjectured behaviours thought to influence emissions include altering the size of the batches of biomass used, changing whether one loads from the side or the top of the stove and leaving greater intervals of time between refuelings (Cowlin *et al.,* 2005). While the former two are simply mentioned in the literature without any further detail, there was a statistically significant increase in CO over a 24h period found with an increase in the number of refuelings during that period (Cowlin *et al.,* 2005). A majority of emissions are released when the combustion chamber is opened and thus refueling patterns have a large impact on concentrations (Cowlin *et al.,* 2005). Future studies on combustion device emissions must pay greater attention to these issues in order to determine their potential as exposure reduction tools.

Another component in which behavioural choices have been shown to affect exposure is that of time-activity patterns. Bruce *et al.* (2000) assert that "[i]nformation on such patterns is very important for understanding the dynamic relationship between levels of pollution and behaviour". This pertains specifically to how much time any individual or demographic group spends in proximity to the source of pollutants. In one study Bruce *et al.* (2004) found that the position of the child (placement with respect to the fire) was one of the most important determinants of child CO exposure. Another review article advocated keeping children away from smoke, preferably in another room (Bruce *et al.*, 2006). Moreover, Saksena *et al.* (2007) attributed preliminary observations of a low health risk related to IAP exposure in the area studied to the measures taken by the women to keep their children at a distance from the fires. This may be a greater challenge to enact in many countries where young children are carried on their mothers' backs while the cooking is taking place. This practice juxtaposed with the high level of women's involvement in the cooking tasks means that these children spend many hours breathing in smoke (Bruce *et al.,* 2000). Boadi and Kuitunen (2005) found that child respiratory infection was positively correlated with the presence of children in the kitchen during cooking while Barnes *et al.* (2004) found that children with low incidence of ALRI spent significantly less time within 1.5metres of the fire than those with high incidence. The connection between exposure and time-activity patterns is also important when implementing improved technologies. Bruce *et al.* (2000) contend, for example, that a reduction in visible or bothersome pollutants may result in more time spent indoors near the source and thus harmful exposure may not necessarily decrease proportionately. This risk has been contested by Ezzati and Kammen (2002) who found that the time spent near the fire in this scenario would change only by a relatively small fraction of the total time spent indoors and thus not have the impact on exposure that others have suggested. Consideration of this phenomenon may still be worthwhile when communicating health implications of improved technology to users.

Conclusions on intervention options

This chapter has outlined the more prevalent findings of IAP research and the trends that have guided pollution reduction efforts in recent years. It also illuminates the inconsistencies, ambiguities and basic lack of conclusive data in many areas faced by those engaged in intervention design within the field. Despite these limitations, there is clearly still great potential amongst these options to reduce household exposure to harmful pollutants. While the majority of the experts referenced above have asserted this repeatedly, this review also finds that, crudely speaking, moving up the energy ladder, improving combustion devices, ameliorating ventilation conditions and adopting behaviour modifications have the ability to reduce either pollutant concentrations or exposure to them. What have been consistently overlooked, however, are the myriad of factors and circumstances that are necessary for the intervention, once implemented, to produce these optimal results. It is to these that we now turn our attention in Chapter Two.

Chapter 2- Socio-Economic and Technological Factors

The preceding survey of possible interventions concludes with a promise to reduce pollutant emission levels from cooking. This theoretical potential, however, has not been consistently realized in practice. A dichotomy of outcome failings finds either that interventions, once implemented, don't result in the expected decreases in exposure, or simply that they are not adopted by households in the first place. This reality has been acutely exemplified with fuel and combustion device initiatives. Referring back to the energy ladder theory discussed in Chapter One, the tenet of ascension to cleaner fuel use with improved socio-economic conditions has in fact been disproved in the majority of experiences (Heltberg, 2005). Instead, what has been observed is a trend of multiple fuel use wherein households use a combination of traditional and modern fuels to fulfill total energy needs (Albalak *et al.,* 2001; Gupta and Kohlin, 2006; Howells *et al.,* 2005; Rehman *et al.,* 2005; Rollin *et al.,* 2004; Schei *et al.*, 2004). Similarly, improved stoves are often used only for a part of the household cooking, while the traditional alternative continues to be used for the balance (Albalak *et al.,* 2001; Heltberg, 2005; Schei *et al.*, 2004). The result, as highlighted above, is less impressive pollutant exposure reductions than anticipated. The subsequent extrapolation is that the energy ladder places too heavy an emphasis on income to explain household energy choices and clearly overlooks a multiplicity of other factors that contribute to the ultimate selection (Heltberg, 2005). Experience to date has bolstered this assertion. Howells *et al.* (2005) assert that it is a lack of knowledge by policy makers about these factors that is one of the main obstacles to energy transition and intervention success. Jin *et al.* (2006) further explain that "limited empirical research to form the basis for design and delivery of effective interventions" results from the fact that "much of the initial research overlooks the complex interactions of technological, behavioural, economic and infrastructural factors that determine the success of environmental health interventions, especially those with non-health dimensions such as household energy". What has often ensued is an overestimation of intervention potential "by planners and experts who focus on the technical and economic viability of the technologies while insufficiently considering the social and cultural conditions and economic realities of daily life in the region" (Murphy, 1999). Further, "[t]here is a gap or clash between the intentions of those who want to improve the quality of life of communities, and the perceptions, responses, and social and cultural patterns of those people" (Ballard-Tremeer and Mathee, 2000). Heltberg (2005) insists that "[u]nderstanding household fuel choice is of vital importance in the search for policies to combat unsafe cooking practices". Moreover, the WHO (2002) affirms that while "experience regarding the acceptance and sustainability of household energy programmes has increased, […] these aspects have rarely been the subject of systematic research". This section strives to provide this type of systematic treatment of the topic, to the extent that current reported experiences permit. It categorically addresses those factors encountered in the literature reviewed and qualifies each with available anecdotal evidence of its potential influence on energy choice.

Other uses of energy

An easily assessed, and yet commonly overlooked factor is the multi-functional nature of traditional cooking appliances (Howells *et al.*, 2005). Fires and traditional stoves offer intrinsic by-products in the form of other services (Howells *et al.*, 2005). The first of these is space heating which is a major requirement in many areas (Aggarwal and Chandel, 2004). Many persons living in households that are provided with LPG stoves stated that their continued use of an open fire for cooking was due to the space heating benefit (Albalak *et al.*, 2001; Schei *et al.,* 2004). Likewise, households with improved closed-chamber stoves that did not produce sufficient heat to warm the house were found to light separate fires, thus reducing improvements in indoor concentrations of pollutants (Hessen *et al.,* 2001). Conversely, Albalak *et al.* (2001) partially attributed the success of the *Plancha* stove to its ability to provide longer duration space heating than an open fire[24]. Secondly, fires provide light in often-dark quarters where there are few windows or other openings to the outside surroundings. The low luminosity of kerosene stoves and improved closed-chamber biomass devices has meant that households often make a small fire on top of the stoves to replace the lost light, once again increasing pollutant concentrations from expected levels (Hessen *et al.,* 2001; Rehman *et al.,* 2005). Other subsidiary functions of the fires include food drying[25] and insect (especially mosquito) repulsion attributed to the smoke (Smith, 1987). Thatch preservation by repelling termites and pests has been noted with open fire use and food drying is a common practice in many areas, making provision for alternative accommodation for both an important consideration when replacing open fires. A community-operated shared space for food drying and storage in one village in China incited households to extend the chimney outside of the house instead of terminating it in

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[24] Which it achieves by storing heat in a large metal top plate and its brick stove body (Albalak *et al.*, 2001).

[25] For a discussion on the role played by food drying as a route of exposure for combustion pollutants see Jin *et al.* (2006).

the attic, which had maintained the smoke indoors (Jin *et al.,* 2006). Clearly a full assessment of fire functions is imperative before a replacement is selected.

Climate

Closely related to issues surrounding the variety of functions fulfilled by the fire is a need to consider seasonal and climatic factors. The most obvious pertains to outdoor temperatures and the need for space heating in cold climates, which affects the duration of the fire burning, the ventilation requirements of the users and the placement of the household members. In colder regions fires are often left smouldering for warmth through the night, rendering interventions premised on shortening cooking times futile (Budds *et al.,* 2001). Thus, even if more efficient stoves reduce cooking times, a greater total amount of wood is still used when the stove is left burning through the night (Hessen *et al.*, 2001). Areas where space heating is required often boast houses that are relatively airtight (Smith, 1987). This has severe implications for ventilation (Albalak *et al.*, 1999). Windows and doors are generally kept closed for warmth (Budds *et al.,* 2001) thus intervention design must account for the resulting low levels of air exchange. Moreover, people, and children in particular, are often compelled to stay close to the fire for warmth (Budds *et al.,* 2001), making policies that advocate removing children from the vicinity an unrealistic option. Seasonal variations in climates must also be considered, as marked differences in indoor air pollution have been noted between seasons (Rollin *et al.,* 2004). Dry seasons favour outdoor cooking (Akunne *et al.,* 2006) while, due to indoor cooking and reduced ventilation practices, periods of continuing rainfall are characterized by exposure to higher pollutant concentrations (Smith *et al.*, 1983). Stove performance has also been shown to vary based on climate differences

(Smith, 1987), placing the onus on engineers to account for these discrepancies when developing a new stove. This is of particular importance in mountainous regions as stoves have been found to be less efficient at high altitudes (Barnes *et al.,* 1993) and often emit higher levels of pollutants (Smith, 1987). It is important that these areas are targeted with stoves that meet the functional requirements associated with high altitudes (Aggarwal and Chandel, 2004). A final example of climatic considerations relates to wind. Kerosene stoves are particularly sensitive to wind and the latter's presence can seriously affect stove performance (Barnes and Mathee, 2003). Thus, in windy areas use of kerosene for cooking will likely require windows and doors to be closed, hampering overall ventilation. Another study found that when wind direction was not considered before chimney installation, there was often a backflow of smoke into the kitchen, reducing the chimney's emission exhaust capabilities (Khushk *et al.,* 2005). These experiences shed light on the importance of understanding the climatic conditions of the area and how cooking technology and practices are in turn affected.

Economic factors

While this paper aims to shed light on the role of non-economic factors in household energy choices ignored by the classic energy ladder theory, the importance of economic considerations in these choices must not be negated. In general terms, the economic considerations fall into four subcategories - uptake costs for a new technology, cost of fuel use, maintenance costs and income generation. The first two have traditionally been correlated directly with the energy ladder concept and have thus received considerable attention in the literature. It is adequate, in this text therefore, to simply underline the pivotal obstacle that such costs can present to intervention adoption.

Experiences to date are replete with examples of this barrier effect. While biomass is available to most rural households at little or no economic cost (Wijayatunga and Attalage, 2003), ascension of the energy ladder classically entails progressively increased expenses (Anozie *et al.,* 2007). There is indeed a higher incidence of clean fuel use reported among higher-income houses (Dasgupta *et al.,* 2006). Not only do LPG, electricity, biogas and high density briquettes represent high capital costs in terms of equipment, appliances and set-up, but the former two also involve the recurring costs of fuel supply which are often far beyond the means of many households (Ahmed *et al.,* 2005; Albalak *et al.,* 2001; Ballard-Tremeer and Mathee, 2000; Karekezi, 2002; Lucky and Hossain, 2001; Masera *et al.,* 2000; Murphy, 2001; Pohekar *et al.,* 2005). It is imperative, however, that accurate analyses are performed to assess the actual cost differences between fuel options, as factors such as efficiency may alter the total implied costs[26]. Both Howells *et al.* (2005) and Anozie *et al.* (2007) calculated that supplying low volumes of electricity from a new grid connection would in fact be up to four times less costly than inefficient use of kerosene. Masera *et al.* (2000) also note that upgraded options require less input of labour and fuel, once again altering the aforementioned cost assumptions. Improved stoves and their accessories must obviously be affordable to users but these vary greatly in cost so no universal pricing trend can be referenced here (Ballard-Tremeer and Mathee, 2000). These new technologies also frequently require the purchase of new cookware, increasing the overall cost of a fuel or stove switch even further (Masera *et al.,* 2000). Nevertheless, Edwards *et al.* (2004) advocate improved

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[26] Pokharel and Chandrashekar (1995) explain that prices may be based on resource availability, currency exchange rates, government taxes, as well as transport and distribution costs, thus these must all be accounted for.

stoves as a comparatively cost-effective option and Goldemberg *et al.* (2004b) assert that adding a flue is an affordable alternative to fuel switching, while Ramanakrishna *et al.* (1989) highlight the costly nature of hoods.

A common oversight when accounting for costs of household energy transitions is the importance of maintenance[27], lack of which is one of the most commonly cited causes of high emissions despite technology improvements (Barnes and Mathee, 2003; Bruce *et al.,* 2006). Ramakrishna *et al.* (1989) emphasize that systematic follow-up is the only way to ensure that technologies continue to operate with reduced emissions and increased efficiency. The importance of this follow-up to the proper functioning of improved stoves, LPG, electricity and biogas is consistently referenced in the literature (Bruce *et al.,* 2006; Masera *et al.,* 2000; Pohekar *et al.,* 2005). With 'smokeless' stoves that are not maintained properly, Hessen *et al.* (2001) describe high levels of visible smoke in Nepali kitchens, while Aggarwal and Chandel (2004) noted frequent backfire when pipes and flues were not cleaned. There is typically a lack of technical support once appliances are installed (Heltberg, 2005), and even when available, the cost of specialized technicians, such as electricians, is often prohibitive (Murphy, 2001). A variation in this phenomenon was the experience with a community biogas plant in India that did not generate enough profit for maintenance and was thus an unsustainable venture (Reddy, 2004). Clearly, maintenance costs must be factored into the ability of a household or community to afford the use of a new technology.

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[27] Barnes and Mathee (2003) list some common stove maintenance needs such as filling holes in chimneys, cleaning chimneys, fixing hinges on doors and replacing missing burners.

Closely associated with the concept of maintenance is that of stove design and durability. Overlooked design shortcomings have been cited numerous times in intervention experiences. In one example the damper, when used, caused burns while, when unused, decreased efficiency; in addition the pot hole rims were improperly designed so that smoke escaped into the kitchen (FAO, 1993). Khushk *et al.* (2005) found faults in "the design of smoke-free stoves such as smoke leaking from the sides of cooking pots, backward flow of smoke from the fuel inlet, or improper height or direction of the chimney". These problems result not only in degraded performance producing higher emissions but also demand greater maintenance (Barnes *et al.,* 1993). Similarly, stove durability has been shown to be one of the more pivotal considerations in stove adoption and longevity of use. Poor durability has consistently hindered the long-term use of improved stoves (Desai *et al.*, 2004; Heltberg, 2005; Khushk *et al.,* 2005; WHO, 2002). Cracking and warping of the bodies as well as holes in chimneys have commonly plagued the *Plancha* and because these are quite difficult to repair, houses usually become smoky and the lifespan of the stove is greatly reduced (Ahmed *et al.,* 2005; Albalak *et al.,* 2001; McCracken and Smith, 1998; Murphy, 2001). Poor installation also results in performance deficiencies (Smith *et al.,* 1983). While perceived lack of durability has limited the adoption of improved stoves (Khushk *et al.,* 2005), many programmes found that once the stove function began to deteriorate the technology was abandoned instead of been repaired or replaced (WHO, 2002)[28]. Conversely, programmes that diffused highly durable stoves have, by and large, experienced strong

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[28] See Murphy (2001) for recommendations on design improvements and quality standardization.

acceptance, with durability being cited as a vital feature (Ballard-Tremeer and Jawurek, 1996; WHO, 2002). Many studies have thus concluded that longer lifespan should be a primary focus of improved stove efforts (Kishore and Ramana, 2002), and this rationale must also be applied to fuel changes that in turn require a change in combustion devices.

A final economic consideration on which there is very little evidence is that of potential income generation from different energy technologies. Whether or not the adoption of a new technology in a region will create or eliminate jobs can be imperative to the economic viability of an intervention. While collection and marketing of biomass fuels for sale can be a source of local employment for the poor (Heltberg, 2005), local manufacture of improved stoves could similarly generate additional employment opportunities (Ballard-Tremeer and Mathee, 2000). Kerosene and LPG industries only employ 10% and 20% of the labour that does the fuelwood industry, thus their use on a large scale may have an economic impact through the job market (Ballard-Tremeer and Mathee, 2000). As "income generation is an important precursor to improved technologies adoption" (Kanagawa and Nakata, 2007), the effects on local employment are as important as the cost of the technology itself.

Opportunity costs are also important considerations. In economic terms, the time and energy that is spent gathering biomass for fuel takes away from that which can be spent on other, potentially income generating, activities[29] (Barnes *et al.,* 1993; Heltberg, 2005; Kanagawa and Nakata, 2007; Sims, 1994). Moreover, Goldemberg *et al.* (2004b) assert that if this labour were monetarily valued along with the household absorption of

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[29] See Barnes *et al.* (1993) ; Kanagawa and Nakata (2007); and Wijayatunga and Attalage (2003) for estimations of time allocated to fuel collection.

costs associated with the health effects of solid fuel use, biomass would be conceived as a far more expensive option than modern, clean cooking fuels. Kanagawa and Nakata (2007) provide detailed calculations of opportunity costs for various fuels, demonstrating that they further affect the total cost of the technologies discussed above. Finally, the opportunity costs of the biomass itself, for example the loss of dung for use as fertilizer (Budds *et al.,* 2001) or agricultural residues for animal fodder (Edwards *et al.,* 2004), and the use of the land on which it's produced (Reddy, 2004), has rarely been evaluated, but may also contribute to the true, externality-included value associated with its use as a fuel. A complete valuation equation should factor in these opportunity costs more reliably to represent the economic impact of an intervention.

While this section underscores that household economic status is a significant determinant in choice of cooking technology (Boadi and Kuitunen, 2005), Ezzati *et al.* (2004) clarify that it is "important to treat income not as a deterministic cause of energy transition but rather as a source of additional freedom to choose certain types and quantities of fuel or the technology for fuel utilization".

Access, Availability and Reliability of Supply

Despite initial programme efforts to catalyze the adoption of cleaner fuels and stoves, the long-term usability of the technology depends on its availability and the users' access, as well as the reliability of this access.[30] As Howells *et al.* (2005) found "access to safe, reliable and affordable energy is crucial to development, as virtually all potential

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[30] See Ezzati *et al.*(2000); Goldemberg *et al.*(2004b)*;* Reddy (2001) for information on global energy demand and availability.

economic activity will be dependent on some form of energy service". There are countless examples of insecure fuel supplies that have inhibited their use. In India, kerosene distribution outlets are often located far from where the majority of the poor population resides, while both LPG and kerosene ration cards require permanent verifiable residential addresses and documentation of nationality that are often difficult to obtain (Gupta and Kohlin, 2006). Furthermore, this segment of the population is not always aware of the quotas to which they are entitled and the days on which the supplies arrive, and thus are provided with less than they need or at times supplies have run out by the time they arrive (Rehman *et al.,* 1995). Availability of both kerosene and LPG has been characterized by poor distribution and unreliability in most rural areas (Pohekar *et al.,* 2005). Heltberg (2005) highlights the even greater difficulties that indigenous populations, often removed from global economic systems, have in accessing clean energy, leading to a strong preference for fuelwood. Difficulties with storage and transportation, as well as production uncertainties often hinder the consistency of modern fuel supplies (Gupta and Kohlin, 2006; Pohekar *et al.,* 2005). Breakdowns at oil refineries restrain the supply of LPG and kerosene (Anozie *et al.,* 2007), and constant blackouts have plagued rural Indian electricity users (Reddy, 2001). Electricity has not gained popularity in Nigeria because the availability is notoriously erratic (Anozie *et al.*, 2007), while 65% of households in electrified villages in South Africa are not able to enjoy the benefits because of the poor supply reliability (Rehman *et al.,* 2005). Fuel prices increase with distance from the urban distribution sources (Dasgupta *et al.,* 2006), once again affecting the economic viability of a technology (Masera *et al.,* 2000).

Other fuels are also subject to availability considerations. Despite widespread advocacy for its technological viability, biogas initiatives have rarely been successful because they require very large quantities of both dung and water to produce enough biogas to meet cooking energy needs and very few settings have ample supplies of these resources (Reddy, 2004). On the other hand, while coal is not available in all regions, charcoal briquettes can be produced locally and thus be readily available to that population (Budds *et al.,* 2001). Conversely, McCracken and Smith (1998) highlight areas in Guatemala where wood is brought to the highlands from the coast, thus access to more modern fuels may be comparatively less of an obstacle. Given the unpredictability outlined above it is understandable that households adopt a multiple fuel strategy to maximize their fuel security (Masera *et al.,* 2000), and this explains why addressing access and reliability problems are paramount to motivating clean energy transitions.

Availability and supply issues also apply to improved-stove initiatives. While locally available materials are used because of their reliability, these may be insufficiently durable (Desai *et al.,* 2004; Smith, 2002). A transition to higher quality, more durable alternatives that must be imported, however, subjects production and maintenance to all the causes of insecurity listed above for fuels. It has been quite common for transportation barriers to afflict stove producers and manufacturers. Communities are often remote and accessible only by poor roads (Ahmed *et al.,* 2005). In one account, fragile clay chimneys were transported to villages on such roads. Many of them sustained severe damage, and obtaining replacements was virtually impossible (Ahmed *et al.,* 2005). This reality, in turn has led to inconsistencies in the quality available at affordable rates (Ahmed *et al.,* 2005; Murphy, 2001). In one area of India where a programme had been implemented, 30% of households said that no improved stoves were available (Wijayatunga and Attalage, 2003). Similarly, problems with consistent maintenance are especially significant in places without access to necessary tools and replacement parts (Hessen *et al.,* 2001). Conversely, most of the building materials required to install the *Plancha* are easily available in the areas of Central America where they are used, contributing to their continued use (Albalak *et al.,* 2001). Thus, both the durability of a stove, and the local provision of the materials that ensure this quality, have important implications for the sustained success of stove programmes (Barnes and Mathee, 2003).

Infrastructure

The above discussion emphasizes the need to ensure reliable access to energy sources for rural populations for whom this is often not the case. Jin *et al.* (2006) further explain that "community level and regional physical and institutional energy infrastructures are important but often overlooked components of successful intervention programmes". Infrastructure is particularly critical for addressing accessibility issues. Effective delivery and marketing systems depend on physical infrastructure such as roads, electric grids, pipelines for LPG and distribution centres for this last and kerosene, while the management of such systems necessitates institutional organization at the community and regional levels (Ahmed *et al.,* 2005; Jin *et al.,* 2006; Pohekar *et al.,* 2005). Murphy (2001) also highlights the need for intervention programmes to "understand social institutions and common property regimes to gauge supply distribution". Moreover, biogas and LPG require storage facilities that demand infrastructural orchestration beyond the households themselves (Gupta and Kohlin, 2006;

Rajvanshi, 2003). Socio-economic infrastructure may also be crucial in the provision of financing and collective savings initiatives that remove the economic barrier to technology uptake (Howells *et al.,* 2005; Reddy, 1999). Finally, ensuring that stoves are built, installed and repaired properly and with modern, lightweight and durable materials, necessitates widespread and localized training programmes preferably through local trade schools, the creation of which often hinges upon an adequate educational infrastructure (Aggarwal and Chandel, 2004; Jin *et al.,* 2006). While this is a challenge, the encouragement of local development of skills can have a concomitant positive impact on the economic vitality and security of the area.

The benefits of a strong education system extend well beyond the reaches of the above example. Education has been postulated to play an important role in both the dissemination and adoption of new technologies (Smith, 2002). Education and literacy facilitate the exposure to information about the harmful impact of smoke, the value of clean kitchen air, and, in turn, the energy choices available (Aggarwal and Chandel, 2004; Anozie *et al.,* 2007; Desai *et al.,* 2004; Muneer *et al.,* 2003). Ahmed *et al.* (2005) found that behavioural changes were adopted only when the correlation to poor health was established for the users; Aggarwal and Chandel (2004) specifically called for the need for education about proper ventilation practices. Smith (2002) suggests that training for improved kitchen hygiene should be part of all household health initiatives. Once a new stove is adopted it is also imperative that the stove user know the limitations of its use and how to care for it properly (Ahmed *et al.,* 2005). The general population should also be informed of the need for energy efficiency and conservation programmes where applicable (Anozie *et al.,* 2007). The education system is vital toward all of these ends and both schools (formal) and media (informal) can be used to disseminate the information (Bruce *et al.,* 2006). Pohekar *et al.* (2005) confirm that low education levels have made technology dissemination difficult. Dasgupta *et al.* (2006) suggest that an information strategy may offer the best short term option for encouraging clean energy use, which Aggarwal and Chandel (2004) qualify by calling on "education programmes to create a scientific understanding among the rural masses" to catalyze change in household energy systems.

Gender and Susceptible Demographics

The issue of indoor air pollution from cooking is one that is subject to major gender discrepancies, and interventions must account for the varied way in which the problem and proposed solutions are perceived and experienced by each gender. Certain demographics are more vulnerable to the harmful effects of smoke exposure than others. The populations most at risk are the poor, females, young children and the elderly (Budds *et al.,* 2001). Poor women are the largest users of biomass for fuel and they spend a disproportionately large amount of time in proximity to the combustion source. The discussion on economics given above has established why poor households must rely on biomass for their energy needs. Significantly, every study cited found that women did the vast majority of the cooking, resulting in disproportionately high exposure. Further, the children and the elderly, for whom women are the primary caregivers have similar prolonged exposure (Boleij *et al.,* 1989*;* Sims, 1994). It is worth noting that unborn children also experience increased exposure, albeit indirectly, through the mother (Smith, 2006b). There is clearly a vastly uneven burden of exposure and potential disease, and this means that interventions to improve IAP from cooking primarily benefits these groups (Goldemberg *et al.,* 2004b).

In many low-income rural societies, the classic structure of household decision-making dictates that economic decisions are made predominantly by men (Subramaniam, 2000). It has been observed that in many instances, any discretionary income held by a poor household will be spent on items that will benefit primarily the male members (Goldemberg *et al.,* 2004b). This has meant that spending on kitchen improvements, including energy technologies, rarely takes precedence over other expenditures (Hessen *et al.,* 2001). Moreover, the kitchen is traditionally considered a woman's space, and thus expenses associated with it are often expected to come out of whatever small portion of household resources that are allocated to women (Muneer and Mohamed, 2003).

While the practical implication is that economic barriers to intervention adoption are created by gender inequalities, there is also an implied theoretical undervaluation of women and their concerns. An observed tendency for women's respiratory diseases to go untreated in many areas further undermines the valuation of women and their health (Sims, 1994). These are issues that must be considered when designing, marketing and pricing interventions. Muneer and Mohamed (2003) observed that extension campaigns for new stoves were aimed at men who had no interest in the benefits they offered, resulting in low uptake rates. Similarly, even higher income households tend to continue cooking with polluting technologies as it is mostly servants who do the cooking; thus those who control the finances are not those who are primarily exposed (Wijayatunga and Attalage, 2003). This notion of undervaluation is also seen where fuel shortages occur, as the onus is placed almost exclusively on the women to find solutions, in turn having to invest more physical energy to procure fuel instead of using household income to purchase alternatives even where affordable (Sims, 1994). A similar stance is observed when the price of mass transportation to fuel collection locations increases; the burden is placed on women to find other means of travel, often involving greater physical demands (Parikh, 1995). In general this unwillingness to value energy costs when in the form of women's labour is a severe barrier to clean energy sources as the indifference inhibits a search for alternatives or a willingness to pay for them (Reddy, 1999).

Clearly household energy needs relate directly to women's workload and time (Mahat, 2007). Women's efforts procure 10-80% of the total supply of household energy in low- and middle-income countries (Parikh, 1995). Thus whether or not fuel and technology changes impose additional demands upon them or fail to meet all needs as did the traditional alternative, will greatly determine their willingness to switch (Masera *et al.*, 2000; Parikh, 1985). This raises an issue that will be addressed in the following section which highlights an array of areas in which user preferences and perceptions are central to the motivation to adopt a technology. Hessen *et al., (*2001) assert that the most successful programmes relied on participatory processes. Implicit in this point is the critical nature of women's participation at both the innovation and implementation phases to ensure that their needs are incorporated (Subramaniam, 2000). A programme in Northern India attributed its success in great part to the involvement of women users for the development and construction of stoves (Subramaniam, 2000) while organizers of the Guatemala stove programme cited the use of women's input as one of its dominant strengths (Ahmed *et al.,* 2005). It must be emphasized at this stage that women's input and needs often differ from those of men's. For example, while women often operate biogas plants, it is the men that traditionally select the land on which they are installed. This has resulted, however, in a failure to ensure the efficacy of the location for performing the vital tasks of water fetching and dung carrying, both carried out by women (Mahat, 2007). A related gender consideration involves training in stove use and maintenance, which intuitively should be geared to the women who use them, but examples of training courses marketed to and attended solely by men abound (Muneer and Mohamed, 2003). The exclusion of women from these activities indirectly obstructs technology adoption. The following section examines the preferences, perceptions and motivations of users, primarily women, that have had a strong impact on intervention success.

Preferences, Perceptions and Motivations

It is frequently noted that "many initiatives have failed due to inattention to user's needs, which include both practical and socio-cultural considerations" (Khushk *et al.,* 2005). These considerations can be conceived of as preferences that will either motivate or impede the uptake of new technologies. Moreover, households often form perceptions about proposed changes and how their adoption will affect them (Gupta and Kohlin, 2006). Households evaluate their priorities based on these perceptions, regardless of their accuracy, and these in turn dictate their motivation to switch. Thus the cultural acceptability of a technology and the household's valuation of an intervention's attributes must be evaluated based on needs, determined by these preferences and perceptions. Unfortunately, interventions to reduce IAP from cooking have been characterized by a "mismatch between the felt needs of the rural poor and the assumptions of the institutions and individuals designing and promoting" them (Muneer and Mohamed, 2003). A more complete understanding of these needs and their role as either motivators or inhibitors of intervention adoption is paramount to the appropriate selection and design of these interventions. Further, large differences between living conditions and cultural practices throughout the world suggest that “generally accepted explanations of success will not necessarily apply to local conditions” (Hessen *et al.,* 2001), underlining the importance of ascertaining the above-discussed needs on a location-specific basis. Below is a categorized summary of user’s needs and motivating features that have been consistently cited in the literature as important considerations for intervention programmes but are classically overlooked in their design and implementation, and to varying degrees blamed for their failures.

Health, Sanitation and Cleanliness

The prospect of a reduction in smoke and the ensuing health benefits begets varying reactions from different populations. While some authors found them to be dominant motivational factors for changing to improved technologies, others encountered an indifference to health concerns (Dasgupta *et al.,* 2006; Gupta and Kohlin, 2006; Hessen *et al.,* 2001; Masera *et al.,* 2000). Motivated users tended to avoid unhealthy fuels, showed a preference for clean energy marked with the popularity of LPG due to its cleanliness and in one example males in Kenya were convinced to spend household resources on improvements only when they were persuaded that their children’s health would benefit (Budds *et al.,* 2001; Dasgupta *et al.,* 2006; Howells *et al.,* 2005; Pohekar *et al.,* 2005). Similarly Barnes and Mathee (2002) found that women appreciated that less dust in the house from smoke entailed less cleaning for them. Where health concerns did not appear to factor into choices, researchers were unsure whether this was due to a lack of awareness about the connection between smoke and health risks or simply that health is of secondary importance within household energy decisions (Gupta and Kohlin, 2006). Lan *et al.*'s (2002) evidence that many residents did not change to clean technologies until they had already developed respiratory symptoms or on a physician's advice would point to the former, emphasizing the need for greater awareness raising in conjunction with intervention marketing. Where the latter is a reality, however, other technology advantages besides IAP reduction must be propagated to motivate a user switch.

Cost and Income

The earlier discussion of economic factors demonstrates how costs and income can present considerable obstacles to technology adoption (Albalak *et al.,* 2001; Dasgupta *et al.,* 2006; Gupta and Kohlin, 2006; Wijayatunga and Attalage, 2003). Policies based on economic conditions, however, must grasp the user's perceptions of household energy economics. While it can be taken as a given that high costs and low incomes may prevent technology switches, the economic benefits that may result from improvements in efficiency can often act as a catalyst for change. In the marketing of improved stoves, Qiu *et al.* (1996) found that adoption was more likely when they stressed the economic benefits of efficiency. The price elasticity of fuels, in other words, how changes in price of different fuels influence their adoption, can affect the selection of technology, pricing and marketing policies. Where the cost of wood is low, this generally limits the uptake of alternatives (Howells *et al.,* 2005), while conversely uptake is stimulated by a drop in LPG prices where wood prices are rising (Ahmed *et al.,* 2005). Similarly, Hessen *et al.* (2001) found that the most successful programmes were those run in areas where wood prices and collection times were high. This last point also indicates a valuation of the opportunity cost of the collection time, which can be incited to stimulate changes. Misconceptions about prices may also speak to energy choices, and need to be addressed to overcome consumer inertia. Anozie *et al.* (2007) describe households as having a false notion of cooking with electricity as very costly, when it was in fact cheaper than kerosene. Household willingness to pay for technologies will vary greatly and must be assessed before intervention selection. Reddy (2004) reported a sustained willingness of all households to pay for biogas from their locally operated plant whereas other fuels may not be perceived with such esteem, thus making them unappealing even at affordable rates. Other examples of economic preferences include an observed preference for fuels that can be purchased in discrete quantities such as kerosene as opposed to LPG, which is only reasonably priced when purchased in full tanks (Howells *et al.,* 2005). Likewise Pohekar *et al.* (2005) observed a preference to invest in consumer durables instead of energy technologies such as fuel, so pricing and economic policies would have to reflect these inclinations. Each of these examples of economic proclivities extraneous to the basic assumption of cost barriers should be considered to ensure the complete economic viability of a programme.

Efficiency

Closely connected to the aforementioned issue of cost is that of efficiency. Efficiency can offer primarily two benefits, namely fuel savings or reduced cooking time. Efficiency will generally be of greater concern where fuel costs, or time to collect the fuel, are higher, or supplies are less reliable. Thus where this is the case, successful programmes commonly offered efficiency improvements (Desai *et al.*, 2004). Hessen *et al.* (2001) reported that the predominant complaint about improved stoves was that they used more wood than the fire for any given cooking task. For example, the introduction of chimneys often reduces fuel efficiency through added airflow, increasing overall fuel consumption (Ballard-Tremeer and Mathee, 2000; Desai *et al.,* 2004). While some studies found that people tended to adopt stoves because of expected fuel savings and then continued use because of smoke reduction (Smith, 1987), others found these savings to be of secondary importance (Hessen *et al.,* 2001). Where efficiency does not appear to be highly valued it is commonly assumed that this is due to the free availability of wood (Khushk *et al.,* 2005). Similarly Theuri (no date) found that where improved charcoal stoves saw 50% penetration in the local market, improved wood cookers only boasted 5% market uptake, which he explained by a lack of incentive to save wood where it is free and easily available. Which of these circumstances pertains to the local setting will affect whether efficiency should be a focal feature of the stove design and marketing strategy, as well as whether its absence will hinder widespread dissemination and use. Similarly, the time it takes for a given cooking task has often displayed a strong effect on technology choice (Masera *et al.*, 2000). McCracken and Smith (1998) claim that faster cooking was in fact the most important improvement for women in Guatemala. The *Lorena* stove has been widely accepted by women, credit for which is given in large part to the 50% efficiency improvement in tortilla making that it offers over use of an open fire (Masera *et al.,* 2000). That the *Plancha* stove required more cooking time than an open fire, however, was cited as one of its greatest flaws (Park and Lee, 2003), while kerosene is hailed for how quickly it boils water (Howells *et al.*, 2005). Clearly in many places improvements in cooking time will motivate a switch, while the converse threatens to impede it.

Convenience and ease of use

The facility with which a new technology can be introduced into a household and used has proved to be a chief concern of users, particularly women. Hessen *et al.* (2001) found that the greater ease of use of improved stoves was one of the main features motivating transition from traditional fires in Nepal. This impression of superior convenience was a function of testimonies from those who already owned improved stoves, demonstrating the potency of reported experiences on perceptions. Conversely, Dasupta *et al.* (2006) found that 39% of those surveyed in Bangladesh viewed improved stoves as inconvenient, deterring them from purchasing one. Improvements and reductions in convenience can pertain to all facets of operation. The height and size of the working surface of the stove must cater to all traditional cooking tasks (Qiu *et al.,* 1996), while the stove must abstain from obstructing the general kitchen space (Wijayatunga and Attalage 2003). The LPG stove, for example, does not provide a large enough surface for tortilla preparation, prolonging total preparation time for the cooks (Masera *et al.,* 2000). To achieve higher efficiency, fireboxes in improved stoves are often too small for the typical size of fuelwood, forcing women to add the cutting of wood into smaller pieces to their daily tasks (Ahmed *et al.,* 2005; Ballard-Tremeer and Mathee, 2000; Murphy, 2001). Often women simply stop using the improved stoves to avoid this added burden (Barnes *et al.,* 1993), or alternatively they enlarge the firebox to accommodate their fuelwood, removing most of the efficiency gains (Budds *et al.,* 2001). Some households that continue to use elongated pieces of wood left the chamber doors open or removed them altogether, causing higher emission concentrations in the kitchen as well as increasing the amount of fuel consumed (Hessen *et al.,* 2001). Combustion chambers must thus be suitably sized to accommodate the fuel used by that household. Budds *et al.* (2001) explain that hoods are often difficult to integrate into homes and a study in Kenya found that people complained that they took up too much space, got in the way while cooking and frequently presented an obstacle on which cooks hit their heads. The height of the houses and whether or not there is an attic should determine the length of the chimney. At times, however, these are not coordinated in the available designs and the chimney ends in the attic, ultimately dispersing pollutants back into the living area through typically porous ceilings (Jin *et al.,* 2006). Cooking utensils such as pots and pans are also subject to stove size and people have expressed frustration at having to purchase replacements of such items, while their immediate availability is not always a given (Barnes *et al.,* 1993; Bhattacharya *et al.,* 2002b). The ability of an improved stove to combust all forms of fuel used in that area is also important to its sustained use through seasons that dictate changes in biomass type availability (Qiu *et al.,* 1996). Lastly the height of the stove determines the extent to which the cook must lean over the fire, thus a raised stove will reduce the amount of smoke inhaled (Ballard-Tremeer and Mathee, 2000). These physical characteristics and compatibilities are important to establish before intervention selection. *Plancha* stove users praised its ease of use and straightforward adaptability from open fires, as it required no special manual dexterity (Albalak *et al.,* 2001). Other improved stoves, however, have garnered complaints about difficulties controlling the heat to each hole when using two pots, the difficulty of controlling the damper and the added work in cleaning the flue and combustion chambers due to excessive ash build-up (Aristani, 1996; Ballard-Tremeer and Mathee, 2000). Stoves that require the removal of the pots to refuel also receive a great deal of criticism as this not only an added inconvenience during cooking but it increases smoke emissions and exposure (Ballard-Tremeer and Jawurek, 1996). The portability of certain stoves can be a vital feature for certain populations (Aggarwal and Chandel, 2004; Qui *et al.*, 1996). Women in Indonesia cited the fact that they could bring their improved two pot ceramic stove to the fields and move around with it as a favoured attribute while migrant labourers in particular appreciate lightweight, portable options (Aggarwal and Chandel, 2005; Aristani, 1996). Similar to these considerations for stoves, the convenience of modern fuels is a critical trait for their uptake (Heltberg, 2005). They can reduce time spent on fuel collection, cooking and cleaning while permitting easy adjustment of the flame during cooking (Heltberg, 2005). Kerosene is typically considered easy to use but women have cited difficulties in lighting the stove as a limitation (Howells *et al.*, 2005; Pohekar *et al.*, 2005). Moreover, the flame on a kerosene stove is sensitive to air movements and thus cooking cannot be done near sources of ventilation for fear of it being extinguished (Barnes *et al.*, 2004). Such inconveniences may deter users from adopting it. LPG and biogas are generally both regarded as easy to use fuels that don't add any greater burden to users (Pohekar *et al.*, 2005). Finally, mothers in South Africa revealed improvements in ventilation practices and removing children from the vicinity of the pollution as interventions that they could feasibly adopt, and Barnes *et al.* (2004) highlight the importance of establishing this sense of adaptability and practicability in the users so as to avoid a perception of inconvenience.

Traditional customs and cooking practices

Much like the issue of convenience, new technologies must interrupt traditional customs and cooking practices as little as possible if they are to appeal to the target populations. Rural families are often quite large and the capacity of a stove to cook large amounts can be of primary importance. A biogas plant in an Indian village, for example, was only able to produce enough energy for one meal a day for a family no larger than 5 people (Reddy, 2004). While a regular LPG stove was only able to cook small meals, the specially designed *El Comal* LPG high-powered burner was highly functional for preparing large quantities (Albalak *et al.,* 2001). Where cattle raising is common, kerosene stoves are often abandoned because their small size is unsuitable for preparing the fodder which is done in large quantities (Rehman *et al.,* 2005). Other shortcomings include complaints in Indonesia that the improved ceramic stove burns rice, their staple food, too quickly (Aristani, 1996), and that an improved stove in Rwanda, while being more efficient when cooking beans, did not offer the same savings when preparing rice in sauce (Barnes *et al.,* 1993). These requirements are rather location specific, as exemplified by the need for slow heat to warm milk in India compared to the high heat used for stir-frying in China (Budds *et al.,* 2001). One study found that locals did not use the new stove because the pot used to produce traditional liquor did not properly fit the hole (Hessen *et al.,* 2001). Religious practices can also determine fuel choice. Gupta and Kohlin (2006) mention that Muslims have unique cooking practices that require cooking conditions that all fuels may not provide, while Aggarwal and Chandel (2004) describe finding that households had broken the top of the firebox because of religious beliefs, which both reduced efficiency and increased emission concentrations. One of the most widespread critiques of modern fuels in this context relates to tastes and odours. In many places the staple foods are baked which requires the indirect heat offered by traditional mud stoves but not the kerosene and LPG alternatives (Rehman *et al.,* 2005). Those accustomed to the taste given to food by traditional fires and woodstoves have shown a great aversion to their perception of a lack of taste in food cooked with other fuels such as kerosene, LPG and electricity (Heltberg, 2005; Masera, 2000; Wijayatunga and Attalage, 2007). These households usually continue cooking many items with their traditional stoves even when provided with modern substitutes (Rehman *et al.,* 2005; Wijayatunga and Attalage, 2007). An alternative outcome is that households using these modern fuels exclusively spend a great deal on purchasing wood-baked products outside of the home, incurring additional economic costs (Heltberg, 2005). Kerosene has the unfortunate trait of emitting an unpleasant odour to both the food prepared with it and the cooking area in general, making it undesirable as a choice for many households (Pohekar *et al.,* 2005; Rehman *et al.,* 2005). These examples shed light on how cultural practices connected to cooking can influence fuel and stove choices and beg consideration in technology design.

Familiarity with a technology creates a comfort level that many users have been wary of forsaking. Wijayatunga and Attalage (2003) found a strong attachment to the past practice of biomass use for cooking which produced a reluctance to switch without any concrete reason reported. The discomfort with modern technologies, in conjunction with an affinity for old practices, was observed with older women in Guatemala when they were offered LPG stoves, and similarly for women who were proposed improved stoves in India (Albalak *et al.,* 2001; Wijayatunga and Attalage, 2003). Howells *et al.* (2005) found that most people said they used a fuel because they were familiar with it, highlighting this feature's importance. Moreover, the role of the fire in many households as the centre of social activity may add to this attachment (Murphy, 2001). In South Africa 80% of those surveyed agreed that "a fire or coal stove in the home brings and keeps my family together" (Ballard-Tremeer and Mathee, 2000), and Aggarwal and Chandel (2004) reported the universal practice of the whole family sitting around the stove through the winters. These inclinations towards familiarity and comfort may be powerful forces against technology adoption that require creative solutions that export those facets with which people identify from old technologies to new alternatives.

Safety and security

There are a number of both perceived and observed safety concerns that arise with the prospect of technology switches. The possibility of a fire, caused by either poor electrical wiring or kerosene stoves, has been cited as a risk by users (Howells *et al.,* 2005). LPG carries a small risk of explosion and the perception of this risk is noted as an important barrier to switching to its use in India (Pohekar *et al.,* 2005; Wijayatunga and Attalage, 2003). Burns from the outside surfaces of improved stoves, including the damper, have been an issue, and the stability of the stove can be tenuous, increasing the risk of hot, heavy pots falling or being pulled over by a child (Ballard-Tremeer and Mathee, 2000; Budds *et al.,* 2001). A common occurrence in households where kerosene is newly adopted is the accidental poisoning of children who drink the fuel that has been stored in soft drink containers (Von Schirnding *et al.,* 2002). There are 16,000 hospitalizations in South Africa a year due to these poisonings; they therefore present a great concern to those considering its use (Ballard-Tremeer and Mathee, 2000). Windows in the kitchen are often small and kept closed as this space also serves as sleeping quarters for women and openings are considered a safety concern (Ballard-Tremeer and Mathee, 2000). For various reasons, they are kept closed- for privacy, security from intruders, and also to keep wild animals out (Budds *et al.,* 2001). This could be an obstacle to measures intended to increase ventilation. In fact some households cook inside specifically to avoid dangerous animals (Smith, 1987), thus advocating for outdoor cooking in these places may not be widely accepted. Any safety concerns of the households cannot be overlooked so as to ensure the user's willingness to adopt an intervention and their comfort level with its use.

General perceptions

Perceptions of a few of the factors hindering intervention uptake and sustainability discussed prior to this section are also worth highlighting within this section. Murphy (2001), for example, detected a perceived low quality of improved stoves that deterred people from purchasing it, while Rehman *et al.* (2005) described a general discernment of the technical obsoleteness of kerosene stoves, which may deter people from replacing them until designs are improved. Similarly, the perceived availability of fuels such as LPG and improved stoves have been found to have a significant effect on households' decision to use fuelwood (Dasgupta *et al.,* 2006; Gupta and Kohlin, 2006). Survey respondents corroborated this assertion by claming that they chose fuels because they are easily available (Howells *et al.,* 2005). Thus it is not sufficient to attend to these factors in and of themselves, instead, their having been addressed must be disseminated to modify users' perceptions. This segues nicely to a concluding deduction that limited information and its insufficient diffusion may underlie a great many of the aforementioned barriers discussed in this section. Those that cannot be addressed by informational initiatives must instead be assessed for their local applicability to ensure that health benefits are not compromised because of inattention to often minor, but pivotal, preferences and perceptions.

Conclusion

The compilation of the two chapters of this report ultimately conveys an optimistic message, albeit one threaded with caution. Chapter 1 expounds the impact of those more common interventions on particulate emissions and concentrations and displays their potential to substantially reduce human exposure to pollutants. Chapter 2 then examines the literature available on experiences to date with these various interventions and outlines the predominant issues encountered that hindered their overall success. It herein reveals the deeply intertwined nature of the technological and socio-economic facets of indoor air pollution from cooking and affirms the importance of embracing a holistic approach to addressing the problem by considering not only each issue individually, but also how each affects the others. The local specificity of programme requirements is made evident, as is in turn the need for initiatives to be "robust to existing limits" encountered upon implementation in varying locations and conditions (Jin *et al.*, 2006). Moreover, the highlighted importance of participatory programmes echos the WHO's (2002) call for interventions that strive to "broaden the range of secure and sustainable choices available" which will then "enable people to devise their own solutions". As greater numbers of longitudinal studies are carried out that monitor the technical performance of interventions, as well as the socioeconomic and behavioural determinants of their adoption and continued use (Ezzati *et al.,* 2004), more information will be amassed to inform and tailor future programmes as needed. In the meantime, this report provides a starting point for evaluating intervention appropriateness and demonstrates the significance of this assessment to intervention sustainability.

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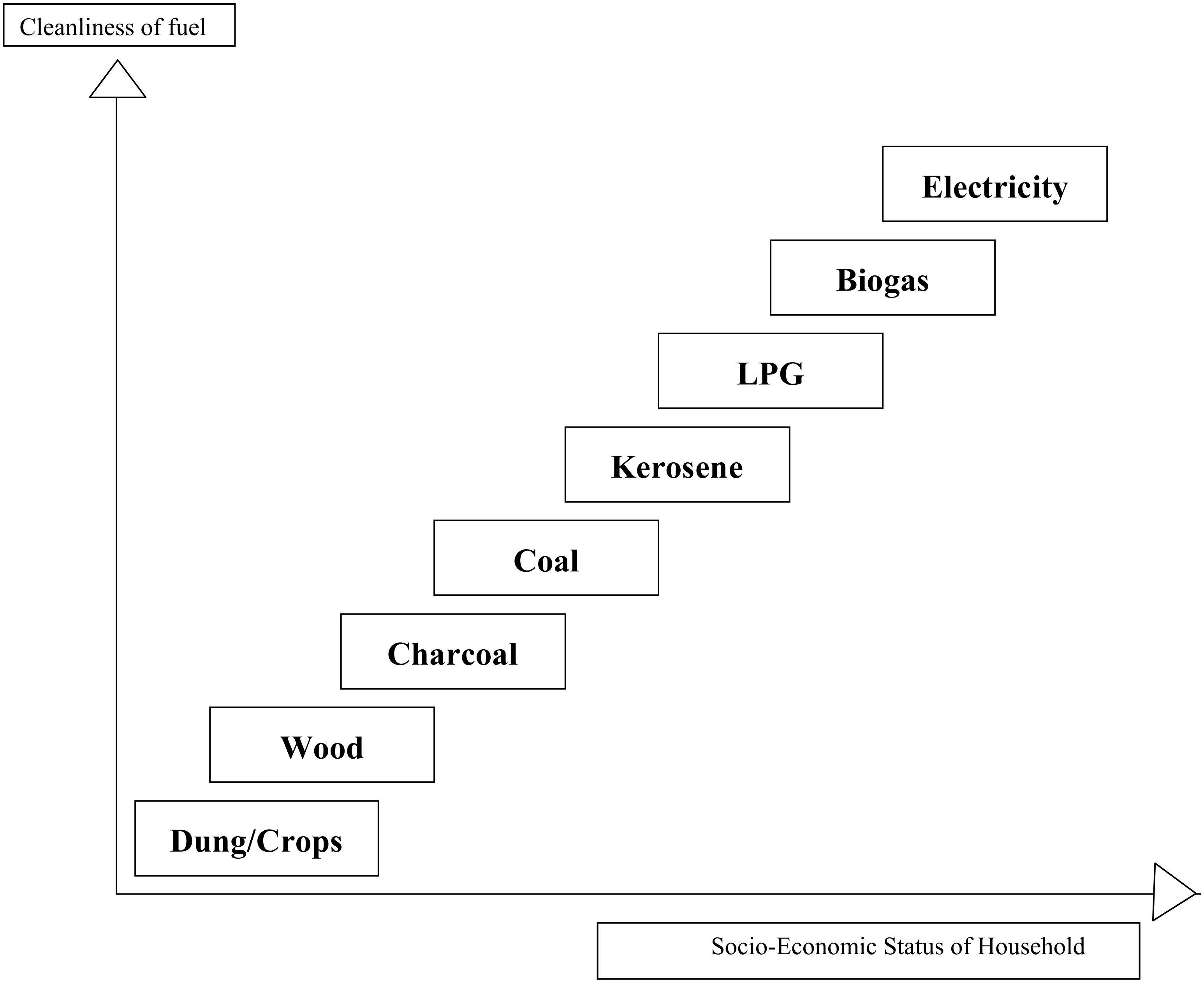
Acknowledgments

I'd like to take this chance to thank my supervisors, Dr Heather Jamieson and Dr Gary vanLoon for not giving up on me, as well as Dr Javier Pintos for being such an astute outside reader at such short notice. A very special thanks is also in order for my mother, who taught me the value of tables and the paint brush icon in word.

Appendix 1

The Energy Ladder



Appendix 2

Table 1. List of articles showing fuel type, stove type, ventilation, and pertinent study outcomes

Table 2. Comparison of concentrations of particulate matter from biomass combustion observed in studies reviewed

Table 3. Comparison of concentrations of particulate matter from coal combustion observed in studies reviewed

Table 4. Comparison of concentrations of particulate matter from LPG observed in studies reviewed

Table 5. Levels of particulate matter as measured in concentrations from different stove types and reductions with the use of improved technology

Table 1. List of articles showing fuel type, stove type, ventilation, and pertinent study outcomes

Author	**Place**	**Fuels evaluated**	**Stove type**	**Ventilation (other than flues)**	**Outcome**
Albalak *et al.*, 1999	Bolivia (2 villages)	Biomass (mostly cow dung)	Traditional cookstove (clay, two-pot)	Indoor and outdoor cooking; housing characteristics: adobe walls, corrugated tin roofs, dirt floors	Significant effects of village (indoor vs outdoor), location (of cooking), and interaction of two on PM10; pollutant concentration in homes lower than kitchens in indoor villages but very high compared to EPA standard; biomass cooking important source of exposure in indoor cooking village compared to outdoor village
Albalak *et al.*, 2001	Guatemala	Biomass, LPG	Open fire, *Plancha mejorada* (improved with flue), LPG/open fire combination	Typical homes made of adobe walls, dirt floors and tile or metal roofs (few with straw roofs which hinders chimneys)	Greatest reductions from open fire to improved plancha with flue; LPG/Open fire combo improved by half that amount
Ballard-Tremeer and Jawurek 1996	Lab tests	Biomass	Open fire, Improved open fire on raised grate, one-pot metal, two-pot metal, two-pot ceramic	N/A	Average emissions of smoke lowest for improved open fire and 2-pot ceramic, CO and SO_2 lowest for 2 open fires
Bhattacharya *et al.,* 2002		Biomass (wood, charcoal)	Improved charcoal; Indian *Harsha*; Vietnamese traditional	N/A	N/A
Biswas and Lucas 1997	Bangladesh	Biomass(wood, agricultural residues, animal dung)	One-pot	N/A	Per capita consumption 6.15 GJ (cooking); agricultural residues higher than others; household consumption 1.72Gj (lighting); 82% of lighting appliances wick lamps
Boleij *et al.*, 1989	Kenya	Biomass (wood, agricultural waste)	Traditional 3-stone open fire	Roofing - thatched or corrugated; kitchens - attached or separate	Comparison of levels of measured pollutants to WHO recommended standards
Brauer *et al.*, 1996	Mexico	Biomass (wood, corn stalks and husks, cactus leaves, cow dung), LPG, and combination of the two	Traditional 3-stone open fire; unventilated LPG stove; ventilated biomass stoves	Kitchens constructed with gaps between walls and roof	High particulate levels when cooking on unvented biomass stoves; concentrations well above national ambient air quality standard (150mgm-3); mean estimated daytime exposures; ventilated stoves can effectively reduce particulate levels provided they are well maintained- where used for space heating reduce economic effectiveness of strategy

Author	Place	Fuels evaluated	Stove type	Ventilation (other than flues)	Outcome
Bruce *et al.*, 2000	Synthesis of health effects reported in developing countries	Biomass	N/A	N/A	Average reported levels compared to US EPA standards
Bruce *et al.*, 2004	Guatemala	Biomass, kerosene, LPG	Open fires, *Plancha*	N/A	Kitchen levels higher with open fires than plancha (lowest) and gas (middle); less polluting the stove, the higher the child's 24h exposure as a proportion of kitchen level; plancha has 58% lower 24h CO concentration than open fire- some effect of size of eaves space and kitchen volume ; predicted child 24h PM exposures high compared to EPA for all stove/fuel combinations
Cowlin *et al.*, 2005	Mongolia	Biomass, coal	Improved coal with chimney	N/A	CO concentrations increased with number of refuellings; improved stove types showed tendency to decrease CO concentrations- not statistically significant differences- probably won't bring levels below guidelines; improved used less coal- reduced fuel use associated with reduced IAP
Edwards *et al.*, 2002		Honeycomb briquettes, unprocessed coal, coal briquettes	Metal with flue/no flue, improved metal, traditional brick	N/A	NO_X higher for processed compared to unprocessed coals; coal briquettes lower emissions than honeycomb briquettes; unprocessed coal ranged from equivalent to 4-6xhigher CO, 5-9xhigher TSP, global warming contributions 3xhigher than honeycomb.
Engelbrecht *et al.,* 2002	South Africa	Coal (D grade), low smoke fuels,	Braziers	Galvanized iron shanties, brick houses with little ventilation	Residential coal is the single largest contributor (62.1% of PM2.5 and42.6% of PM10) followed by biomass (13.8% of PM2.5 and 19.9% of PM10)
Ezzati *et al.*, 2000	Kenya	Biomass (wood, charcoal)	Ceramic. Improved ceramic, Improved charcoal, traditional metal	N/A	Wood to charcoal offers best option for reductions (then improved stoves)
Ezzati and Kammen 2002	Kenya	Wood, charcoal	Traditional 3-stone, ceramic; charcoal: metal *Jiko*, Kenyan ceramic *Jiko, Loketto*	N/A	Significant reductions with improved stoves and charcoal use

Author	**Place**	**Fuels evaluated**	**Stove type**	**Ventilation (other than flues)**	**Outcome**
Goldemberg and Coelho 2004		Modern (sustainable) and traditional biomass	N/A	N/A	N/A
Kandpal *et al.,* 1994	Lab tests	Biomass (Wood, dung cakes, agricultural residues)	Traditional, improved mud	N/A	Traditional releases 2-3 times more CO than improved; dung cakes 22% higher CO concentration than wood; takes 45-50 mins for CO to drop to safe limits for improved- over an hour for traditional; traditional releases 50-65% more NO2 than improved and 50-60% more HCHO. Concentrations of CO and NO2 higher than safe limits
Kandpal *et al.,* 1995 (a)	Lab experiments	Wood, dung cakes, charcoal, biogas	Improved mud cookstove, charcoal *Jwala* stove, biogas stove	N/A	Processed fuels had consistently lower concentrations of all pollutants (biogas, charcoal, wood, dung); All four fuel-technology combinations- CO concentration crosses prescribed safe limit after 20 min of ignition; Combustion of acacia wood, dung cake and charcoal releases PM above prescribed limits; Biogas releases within limits (200-300 mg/m3); max level for all pollutants and all fuels at standing position in kitchen;
Kandpal *et al.,* 1995 (b)	Simulated cooking conditions in developing countries (lab experiment)	Coal, kerosene, LPG	Traditional coal, kerosene and LPG stoves	N/A	Conclude high concentrations for all fuels indoors and recommend well ventilated kitchens
Lan *et al.,* 2002	China	Wood, smoky coal, smokeless coal	Fire-pit, improved stove with chimney	N/A	Vented burning PM10 (34%) and B[a]P (15%) of unvented concentrations
Lodhi and Zain-al-Abdin 1999	Malaysia	Wood, LPG	N/A	Kitchen generally well-ventilated (spacious, practice of leaving windows open)	Firewood emissions higher than LPG; firewood levels exceed WHO recommended levels
McCracken and Smith 1998	Guatemala	Wood	Traditional fire, *Plancha*	N/A	Plancha poor efficiency results, increased time required for cooking but reductions in CO and PM2.5 emissions

Author	**Place**	**Fuels evaluated**	**Stove type**	**Ventilation (other than flues)**	**Outcome**
Mestl *et al.*, 2007	China (National Census and 39 publications on pariculates in China)	Biomass (wood, crop residues, cow dung), coal (honeycomb briquettes), gas, electricity	Improved and unimproved	N/A	Biomass-using population experienced highest exposure; all groups had exposure levels representing health hazard; rural population higher exposure than urban; south had higher exposure than north despite climate
Moschandreas *et al.,* 1980	Boston, USA	Wood	N/A	N/A	Wood burning activity may lead to elevated indoor concentrations of TSP, RSP and B[a]P could be significant factor in human exposure.
Park and Lee 2003	Costa Rica	Wood	*Hierro colado* (cast iron stove); *fogon* (fixed stove)	N/A	Exposure level based on stove type
Raiyani *et al.*, 1993	India	Biomass (dung, wood), kerosene, LPG, coal	Traditional biomass, coal, kerosene and LPG stoves	N/A	Confirmed energy ladder
Ramakrishna etl al 1989	India	Biomass (wood, agricultural residues, dung)	First generation flued (FGF), Second generation flued (SGF), Second generation unflued (SGU), traditional	N/A	No TSP reduction with improved; FGF decreased CO by 2.8 factor, 3.2 for all flued stoves; HCHO means were lower with improved
Rollin *et al.*, 2004	South Africa	Wood, kerosene	N/A	N/A	Proportion of dwellings with detectable 24n concentration of RSP was significantly higher in un-electrified than electrified dwellings (48.1% vs 24.5%); dwellings using solid or mixed fuels had greatest proportion of measurable RSP; measurable levels of CO coincide with time of cooking activities with wood fuel- kitchen CO level sign. lower in electrified
Sarmah *et al.*, 2002	India	Biomass (wood, agricultural residues, cattle dung)	N/A	N/A	Large-scale consumption of fuelwood and wastage of biomass indicate heavy loss of energy; urgent need to strengthen briquetting technology, improve stoves ad introduce biogas programmes

Author	Place	Fuels evaluated	Stove type	Ventilation (other than flues)	Outcome
Smith, Aggarwal & Dave 1983	India	Traditional biomass fuels (wood, crop residues)	Regular *Chula* (block of mud, brick, cement u-shaped opening); smokeless *Chula* 2-pot-hole with flue); pit in floor	Home type - *pucca* (durable bricks cement); *cucha* (mud or thatch); cooking location: main room, veranda separate kitchen	Exposure level, socio-economic and fuel-use determinations

* N/A not evaluated or not published

Table 2. Comparison of concentrations of particulate matter from biomass combustion observed in studies reviewed

Author	Fuel type	$PM_{2.5}$ µm/m^3	PM_{10} µm/m^3	TSP/SPM µm/m^3
US EPA	All	65	150	N/A *
Albalak *et al.*, 1999	Wood – open fire	N/A	3690	N/A
Albalak *et al.,* 2001	Wood – open fire	1930 (PM3.5)	N/A	N/A
Balakrishnan *et al*., 2002	Agricultural residues	N/A	1535	N/A
	Wood	N/A	1307	N/A
Boleij *et al.,* 1989	Biomass (wood & agricultural residues)	N/A	N/A	3500-4000
Bruaer *et al.,* 1996	Biomass (wood & agricultural residues)	554.7	767.9	N/A
Dasgupta *et al.,* 2006	Dung	N/A	291	N/A
	Straw	N/A	197	N/A
	Jute	N/A	190	N/A
	Twigs, branches	N/A	173	N/A
Kandpal *et al*., 1995 (a)	Dung	N/A	N/A	2900 Standing 1710 Squatting
Lodhi and Zain-al-Abdin, 1999	Wood	N/A	N/A	500
McCracken and Smith, 1998	Wood – open fire	27200	N/A	N/A
Mestl *et al.,* 2007	Biomass (wood, agricultural residues, dung)	N/A	1056	N/A
Naeher *et al. 2000*	Biomass	528	N/A	N/A
Naeher *et al*., 2001	Wood – open fire	528	717	N/A
Parikh *et al.,* 2001	Wood, dung	N/A	1500 – 2000	N/A
Raiyani *et al*., 1993	Dung	2083	2642	2743
	Wood	770	1312	1441
Smith *et al.,* 1994	Agricultural residues	N/A	2800	N/A
	Wood	N/A	2000	N/A

- N/A not evaluated or not published

Table 3. Comparison of concentrations of particulate matter from coal combustion observed in studies reviewed

Author	**Fuel type**	**$PM_{2.5}$ µm/m^3**	**PM_{10} µm/m^3**	**TSP/SPM µm/m^3**
Cowlin *et al.*, 2005	Coal	N/A	700	N/A
Engelbrecht *et al.*, 2002	D-grade coal	70	52	N/A
Kandpal *et al.,* 1995 (b)	Coal	N/A	N/A	950 *Standing* 680 *Squatting*
Mestl *et al.,* 2007	Coal	N/A	901	N/A
Raiyani *et al.,* 1993	Coal	650	994	1085
Smith, 1993 (Review of 7 studies)	Coal	N/A	340-2700	270-2800
Smith *et al.*, 1994	Coal	N/A	550	N/A

Table 4. Comparison of concentrations of particulate matter from LPG observed in studies reviewed

Author	**$PM_{2.5}$ (multiple by which reduction in emissions from solid fuel) µm/m^3**	**PM_{10} (multiple by which reduction in emissions from solid fuel) µm/m^3**	**TSP/SPM (multiple by which reduction in emissions from solid fuel) µm/m^3**
Balanakrishna *et al.,* 2002	N/A	N/A	83 (18x agricultural residues)
Brauer *et al.*, 1996	70 (8x biomass)	225 (3x biomass)	N/A
Kandpal *et al.*, 1995 (b)	N/A	N/A	200 *Standing* (4x kerosene; 7x coal; 14x dung) 90 *Squatting* (5x kerosene; 5x coal; 19x dung)
Lodhi and Zain-al-Abdin, 1999	N/A	N/A	50 (6x wood)
Naeher *et al., 2000*	57 (9x biomass)	N/A	N/A
Raiyani *et al.,* 1993	188 (11x dung)	420 (6x dung)	487 (6x dung)
Smith *et al.,* 1994	N/A	250-370	N/A

Table 5. Levels of particulate matter as measured in concentrations from different stove types and reductions with the use of improved technology

Author	**Combustion device name***	**Combustion device type**	**Fuel**	**$PM_{2.5}$ µm/m**	**PM10 µm/m3**	**% reduction in TSP/RSP concentrations from baseline to improved technology**
Albalak *et al.*, 1999	Traditional 2-pot clay indoor cookstove	Closed without flue	Biomass (mainly dung)	N/A	3690	N/A
Albalak *et al.*, 2001	Open fire (baseline)	Open	Wood	1930 (PM3.5)	N/A	N/A
	Improved plancha with flue (improved)	Closed with flue	Wood	330	N/A	85%
	Open fire and LPG combination (improved)	Open and LPG	LPG/Wood	1200	N/A	45%
Ballard-Tremeer and Jawurek, 1996	Open fire (baseline)/ Improved open fire on grate (improved)	Open	Wood	N/A	N/A	40%
	Open fire (baseline)/ 1-pot metal (improved)	Open/ Closed without flue	Wood	N/A	N/A	-9% (increased TSP)
	Open fire (baseline)/ 2-pot metal stove (improved)	Open/ Closed with flue	Wood	N/A	N/A	-44% (increased TSP)
	Open fire (baseline)/ 2-pot ceramic (improved)	Open/ Closed without flue	Wood	N/A	N/A	45%
Brauer *et al.*, 1996	Open fire	Open	Biomass	555	768	N/A
Edwards *et al.*, 2004	Metal with flue (baseline) /Improved metal with flue (improved)	Closed without flue	Honeycomb briquettes	N/A	N/A	49%

Author	**Combustion device name***	**Combustion device type**	**Fuel**	**$PM_{2.5}$ µm/m**	**PM10 µm/m3**	**% reduction in TSP/RSP concentrations from baseline to improved technology**
Edwards *et al.*, 2004	Traditional brick with flue (baseline) / Metal with flue (improved)	Partially open/ Closed without flue	Unprocessed coal	N/A	N/A	10%
	Metal with flue (baseline)/ Metal no flue (improved)	Closed with flue/ Closed without flue	Coal briquettes	N/A	N/A	85%
Ezzati *et al.*, 2000	Traditional 3-stone (baseline)/ Improved metal/ceramic (improved)	Open/ Closed without flue	Wood	N/A	N/A	48%
	Traditional metal charcoal (baseline)/ Improved metal/ceramic charcoal (improved)	Closed without flue	Charcoal	N/A	N/A	63-65%
	Traditional 3-stone (baseline)/ Improved metal/ceramic charcoal (improved)	Open/ Closed without flue	Wood-Charcoal	N/A	N/A	87%
IAP Group, 2006	Traditional stove (baseline)/ Improved (improved)	Closed without flue/ Closed with flue	Biomass	N/A	N/A	49%
	Traditional stove (baseline)/ Improved with flue (improved)	Closed without flue/ Closed with flue	Biomass	N/A	N/A	45%
Masera *et al.*, 2000	Traditional 3-stone (baseline)/ *Lorena* elevated U-type, enclosed chamber with flue (improved)	Open/ Closed with flue	Wood	N/A	N/A	30%

Author	Combustion device name*	Combustion device type	Fuel	$PM_{2.5}$ µm/m	PM10 µm/m3	% reduction in TSP/RSP concentrations from baseline to improved technology
McCracken and Smith, 1998	Open fire (baseline)/ *Plancha* with flue	Open/ Closed with flue	Biomass	N/A	N/A	87%
Naeher *et al.*, 2000	Open fire	Open	Biomass	5310	N/A	N/A
	Plancha with flue	Closed with flue	Biomass	1910	N/A	N/A
Naeher *et al.*, 2001	Open fire	Open	Biomass	528	717	N/A
	Plancha with flue	Closed with flue	Biomass	101	N/A	N/A
Park and Lee, 2003	Steel *hierro colado* with flue	Closed with flue	Wood	37	110	N/A
	Fixed metal and concrete f*ogon*	Closed without flue	Wood	58	174	N/A
Smith *et al.*, 1983	Regular U-type mud, brick or cement *chula* (baseline)/ Smokeless closed combustion 2-pot with flue *chula* (improved)	Partially open/ Closed with flue	Wood	N/A	N/A	28%
	Pit *chula* (baseline)/ Smokeless closed combustion 2-pot with flue *chula* (improved) (4)	Open/ Closed with flue	Wood	N/A	N/A	26%

*The terms traditional 3-stone and open fire are synonymous and are used interchangeably by different authors.