Chapter 10
HAPIT, the Household Air Pollution Intervention Tool, to Evaluate the Health Benefits and Cost-Effectiveness of Clean Cooking Interventions

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Abstract There is a growing focus on interventions seeking to reduce the burden of disease associated with household air pollution. HAPIT provides policy-makers and program implementers an easy-to-use tool by which to compare the relative merits of programs both within and between countries, helping assist with optimization of limited resources. Although a number of uncertainties remain, HAPIT represents the 'state of the science' and relies on the best available knowledge – and is built to easily integrate new knowledge and findings to better hone estimates.

Keywords HAPIT • Cookstoves • Household air pollution • ADALY • Cost effectiveness

10.1 Introduction

Globally, approximately 40 % of the world's population relies on solid fuel combustion for cooking (Bonjour et al. 2013). The household air pollution (HAP) resulting from the use of these fuels (including wood, dung, coal, and crop residues) results in approximately four million premature deaths yearly (Smith et al. 2014; Lozano et al. 2012) and 108 million lost disability-adjusted life years (DALYs) in low and medium income countries (LMICs). This burden comes from HAP's impact on a range of diseases, including chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), stroke, and lung cancer (LC) in adults and acute lower respiratory

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infection (ALRI) in children. In response to this large health burden, international organizations and governments – recently spearheaded in part by the Global Alliance for Clean Cookstoves – have focused on efforts to provide reliable clean cooking technologies to solid fuel users. Deployed interventions span a range of technologies, including simple "improved" chimney stoves (Singh et al. 2012; Smith et al. 2010), 'rocket' stoves (Rosa et al. 2014), advanced cookstoves with fan-assisted combustion (Sambandam et al. 2015; Pillarisetti et al. 2014), as well as clean fuel (including LPG, natural gas, biogas, ethanol and electricity) interventions (Van Vliet et al. 2013; Neupane et al. 2015).

Selecting an intervention requires balancing a number of competing priorities, including the cost of the intervention; its effectiveness, as proven in the lab and pilot field studies; its cultural acceptability, attractiveness, and ability to meet local cooking needs, and its inherent characteristics, like the need for fuel processing, the intervention's durability, and power constraints. One way to frame this selection process is at the scale of a large program, with consideration of its potential to improve quality of life and avoid ill-health not only in absolute terms, but also in relation to resources spent on its deployment and evaluation.

To actually measure the broad range of changes in health from a change in the HAP due to an intervention would require large, complicated, expensive, long-term field studies, particularly as the prevalence of most of the chronic diseases known to be exacerbated by HAP (COPD, IHD, LC, stroke) take many years to develop but also many years to decline with reductions in exposure. There is nevertheless a need for methods to credibly estimate the likely degree of ill-health that could be avoided by an intervention using the best available scientific evidence from epidemiological studies that could be expected from an intervention.

In this chapter, we describe the development of and methodology used in the Household Air Pollution Intervention Tool (HAPIT), an internet-based platform[1] to evaluate and compare health benefits achievable through reduced exposures to fine particulate matter ($PM_{2.5}$) resulting from implementation of fuel and/or stove interventions. It can be tailored to the conditions in each of many dozens of LMICs to give organizations contemplating interventions a rough, but credible, estimate of the comparable health benefits that could be accrued through each scenario.

The idea behind HAPIT is not to provide research-quality evidence of health benefits for all possible situations, which would take many years and involve costs and expertise that is well beyond that possible as part of most planned interventions. Rather, it aims to provide "good enough" evidence based on the best available health effects information linked to air pollution exposures. There is a long tradition of using such risk assessment techniques to evaluate environmental health hazards not only in air pollution (EPA) but from interventions to reduce water pollutants, radiation, toxic chemicals, and so on.

Evaluations of projects to reduce another important environmental health risk also benefit from such tools. Interventions to mitigate climate change use CO_2-equivalent metrics to estimate their benefits. They are not required to actually show

[1] HAPIT can be accessed at http://hapit.shinyapps.io/HAPIT

an impact on climate change, which would take sophisticated studies lasting many years, but rely on links established by the best current science between emissions of greenhouse gases and changes to climate. These come from complex climate models informed by measurements and that are evolving over time. Just so with HAPIT, which relies on the best intermediate variable between HAP and health, exposure to $PM_{2.5}$. Exposure is closely linked to the intervention in one direction and to health impacts in the other via complex published models based on major reviews of health studies in real populations, which, like climate change models, evolve over time.

HAPIT outputs can be shared with policy makers in order to raise awareness about the potential public health implications of the program at a national level, inform them about the relative health benefits expected by scaling up available interventions, and provide information on the relative costs of scaling up different intervention options. As such, there is a clear role for such a tool to inform health policy makers in the implementation of the World Health Organization's Indoor Air Quality Guidelines focused on household fuel combustion. Beyond the health sector, this tool can be used by clean cooking implementers (1) to help both design better interventions (how clean do interventions need to be to achieve health benefits) and (2) to potentially help raise funds to implement dissemination projects through results-based financing.

HAPIT estimates both averted DALYs (aDALYs) and averted premature deaths and calculates a simple cost-effectiveness metric based on the World Health Organization's Choosing Interventions that are Cost-Effective (WHO-CHOICE) framework. For illustration, we demonstrate use of HAPIT to evaluate a chimney stove intervention deployed as part of the RESPIRE randomized controlled trial and an LPG intervention, both in the Western Highlands of Guatemala. Finally, we conclude with a discussion of the methodological and conceptual issues raised by HAPIT in the context of broader health and sociopolitical concerns and introduce the potential for results-based financing based on averted DALYs.

10.2 Methods

HAPIT relies (1) on up-to-date national background health data and (2) on the methods and databases developed as part of the Comparative Risk Assessment (CRA), a component of the 2010 Global Burden of Disease (GBD 2010). HAPIT utilizes exposure-response information for each of the major disease categories attributable to particulate air pollution and 2010 background demographic, energy, and economic conditions for the 57 countries in which solid fuels are the primary cooking fuel for 50 % or more of homes (Bonjour et al. 2013). HAPIT additionally includes a number of countries in which household energy disseminations are underway or planned but who have less than 50 % solid fuel use nationally. All data are for year 2010, the most recent year for which country-level data are currently available from GBD. Figure 10.1 visually depicts HAPIT inputs and methods.

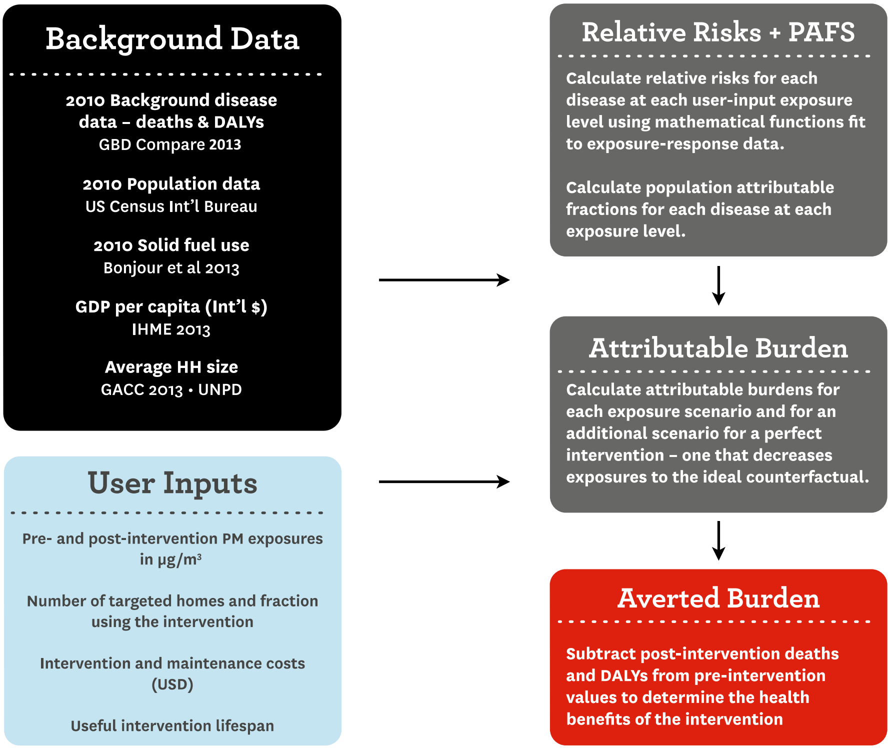

Fig. 10.1 A conceptual diagram of the inputs, outputs, and methods used to estimate averted ill-health using HAPIT

10.2.1 Background Data Used by HAPIT

All background disease information employed in HAPIT was downloaded from the Institute for Health Metrics and Evaluation's (IHME) GBD 2010 Country Databases. The deaths and DALYs from lung cancer includes the GBD 2010 estimates of trachea, bronchus, and lung cancers. Cardiovascular diseases are broken down into two categories – Ischemic Heart Disease (IHD) and Ischemic & Other Hemorrhagic Strokes (Stroke). HAPIT calculates deaths and DALYs due to ALRI only among the population of 0–4. Average household sizes were extracted from the Global Alliance for Clean Cookstoves' Data and Statistics website (GACC). Population data were extracted from the US Census International Bureau (USCB 2015) and the UN's World Urbanization Project (UNDESA 2014).

Cost-effectiveness is determined by comparing the expected annual cost of the intervention per averted DALY (described below) in USD to the gross domestic product per capita (GDP PC, USD). WHO-CHOICE advises that interventions costing less than the GDP/capita are very cost-effective, those costing one to three times the GDP/capita are cost-effective, and those costing more than three times the GDP/capita are not cost-effective (Evans et al. 2006).

HAPIT estimates program cost-effectiveness using a financial accounting approach. In doing so, it (1) does not take into account changes in household costs due to medical expenditure or the time or money spent acquiring fuel and it (2) assumes that programs are covering the cost of fuel-based interventions (such as monthly LPG costs per household). For custom scenarios, users can adjust the per-household maintenance or fuel cost based on the characteristics of their programs to take into account these parameters. For example, the total financial outlay of the intervention program may decrease if households pay for a portion of the fuel or intervention cost up-front or over time.

10.2.2 User Inputs

HAPIT users are able to input (1) pre- and post-intervention population average exposures to $PM_{2.5}$ in μg/m^3, based on measurements performed in the target communities, and the standard deviation of those measurements; (2) the number of households targeted by the intervention; (3) the average percentage of the population using the intervention throughout the intervention's useful lifetime; (4) the cost per intervention to the program in current US Dollars (USD); and (5) the yearly maintenance cost (including fuel costs) per household in current USD. For users with limited knowledge to inform these inputs, default values are available for all of the above.

Users are strongly urged to address the following concerns prior to scaling up an intervention:

– Intervention Effectiveness: selected interventions should have the ability, under ideal conditions, to reduce emissions of health damaging pollutants to acceptable levels, as assessed in the laboratory (Jetter et al. 2012; Jetter and Kariher 2009). Interventions that perform poorly in the laboratory are unlikely to perform well in the field.
– Intervention Acceptability: interventions should be fully vetted by community members to ensure appropriateness for local cooking and otherwise to suit local needs.
– Exposure Reduction: interventions should result in a demonstrable and significant reduction in $PM_{2.5}$ population exposures in pilot work in the community of interest, or one like it.
– Sustained Intervention Usage: declining usage of the intervention over time may indicate reversion to traditional cooking methods and an elimination of any meaningful exposure reductions. Interventions should be used regularly and should, ideally, displace use of the more polluting traditional stove.

Because HAPIT relies on measured exposures to estimate averted ill-health, we briefly clarify the distinction between (a) emissions, (b) concentrations, and (c) exposures in the context of household air pollution studies:

(a) Emissions refers to the rate of release of a pollutant per unit time or per unit of fuel; emissions measurements are often taken 'directly' from the combustion source and can be performed in the laboratory or the field. Although emission measurements can be conducted over an entire day, it is most common to conduct them in conjunction with one cooking cycle, either typical to the area if done in the field or with a standard cooking cycle if done in the lab.
(b) Concentrations are a result of emissions and various room conditions, like ventilation rates, and processes, like deposition and exfiltration. Concentrations are often measured in microenvironments – for instance, in the kitchen and in the living room – but do not directly take into account the presence of people. Because it is difficult to simulate real world situations, reliable concentration measurements normally are measured in households themselves. Commonly, for example, kitchen air pollution (KAP) measurements are made by placing a monitor on the wall of the kitchen for 24 h.
(c) Exposures are complex, spatiotemporal relationships between individuals and the concentrations of pollutants in their vicinity. A population exposure thus depends on the concentration of pollutant in an area, the number of people in the area, and the time spent in that given area. Similarly, an individual's daily exposure is impacted by the variety of sources they experience in the spaces they inhabit for varying lengths of time throughout the day. For example, high concentrations of pollutants in a smoky kitchen do not necessarily result in high exposures; if the cook spends most of her time outside of the kitchen, her average exposure may not be as high as a concentration may predict. Exposure involves contact between humans and pollution. Because of the nearly universal diurnal pattern of human activity, exposure monitoring is best done for at least 24 h or in multiples of 24 h (48, 72, etc).

Data on lab-based emissions, although fewer than desirable, are increasingly publically available (catalog.cleancookstoves.org). In contrast, the availability of exposure data across a range of geographies, fuel and stove combinations, and cooking practices remains limited, especially for the most promising (based on lab performance) stoves and fuels. Moreover, given the complexity of exposure characterization and the paucity of available data linking exposure and emissions, it is not currently possible to reliably estimate exposures based on lab-based emissions data without extensive measurements followed by modeling at the local level. Default exposures in HAPIT are based on the currently available literature and informed largely by global modeling of HAP exposures (Balakrishnan et al. 2013; Smith et al. 2014).

10.2.3 Integrated Exposure-Response Functions

Estimating the burden of disease attributable to all types of air pollution – including household air pollution (HAP) – during the 2010 Global Burden of Disease required elaboration of integrated exposure-response (IER) relationships (Burnett et al. 2014)

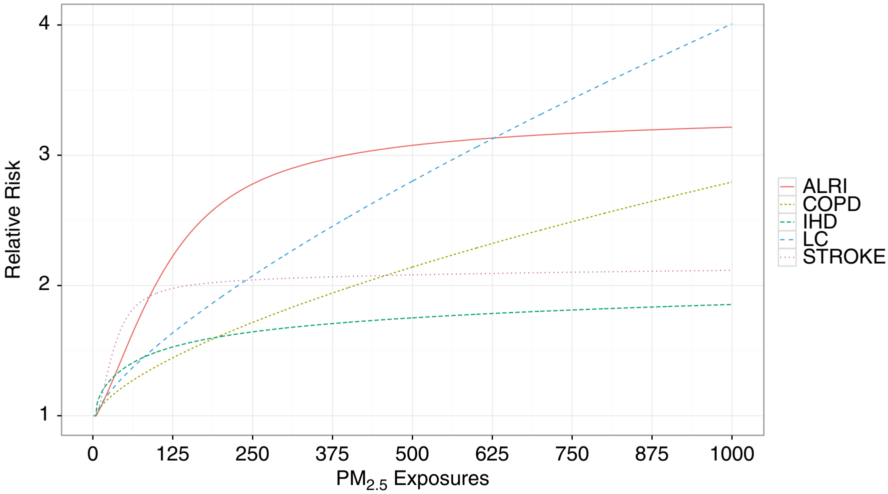

Fig. 10.2 Integrated Exposure Response (IER) curves relating Exposure to $PM_{2.5}$ to health endpoints associated with exposure to air pollution, including ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), and lung cancer (LC) in adults and acute lower respiratory infection (ALRI) in children (See Fig. 10.4 for an elaboration of uncertainties around the IERs)

that relate $PM_{2.5}$ exposures to risk for a number of health endpoints. The IERs leverage epidemiological evidence from a wide range of $PM_{2.5}$ exposures spanning multiple orders of magnitude (ambient air pollution, active and secondhand tobacco smoke, and household air pollution) and result in supra-linear exposure-response curves (Fig. 10.2).

In Burnett et al. the parameterization of the IERs took a common form:

$$\mathrm{RR}_{\mathrm{IER}}(z) = 1 + \alpha\left\{1 - \exp\left[-\gamma\left(z - z_{cf}\right)^{\delta}\right]\right\} \tag{10.1}$$

where z is exposure to $PM_{2.5}$ in μg/m³, z_{cf} is the counterfactual exposure to $PM_{2.5}$ in μg/m³, and where α, γ, and δ are model parameters. In initial versions of HAPIT (version 1 and 2), Eureqa (Nutonian, Inc.) was used to fit a line to a table of central relative risk estimates (and lower and upper confidence bounds) provided by Burnett et al. for concentrations ranging from 0 to 1000 μg/m³. In version 3 of HAPIT, we utilize data released by the Institute of Health Metrics and Evaluation (IHME) to create a lookup table of relative risks, using methods similar to those reported elsewhere (Apte et al. 2015). For each health endpoint – and for twelve age-categories for IHD and Stroke – 1000 values of z_{cf}, α, γ, and δ were provided (IHME 2010). We calculated the lower bound (5th percentile), central (mean), and upper bound (95th percentile) relative risk estimates from the distribution of provided values for each health endpoint, age-category, and for exposures ranging from 1 to 1000 μg/m³ in discrete 1 μg/m³ steps. For concentrations less than the counterfactual concentration of 7.3 μg/m³, the relative risk was fixed at 1 – an indication of no difference in risk.

10.2.4 Evaluating Averted Ill-Health

HAPIT generates 1000 pairs of pre- and post-intervention exposures by sampling from a lognormal distribution reconstructed from the user input mean exposure and measurement standard deviation. For each pair of exposures, HAPIT identifies the corresponding relative risks from the look-up table. The population attributable fraction (Eq. 10.2) is then calculated as follows:

$$PAF = \frac{SFU(RR-1)}{SFU(RR-1)+1} \tag{10.2}$$

where SFU refers to the percent of the population using solid fuels and RR refers to the relative risk calculated using the IERs. The approach utilized is based on methods developed by the GBD and others (Smith and Haigler 2008; WHO 2004), but adapted to take advantage of the continuous IERs.

To estimate changes in deaths and DALYs attributable to an intervention (AB_{int}), we subtracted the PAF after the intervention ($PAF_{post\text{-}intervention}$) from the PAF prior to the intervention ($PAF_{pre\text{-}intervention}$) and multiplied by the user input usage fraction; the underlying disease burden ($B_{endpoint}$) for a specific country, health endpoint, and age-group as follows; and the percentage of solid-fuel use in the target population:

$$AB_{int} = \left(PAF_{pre\text{-}intervention} - PAF_{post\text{-}intervention}\right) \times B_{endpoint} \times Use_{fraction} \times SFU_{fraction} \tag{10.3}$$

Averted burdens are calculated for all combinations of the lower, central, and upper relative risk estimates and the central background disease rate estimates for each of the 1000 exposure pairs. HAPIT outputs the following:

(a) the mean averted deaths and DALYs – the mean of the 1000 attributable burdens calculated using the central relative risk
(b) the minimum averted deaths and DALYs – the mean of the 1000 attributable burdens calculated using the lower bounds of the IERs
(c) the maximum averted deaths and DALYs – the mean of the 1000 attributable burdens calculated using the upper bounds of the IERs
(d) the maximum avertable deaths and DALYs – the burden that could be averted by going from the pre-intervention exposure to the counterfactual, assuming 100 % stove usage

HAPIT assumes that all deaths and DALYs due to ALRI are accrued instantaneously upon implementation of the intervention. For chronic diseases in adults (COPD, stroke, IHD, and lung cancer), HAPIT utilizes the 20-year distributed cessation lag model of the United States Environmental Protection Agency (US EPA), a step function for estimating the accrual of benefits due to changes in exposure to air pollution (Fig. 10.3). The EPA model assumes that 30 % of mortality reductions occur in the first year, 50 % are distributed evenly in years two through

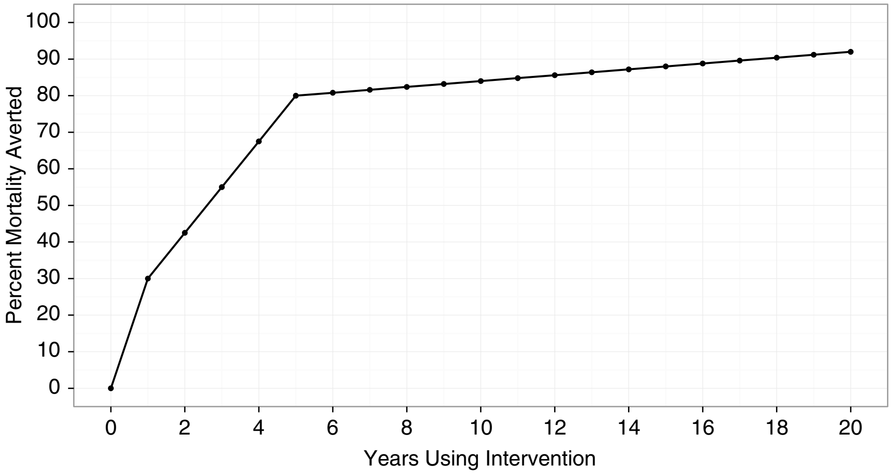

Fig. 10.3 Visual representation of the EPA 20-year cessation lag function. The cessation lag function as outlined by the US EPA is used to adjust downward the attribution of averted DALYs and Deaths from chronic disease due to reduced PM2.5 exposures resulting from an HAP intervention

five, and the remaining 20 % are distributed evenly in years six through twenty (EPA 2004). At the end of the intervention's lifetime, we assume that benefits for children from reduced ALRI cease; an additional 75 % of a full benefit-year accrue for chronic diseases.

HAPIT limits an intervention's useful lifetime to, at a maximum, 5 years. This is due to two issues. First, because attributable burden calculations rely on up-to-date background disease information, extending beyond 5 years unrealistically assumes no change in background disease rates. Second, evidence from the field indicates that many current interventions do not have a useful life beyond 2 or 3 years (Pillarisetti et al. 2014; Hill et al. 2015) at most.

10.2.5 Averted Disability Adjusted Life-Years (DALYs)

While HAPIT outputs averted deaths, a perhaps more interesting and useful output is that of averted DALYs. The DALY is a combined metric of mortality and morbidity that measures the gap between the 'ideal' and the experienced health states of a population. DALYs are composed of two parts: years of life lost (YLLs) to premature death and years lived with disability (YLDs) weighted by the severity of the condition experienced. Fundamentally, the DALY seeks to put death and disability from all diseases on an equal footing for all individuals of the same age in the world, irrespective of social class, country of origin, socioeconomic status, occupation, or other characteristic (Mathers et al. 2006). GBD 2010 used a life expectancy at birth of 86 years to calculate YLLs and, unlike previous GBD undertakings, removed all discounting and age-weighting (Murray et al. 2012). The calculation of disability weights was updated to take into account global heterogeneity in perception of the severity of various conditions and was utilized revised methods by which surveys were translated into severity weights. While a number of concerns about the use of the DALY remain (Voigt and King 2014), to date no other combined metric of morbidity and mortality has been as thoroughly described and used in global health literature. Use of the DALY allows simple comparison of cost-effectiveness across sectors and potential interventions and is commonly used in the global health literature.

10.2.6 Implementation

The basic calculations for HAPIT are implemented in R 3.1 (R Foundation) and utilize Shiny, a framework enabling sharing of interactive R code over the internet (Chang et al. 2015). HAPIT is currently hosted by RStudio for a nominal monthly fee. Figures are generated using ggplot2 (Wickham 2009).

10.3 HAPIT in Use – Hypothetical Chimney Stove and Liquefied Petroleum Gas Interventions in the Western Highlands of Guatemala

10.3.1 Background

As an illustration of the use of HAPIT, we adapt findings from the Randomized Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE), a randomized control trial (RCT) that assessed the impact of reduced emissions from a chimney stove on childhood pneumonia (Smith et al. 2011), and subsequent studies in the region (Smith et al. 2010; McCracken et al. 2007, 2011; Northcross et al. 2010). The study design has been described extensively elsewhere (Bruce et al. 2007; Smith-Sivertsen et al. 2009). Briefly, it took place in the Western Highlands of Guatemala between October 2002 and December 2004. Most study homes were located between 2000 and 3000 m above sea level and used wood as their primary cooking fuel. Five hundred and eighteen households contributed to the final dataset, with approximately half receiving a chimney stove and the other half cooking using the traditional open fire. Across Guatemala, 64 % of households rely on solid fuel for cooking. The GDP per capita in Guatemala is approximately 5000 USD.

10.3.2 Inputs

While carbon monoxide (CO) exposures were the primary exposure measurement collected during RESPIRE, $PM_{2.5}$ exposures were also assessed at various points throughout and after the primary RESPIRE trial, including as described in McCracken et al (2007, 2011). For this analysis, we assume any new chimney stove implemented in the region would perform similarly to findings during those assessments; that is, we expect to see adult exposure reductions to $PM_{2.5}$ from 264 μg/m³ (SD = 297) when using the traditional stove to 102 μg/m³ (SD = 130) when using the intervention chimney stove.[2] For children, we use the ratio of child to mother exposures to carbon monoxide to scale exposure reductions appropriately. Because of the rich data available on these exposures, we are able to estimate mother to child ratios for both the pre-intervention and post-intervention periods. During the pre-intervention period, child exposures are ~45 % of the mother's exposure; in the post-intervention period, child exposures are ~54 % of the mother's exposure. Accordingly, for children, the pre- and post-intervention $PM_{2.5}$ exposures are 119 μg/m³ (SD = 133) and 55 μg/m³ (SD = 70), respectively.

We additionally assume the intervention will reach 25,000 households, be used consistently by 90 % of households as previously reported (Ruiz-Mercado et al. 2013), have a 5-year lifespan, cost 200 USD per stove, and have a maintenance cost of 5 dollars per year per stove. For comparison, we will also consider an LPG intervention that reduces exposures of both mothers and children to the level of ambient pollution in these communities of 30 μg/m³ (SD = 20),[3] has an identical useful lifespan and fraction of households using the intervention, and costs 75 USD per stove with a fuel cost of 175 USD per year per household. Inputs for both scenarios are summarized in Table 10.1.

10.3.3 Findings

Figure 10.4 depicts the simulated exposures before and after distribution of the chimney-stove intervention. The depicted IERs illustrate the non-linear nature of expected health-benefits associated with an exposure reduction. For instance, for adults, the relationship is relatively 'flat' for Stroke and IHD for an exposure

[2] Application of HAPIT should ideally include up-to-date personal exposure measurements of $PM_{2.5}$.

[3] The post-intervention concentration in this LPG scenario may seem counter-intuitive: LPG has been shown to very clean and emit almost no particles when operated properly. Why, then, not reduce the exposure to the ideal, 7.3 μg/m³ counterfactual? In this case, we assume some pollution arises from households in the community who may not have transitioned to LPG or from other sources, such as trash burning, power generation, or vehicles, to name a few possibilities. LPG exposure reductions for this example are set to background ambient $PM_{2.5}$ concentrations as measured during RESPIRE.

Table 10.1 HAPIT inputs for chimney stove and LPG interventions in rural Guatemala

	Pre-intervention exposure μg/m³ (SD)		Post-intervention exposure μg/m³ (SD)		#Homes	Average use %	Stove lifetime (years)	Initial cost USD	Yearly cost USD
	Adults	Kids	Adults	Kids					
Chimney	264(297)	118(113)	102(130)	55(70)	25,000	90	5	200	5
LPG			30(20)					75	210

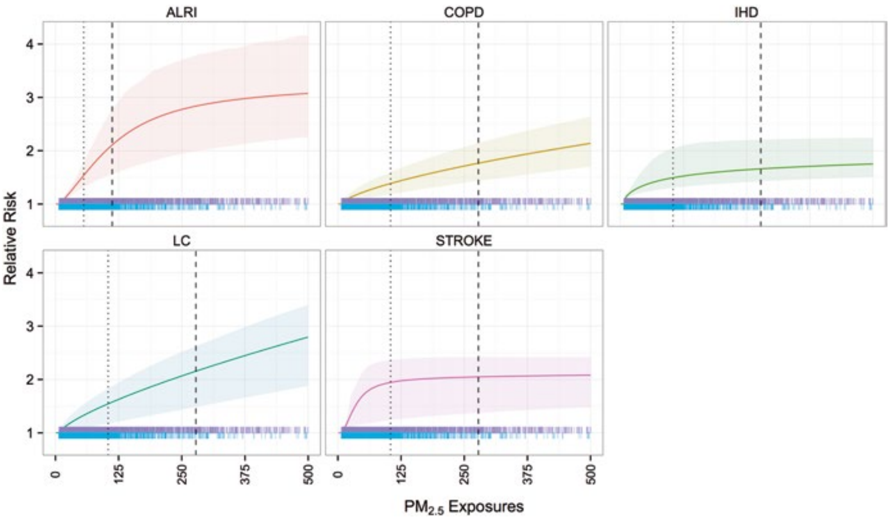

Fig. 10.4 Integrated exposure-response curves and uncertainty bounds (*lightly shaded*) for each of the major disease categories associated with exposure to HAP. The *dashed vertical line* indicates the pre-intervention exposure; the *dotted vertical line* indicates the post-chimney intervention exposure. The *upper* and *lower tick marks* along the x-axis are the distributions of the simulated pre- and post-intervention exposures, respectively

reduction due to the intervention. For COPD and lung cancer in adults and ALRI in children, the relationship is relatively linear, though the slope varies. For all health endpoints, the uncertainties are large and variable depending on the location on the curve corresponding to a specific exposure.

10.3.4 Assumptions

In the above examples, we do not consider the common practice of stove stacking, which would result, most likely, in modified post-intervention exposures. We do not include costs or savings to households, which may include time saved and put towards other productive activities. Additionally, we do not consider dissemination costs or monitoring and evaluation costs, though as mentioned above we do assume that fuel costs are covered by the program. We assume that background disease rates for all of Guatemala are applicable to this region.

Estimates from HAPIT suggest that dissemination of 25,000 chimney stoves – similar to those used during the RESPIRE RCT – with 90 % usage, no stove stacking, and a 5-year lifespan would avert approximately 3270 DALYs (uncertainty bounds 1760–4470) and 65 (uncertainty bounds 35–90) deaths given the exposure reductions modeled above. The majority of the health benefits result from reductions in ALRI in children under 5 (Table 10.2). Figure 10.5a displays the Averted DALYs and Deaths by disease category and the burden remaining for each group. On average, approximately 72 % of the burden remains, though there is heterogeneity between disease categories (range: 62–85 %). When using the least conservative estimate, approximately 62 % of the burden still remains. Similarly, 57 % (range: 57–75 %) of the burden remains if trying to reach 30 μg/m^3, the level of background ambient pollution in RESPIRE communities.

For an LPG dissemination of 25,000 stoves with 90 % usage, no stove stacking, and a 5-year lifespan, HAPIT estimates approximately 5700 DALYs (uncertainty bounds 3750–6360) and 125 deaths averted (uncertainty bounds 80–160). Figure 10.5b displays the Averted DALYs and Deaths by disease category for an LPG intervention as described. On average, approximately 52 % percent of the burden remains (range 39–69 %). When using the least conservative estimate of the potential impact of an LPG intervention, approximately 39 % of the burden remains. Contrastingly, the ill-health remaining on the table relative to ambient air pollution is only approximately 16 %. This latter would be taking ambient air pollution as the counterfactual, i.e. the minimum achievable by a change within the household itself.

Despite its large unaverted burden, the chimney stove intervention is considered ‘very cost effective’ across its entire range of potential averted DALYs using the simple WHO-CHOICE rubric (Fig. 10.6a). The LPG stove intervention is also considered very cost-effective, though the range of uncertainty around this estimate is greater than for the chimney stove (Fig. 10.6b), extending into the “cost-effective” range. The LPG intervention is sensitive to price shocks; if the January 2015 price for an LPG cylinder is used (18 USD), the intervention and its uncertainty bounds move entirely into the “cost-effective” category. In these examples, the households may be willing to bear part of the cost of either a chimney stove or LPG stove and/or the monthly cost of the LPG, thus reducing the direct cost to the program itself and impacting cost-effectiveness estimates.

Table 10.2 HAPIT outputs for chimney stove and LPG stove interventions in Guatemala

	ALRI		COPD		IHD		Lung cancer		Stroke	
	DALYs (range)	Deaths (range)	DALYs (range)	Deaths (range)	DALYs (range)	Deaths (range)	DALYs (range)	Deaths (range)	DALYs (range)	Deaths (range)
Chimney	2385 (1290–3230)	30 (15–40)	240 (180–290)	7 (5–10)	380 (240–580)	20 (10–25)	80 (50–90)	3 (2–4)	250 (95–330)	12 (5–15)
LPG	3900 (2570–4780)	45 (30–55)	390 (290–470)	12 (8–14)	730 (540–1150)	35 (25–55)	130 (85–150)	5 (4–6)	600 (280–660)	30 (15–30)

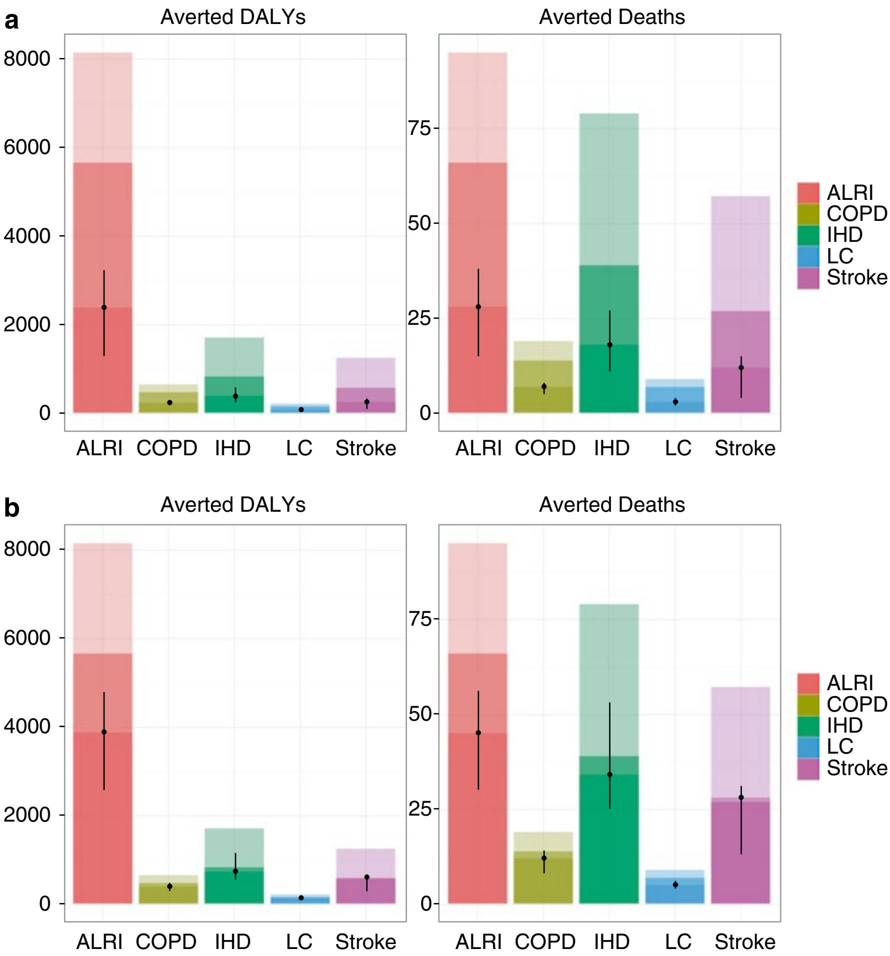

Fig. 10.5 Averted deaths and DALYs by disease category for (**a**) a chimney stove intervention and (**b**) an LPG stove intervention in Guatemala. The *darkest bars* are the central estimate of averted ill-health; the *lightest bars* are the total burden avertable by the best possible intervention – one that gets down to the counterfactual exposure of 7 μg/m^3. The remaining bar represents the burden left by an intervention that gets down to 30 μg/m^3, the outdoor ambient level measured during RESPIRE. *Vertical lines* indicate the range of averted ill-health attributable to the intervention modeled by HAPIT

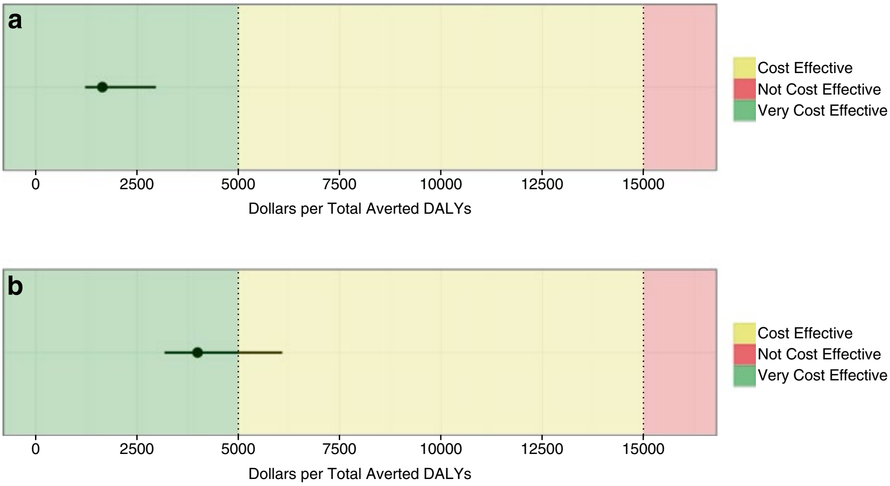

Fig. 10.6 Dollars per total averted DALYs. The green shading indicates the WHO-CHOICE "very cost-effective category" (< GDP PC per DALY), the yellow shading indicates the "cost-effective" category (between 1 and 3 x GDP PC per DALY) and the red indicates "not cost-effective." The (**a**) *top panel* is for the chimney stove intervention; the (**b**) *bottom panel* is for the LPG intervention. The 2010 GDP PC in Guatemala was approximately 5000 USD

10.4 Considerations Arising During the Development and Use of HAPIT

HAPIT provides an easy-to-use, web-based application for assessing the impact of a household air pollution intervention for countries in which there is a significant solid fuel using population. It estimates a range of DALYs and deaths averted by an intervention based on epidemiological methods and using the best available background disease and exposure-response data available. The somewhat simple interface masks significant computational and methodological complexity, and should thus be used with care when making significant policy decisions and considering large interventions with substantial financial and logistical costs.

During the development of HAPIT, a number of methodological and conceptual issues came to the fore. We conclude with a discussion of these issues, of the limitations of HAPIT, and of next steps to further enhance the robustness and reliability of HAPIT-based estimates.

10.4.1 Assumptions and Limitations of HAPIT

HAPIT makes a number of assumptions and has a number of limitations. The most prominent follow.

(1) HAPIT assumes that measurements of changes in exposure made over a short period of time are indicative of long-term trends. For results-based financing centered around using averted DALYs and deaths, it will be necessary to perform periodic verification of benefits throughout the period of time financing is sought.
(2) As currently designed, changes in exposure to the cook, upon whom measurements were taken, reflect changes in other household members. The impact on children under the age of 5 is adjusted by the default relationship described above for all scenarios in HAPIT unless an alternate ratio is provided. It is strongly suggested that any alternate ratio be grounded in measurements in the community of interest.
(3) HAPIT assumes background disease and economic characteristics are relatively static. For interventions with a short life-span, this assumption may hold; for long-lived interventions, such as transitioning a community to clean fuels or electricity, HAPIT estimates would need to be revised regularly. In addition, economies of scale are not considered when evaluating cooking interventions costs. Human development indicators may change rapidly depending on social, economic, and political conditions in countries in which HAPIT may be used. These changes can impact the relative merits of a HAP intervention, swaying an intervention from not cost-effective to cost-effective based, for example, on more recent GDP per capita estimates or, for fuel interventions, on fuel costs. For example, the price of LPG in Guatemala has been fairly volatile, varying between 5 USD in 2003 and 18 USD in early 2015 before dropping back down to 10 USD in May of 2015. HAPIT's simplistic cost-estimates do not currently account for monthly or yearly fuel price fluctuations.
(4) HAPIT currently relies on IHME's GBD of disease data, which is, as of now, the most complete and comprehensive burden of disease data available. This completeness comes with the price of some methodological opacity. Continued burden of disease efforts from the World Health Organization and others may result in more rigorous and open model comparison efforts, similar to those seen among climate scientists.

HAPIT highlights the tension between cost-effectiveness and the burden left 'on the table.' As seen in both of the example scenarios above, deployment of an intervention seeking to reduce household air pollution leaves significant ill-health in target communities. This "unaverted" burden poses a quandary to policy makers and health practitioners seeking cost-effective solutions to myriad health problems. The aforementioned chimney stove example is more cost-effective by the admittedly simple form of WHO-CHOICE implemented here; however, it leaves a substantial health burden on the table. The LPG intervention, meanwhile, is less cost-effective, but removes more of this burden from the table. Some may argue that the chimney stove represents an incremental change toward cleaner energy systems; others may counter that leapfrogging attempts at cleanly burning biomass may represent the clearest path forward towards reducing the HAP-related health burden. Rather than make an argument in either direction, we highlight the types of fundamental questions that HAPIT brings to light. These questions are further complicated by considering other health programs – such as a rotavirus vaccine program, the widespread deployment of insecticide-impregnated bednets, efforts to improve access to pre-natal care services or a scale-up of water purification devices – side-by-side with HAPIT-based avoided ill-health estimates from clean cooking interventions.

As both interventions leave a significant portion of the burden of the table, we assume that there is some background ambient air pollution – from unclean cooking around intervention homes or from other sources – that contributes to exposures. Controlling this air pollution, by for example ensuring widespread access to clean cooking fuels in a community, could lead to more substantial benefits of an intervention. Put another way, deploying interventions to a larger fraction of homes may have the additional benefit of improving ambient air pollution enough to make an intervention appear more cost-effective. Further research is needed to better understand how much population 'coverage' with and usage of the intervention would be needed to maximize benefits. Finally, our consideration of the burden 'left on the table' explicitly acknowledges that reaching a state of no additional ill-health above the counterfactual would most likely require action to reduce all sources of air pollution – including ambient air pollution from non-cooking sources and pollution released by industries and vehicles, to name a few.

Complications are additionally introduced by an appliance-model of household energy use, in which interventions are used concomitantly with traditional cooking technologies to fully meet the cooking and heating needs of the household – a phenomenon known as stove stacking. As shown in a recent modeling exercise, occasional use of a traditional stove can lead to significant exposures (Johnson and Chiang 2015). HAPIT assumes displacement of the traditional stove for the user-specified percentage of households using the intervention. In homes where stacking occurs, HAPIT may over-predict potential health benefits. Part of this shortcoming is accounted for in the probabilistic approach used, in which 1000 exposures across the distribution of measurements are drawn to estimate averted health impacts. However, the potential impact of stacking to dilute potential exposure reductions should not be dismissed (Pillarisetti et al. 2014; Ruiz-Mercado and Masera 2015).

HAPIT estimates will evolve as GBD-provided background disease information and integrated-exposure response curves change over time. Forthcoming data to be released as part of the 2013 GBD update will undoubtedly alter HAPIT estimates, as it includes a number of revisions to the way air pollution burdens are estimated. Updating HAPIT to account for changes in background disease rates estimated by GBD and for updates to the IER curves is a non-trivial task complicated by the unavailability of programmatic access to GBD data. Furthermore, updates to HAPIT may invalidate results from previous versions of HAPIT.

10.4.2 Future Steps

More nuanced probabilistic uncertainty analysis is possible given the wide number of inputs (and corresponding uncertainty bounds) used in HAPIT estimates. Incorporating and propagating these uncertainties throughout the model, however, requires significant computational resources and increases the requisite run time by 10–30 fold. We are evaluating methods to more quickly incorporate these types of uncertainty analyses in HAPIT by utilizing multi-core computing techniques.

An additional and less tractable complexity arises from the model-based uncertainty bounds generated by the IHME modeling of the GBD. As noted elsewhere (Byass 2010; Byass et al. 2013), the uncertainties presented in the GBD 2010 are complex and challenging to interpret and use in further analyses of the type we describe. For some HAPIT parameters, including the IERs and the WHO solid fuel use estimates, more methodological clarity is available, facilitating Monte Carlo and other simulation-based analyses.

10.4.3 Including Reductions in Community-Scale Ambient Air Pollution

A well-performing, well-used intervention may result in benefits to households not using the intervention by way of reductions in emissions contributing to ambient air pollution. Accounting for these benefits without a significant measurement campaign is challenging. Measurement may prove feasible; for example, exposure reductions due to reduced ambient pollution can be estimated by (1) by measuring exposures on individuals who did not receive an intervention and (2) by measuring ambient pollution continuously in villages both before and after the deployment of interventions. These measurements are typically expensive, though may be worth pursuing if a program perceives the benefit to be substantial.

HAPIT does not currently have a distinct module to estimate these benefits, though they could be separately estimated in an analogous fashion to those stemming from an intervention. For instance, if measurements indicated that exposures were reduced from 264 $\mu g/m^3$ to 200 $\mu g/m^3$ for an additional 10,000 households, HAPIT could be run using these measurements to estimate the additional averted DALYs and deaths attributable to the intervention's contribution to cleaning up the community airshed as a secondary benefit.

10.4.4 Enabling Users to Perform Sub-National or Customized Averted Health Estimates Using Custom-Input Background Disease Data

For some countries – including India, Mexico, Peru, and Nepal – where national statistics may not adequately represent sub-national populations, the ability to customize background disease information may enhance HAPIT's reliability. We are exploring methods by which to incorporate this feature.

10.5 Conclusion

There is a growing focus on interventions seeking to reduce the burden of disease associated with household air pollution. HAPIT provides policy-makers and program implementers a relatively easy-to-use tool by which to compare the relative merits of programs both within and between countries, helping assist with optimization of limited resources. Although a number of uncertainties remain, HAPIT represents the 'state of the science' and relies on the best available knowledge – and is built to easily integrate new knowledge and findings to better hone estimates.

HAPIT is freely available for use over the web and can output a summary report to guide later discussions. Like other publically available tools used to assist in resource allocation and policy making decisions (Winfrey et al. 2011; Thompson and Juan 2006), though, it requires a significant understanding of the particulars of the community and country in which an intervention is proposed; confidence in the interventions' ability to reduce exposure to HAP; measurements of exposure to $PM_{2.5}$ before and after an intervention; and significant consideration of optimal ways to deploy and maintain an intervention over time.

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