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Keywords: Carbon pricing, Biomass use, Indoor air pollution, Clean cooking

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1 Introduction

A uniform global carbon price is considered to be the economically efficient instrument to reduce CO_2 emissions and mitigate climate change, in the absence of other externalities. It is often argued that a uniform global carbon price - combined with an international transfer programme - would realize inexpensive climate change mitigation in low- and middle-income countries (LMICs), relative to costly mitigation efforts in high-income countries, particularly in the agriculture, forestry and other land use (AFOLU) sector [1, 2].

Article 6 of the UNFCCC's Paris Agreement in 2015, which subsumes the "Clean Development Mechanism" of the Kyoto Protocol, is motivated by such theoretical considerations, as are efforts to introduce carbon pricing across the world, including in developing countries [3, 4]. Article 6 of the Paris Agreement facilitates trade of "high-quality" emission permits between countries and enables high-income countries to provide climate finance to lower-income countries for sustainable development and poverty alleviation. Emission abatement corresponding to the targets set in the Paris Agreement would require global carbon price levels between US$ 40-80 per tCO_2 for 2020, rising to US$ 50-100 per tCO_2 by 2030 [5]. The highest carbon price on fossil fuels currently prevailing in any major economy is about US$ 80 per tCO_2, which is roughly the average price in the EU ETS in 2024 [6].

International carbon offset markets are propounded as key complementary measures to global carbon pricing of fossil fuels, on the premise that emission abatement in lower income countries is more cost-effective than in high-income countries. Several high-income countries intend to purchase carbon offset credits in voluntary carbon markets in the global South to meet their domestic emissions reduction targets. However, a cross-country study conducted in six developing countries across three continents has suggested that over 95% of the carbon offset projects studied did not yield additional reduction in emissions in the form of reduced deforestation in these countries [7].

In this article, we challenge the notion that climate change mitigation is relatively inexpensive in developing countries. We focus on the potential effects of carbon pricing on fossil-based fuels used for cooking in six developing countries that we consider to be largely representative of low- and middle-income countries. We examine interactions between carbon pricing on fossil fuel-based cooking energy and household biomass demand for cooking purposes. We next compute the global climate benefits from carbon pricing and compare these with the local health costs generated from indoor air pollution as a result of carbon pricing on fossil-based cooking energy.

Current policy recommendations tend to ignore the fact that carbon pricing may exacerbate existing market imperfections and externalities such as local air pollution from biomass consumption and deforestation. A carbon price on coal might reduce outdoor air pollution (caused by sulphur dioxide emissions emitted from burning coal in power plants [8]). However, higher energy prices for cooking sources such as electricity, gas and kerosene, resulting from such a carbon price, might increase indoor air pollution from biomass consumption (primarily charcoal and firewood) [9–11]. Burning solid fuels including biomass causes premature mortality and morbidity from disease, generating substantial health costs in LMICs [12]. This implies that carbon pricing could reduce welfare on aggregate, unless complemented with additional policy measures.

We investigate the potential effects of increases in cooking fuel prices for electricity, gas and kerosene on the consumption of biomass (charcoal and firewood) in a sample of six developing countries, namely, Cambodia, Ghana, Honduras, India, Kenya and Myanmar. We select these countries as a substantial share of their households consume biomass and fossil-based fuels for cooking (Figure 1). Then, we evaluate the costs and benefits associated with implementing domestic carbon prices in these countries. We compare the global climate benefits due to emission reduction that result from a carbon price with the local health effects of additional biomass consumption across diverse regional, cultural and economic contexts. For more comprehensive analyses, we also compute the global climate costs from additional deforestation and methane emissions due to increased biomass consumption in response to carbon pricing [13]. Finally, we compute the local health benefits from reductions in SO_2 emissions due to a carbon price on coal used for electricity generation [14], in countries where electricity is used for cooking.

In so doing, we model interactions between carbon pricing and the use of fossil fuel and biomass for cooking in each of these six countries. We estimate demand responses for fuel consumption to increases in prices for fossil-based cooking fuels. In all calculations, we simulate a carbon price with adequate monetary transfers to households in order to compensate them for the fuel price increases due to the carbon price. We model marginal (1%) increases in prices for fossil energy, which correspond to carbon prices ranging from US$ 2-11 per tCO_2. We then compare the monetised climate benefits (in the form of reduced fossil emissions), applying a social cost of carbon of US$ 80 per tCO_2, to compute climate benefits from emission reduction (and a sensitivity check, applying a social cost of carbon of US$ 185 per tCO_2) [15–18]. We also apply the value of statistical life, per country, to compute the dollar value of health costs from increased premature mortality due to indoor pollution (concentrations of $PM_{2.5}$) [19].

Our results show that biomass consumption rises in response to increases in prices for fossil cooking energy, in most countries and regions in our sample. The resulting increases in indoor air pollution from biomass consumption lead to substantial health costs due to premature mortality. We find that these health costs exceed the climate benefits of emission reduction resulting from carbon pricing on all fuels in each of the countries, except in two cases, namely carbon pricing on (i) electricity use in Cambodia, and (ii) kerosene use in Kenya. In these cases, carbon pricing generates net climate and health benefits.

Our results challenge the notion that climate change mitigation is relatively cheaper in low- and middle-income countries. On the contrary, our findings highlight the salience of domestic air pollution and its public health costs, which could be exacerbated by the introduction of a carbon price on cooking fuels without supplementary policy intervention. We conclude that residential cooking may be exempted from carbon pricing in developing countries, except in cases where carbon pricing would generate net benefits. Complementary policies to promote access to clean cooking energy will be essential to alleviate the trade-offs between carbon pricing and local air pollution in LMICs.

2 Carbon pricing and biomass use

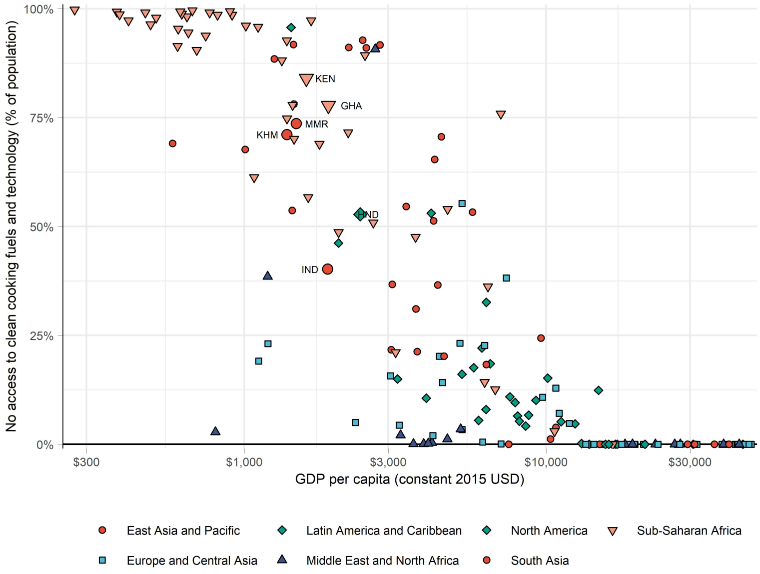
The use of solid fuel for cooking is highly prevalent in developing countries. Around 2.4 billion people globally rely on solid fuels, since they lack access to clean energy sources (such as electricity and gas) and clean technologies [20]. Our sample of countries comprises Cambodia, Ghana, Honduras, India, Kenya and Myanmar. We draw household survey data from the Multi-Tier Framework (MTF) Surveys, 2017, for Cambodia, Honduras and Myanmar. For Ghana, India and Kenya, we draw on national household surveys (Ghana Living Standards Survey, 2016-17; Household Consumer Expenditure Survey, 2023-24 and Integrated Household Budget Survey, 2015-16, respectively).

We select these countries as a substantial portion of households in these countries consume both fossil-based fuels and biomass for cooking purposes

(Appendix Table A2). Further, these are the only countries where fuel price data were available for fossil-based sources and for marketed biomass at the sub-national level. We consider this sample of countries to be broadly representative of lower middle-income countries in the South Asian, Sub-Saharan African and South American regions.

We observe that as per capita incomes rise, across all six countries, households gain access to electricity for lighting and cooking (Figure 1). Within these six countries, an increase in income also decreases the probability of using biomass for cooking (Figure 2). Nevertheless, in LMICs, biomass use persists among high-income households due to a lack of reliable electricity supply and the high costs of using clean fuel use. Households frequently stack biomass with fossil-based fuels for cooking [21].

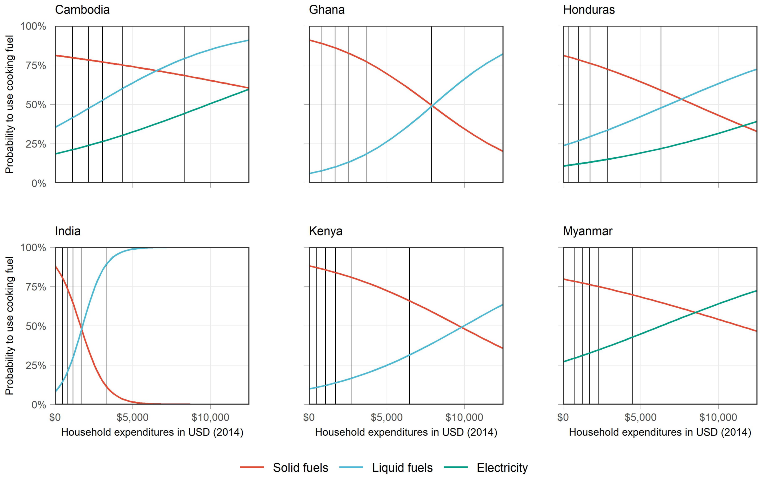
Figure 1: Lack of access to clean cooking fuels over GDP per capita



Note: This figure displays the share of population (in %) without access to clean cooking fuels such as electricity, LPG, and piped natural gas (PNG), and technology over GDP per capita (in constant 2015 US$) for 184 countries in 2018. Source: [22].

To analyse the potential effects of carbon prices on biomass consumption, we estimate consumer demand systems to compute demand changes in biomass use and fossil fuel consumption in response to price increases for fossil cooking energy (electricity, LPG and kerosene). Each demand elasticity measures the

Figure 2: Cooking fuel use over total household expenditures



Note: This figure displays the estimated probability of consuming different cooking fuels over total household expenditure in US$ (2014). 'Solid fuels' comprise coal, charcoal, firewood and other biomass. 'Liquid fuels' comprise LPG, natural gas and kerosene. Curves show fitted probabilities from a logit model. Black vertical lines indicate average household expenditure for each expenditure quintile.

percentage change in demand in response to a 1% price increase for a specific fossil-based fuel. Hence, we consider unilateral price increases for different fuels, but do not simulate simultaneous price increases for multiple fuels. We do so distinctly for rural and urban regions in each of the six countries in our sample. We compute the *compensated* demand responses (or compensated elasticities), wherein we simulate adequate transfers provided to households. Such transfers would enable them to purchase their original consumption baskets at the higher fuel prices. Our results thus imply short-run, immediate estimates of changes in solid fuel consumption in response to fuel price increases and transfers.

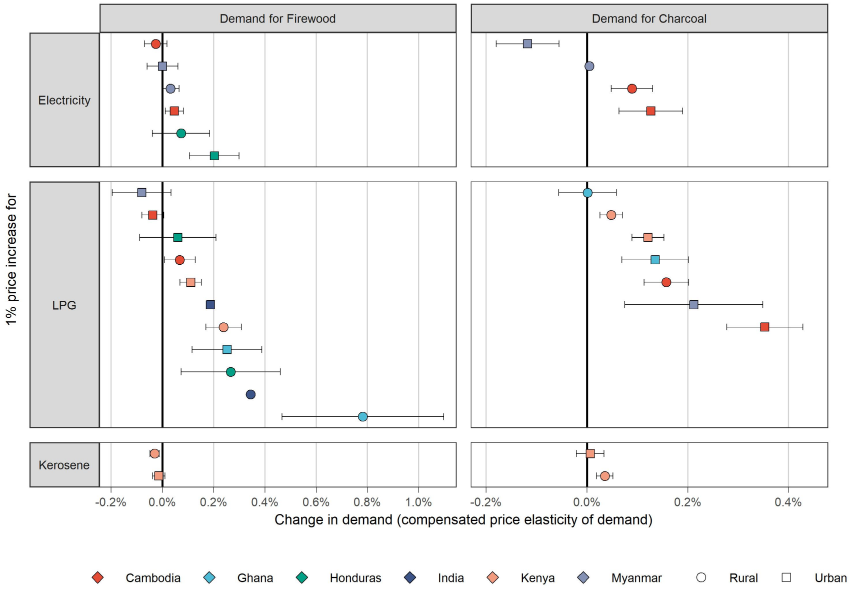
While estimating demand responses, we account for the large share of zero expenditure reported in our survey data by estimating a censored data model, following [23] (see Methods, section 5). These reports occur due to households having limited access to clean fuels and technologies (Appendix Table A2). We present detailed estimations from the demand systems, by country and region in Tables A4 to A27.

2.1 Effects of carbon pricing on fuel consumption

Our results show that compensated own-price elasticities of demand for fossil fuels are negative. This implies that fossil fuel use declines in response to higher prices for fossil energy, when households are compensated with income transfers that are just sufficient to enable them to purchase the same quantities that they were buying before the price increases. Hence, taxing fossil fuels would reduce CO_2 emissions from fossil energy use.

Turning to our main question of interest, namely possible substitution between fossil-fuel based energy and biomass, we find that higher prices for fossil fuel-based cooking energy (electricity, LPG, and kerosene) are associated with an increase in the demand for charcoal in all but one case, namely electricity pricing in urban Myanmar (Figure 3). This indicates that charcoal is used as a substitute for fossil fuel-based cooking energy in nearly all country-region-fuel pairs, when households are compensated with transfers that are sufficient to offset welfare losses.

Figure 3: Compensated price elasticities of demand



Note: This figure displays compensated price elasticities of demand for the six countries in the sample. 95% confidence intervals for the elasticities are displayed above. Detailed descriptive statistics of shares of fuel consumption by country and region are displayed in Appendix Table A2. See Tables A4 to A27 for results on the price elasticities of demand by country and region.

In most country-region-fuel pairs, we find firewood to be a substitute for fossil cooking energy. However in some cases, an increase in the price of electricity, LPG, or kerosene is associated with a fall in the demand for firewood and a simultaneous rise in the demand for charcoal. These effects are observed in the case of (i) electricity price increases in rural Cambodia, (ii) LPG price increases in urban Cambodia, (iii) kerosene price increases in rural and urban Kenya, and (iv) LPG price increases in urban Myanmar. In each of these cases, we find that reductions in the demand for firewood are accompanied by an increase in the demand for charcoal.

In summary, we find that carbon pricing for fossil fuels, LPG, and kerosene used by the poor for cooking and other household purposes would induce a consumption shift towards biomass in general. This result also holds for carbon prices on electricity used for cooking in most countries and regions.

2.2 Associated effects on indoor air pollution

From the estimated demand elasticities, we compute indoor concentrations of particulate matter for each country-region-fuel pair in the sample. We apply $PM_{2.5}$ concentration factors derived from related studies [24, 25] to our estimates of (i) baseline biomass consumption, and (ii) final biomass consumption (in response to 1% price increases for fossil fuel-based cooking energy). The final biomass consumption levels are based on the estimated price elasticities of demand.

The estimated baseline daily $PM_{2.5}$ concentrations range from 64 $\mu g/m^3$ in urban Cambodia to 1,898 $\mu g/m^3$ in rural Ghana (Appendix Table A.4.4). We find sizable increases in indoor concentrations of $PM_{2.5}$ due to increased biomass use resulting from carbon pricing in most country-region-fuel pairs, with the exception of four cases (taxing kerosene in rural and urban Kenya and electricity in rural Cambodia and urban Myanmar). In these four cases, we find small declines in $PM_{2.5}$ concentrations as price increases for fossil energy reduce biomass consumption, despite small increases in charcoal consumption. Given that charcoal and firewood are the dominant sources of biomass energy within households, the changes in $PM_{2.5}$ concentrations are determined largely by changes in biomass consumption.

The baseline $PM_{2.5}$ concentrations depend substantially on reported biomass consumption in the household surveys. High self-reported biomass consumption would generate sizable $PM_{2.5}$ baseline concentrations. However, the further calculations of relative risks from disease and related health costs depend on the ratio of the initial to final $PM_{2.5}$ concentrations, which should be unaffected by high baseline pollution concentrations (Appendix section 5.4.4).

3 Benefits and costs of carbon pricing

Following the estimation of demand responses for fossil fuels and biomass, we compute the marginal costs and benefits of introducing a carbon price that leads to 1% increases in prices for fossil-based fuels. In doing so, we implicitly model transfers to households that would be sufficient to enable them to purchase their original consumption bundles at the higher prices, since we use the compensated price elasticities of demand. The modeled 1% price increases correspond to carbon prices of US$ 2-11 per tCO_2, across countries, based on the respective CO_2 emission intensities of the fossil-based fuels.

We compute (i) the global climate benefits from reductions in fossil fuel consumption and associated CO_2 emissions, (ii) the local health benefits of improved air quality through taxes on electricity generated from coal (in countries where electricity is used for cooking, such as Cambodia, Honduras and Myanmar), (iii) the local health costs from changes in indoor $PM_{2.5}$ concentrations due to biomass consumption from higher fossil fuel prices, and (iv) the global climate costs of deforestation and methane emissions from increased biomass consumption due to carbon pricing (Section 5).

In computing global climate costs from deforestation and methane emissions, we account for the share of non-renewable charcoal and firewood in each country in our calculations [13]. All our cost-benefit calculations are aggregated at the country level and by fossil fuel. Thus, we aggregate costs and benefits across rural and urban areas, weighted by their respective population shares, to evaluate the costs and benefits of introducing carbon prices on specific fuels at the country-level.

We value changes in CO_2 emissions at the social cost of carbon (SCC) of US$ 80 per tCO_2 and changes in CH_4 emissions at the social cost of methane (SCM) of US$ 1,680 per tCH_4, which is approximately 21 times the social cost of carbon [26]. A carbon price of US$ 80 per tCO_2 is close to recent permit prices in the EU ETS [27]. We display the results of cost-benefit-analyses in Table 1 and detailed calculations in Appendix A.4. Additionally, we present a sensitivity check for the calculations, applying a higher carbon price of US$ 185 per tCO_2 and methane price of nearly US$ 4,000 per tCH_4 [15–18, 26], in Appendix Table A28.

We find that global climate benefits from carbon pricing (expressed per thousand persons of a country's population), range from US$ 11 - 227 across countries.

In contrast, the local health costs from increased indoor air pollution, per thousand persons of the national populations, range from US$ 105 - 10,625 across countries. In two cases, we find health benefits resulting from carbon pricing as biomass consumption and related pollution levels decline. These include taxes on electricity in Cambodia and kerosene in Kenya, with health benefits ranging from US$ 172 - 276 across the two countries.

In three countries (Cambodia, Honduras, and Myanmar), where electricity is an important source of cooking, we find that taxing coal used to generate electricity results in health benefits ranging from US$ 16 - 62 per thousand persons of the national populations. In Cambodia, coal comprises over 40% of the electricity generation mix.

In addition to health costs, firewood and charcoal consumption generate global climate costs as a result of deforestation and methane emissions. These costs range from US$ 2 - 346 (per thousand persons) across countries, except in three cases where fuelwood consumption declines in response to carbon pricing and we consequently observe climate benefits from reduced deforestation. These cases include electricity taxation in Cambodia and Myanmar and kerosene taxation in Kenya.

On the whole, we find net costs resulting from carbon pricing that range from US$ 61 - 10,844 per thousand persons across the countries. In two cases, we find net benefits of carbon pricing in the range of US$ 260 - 332 per thousand persons. Taxing LPG generates substantial health costs in Ghana and India, whereas taxing electricity in Cambodia and kerosene in Kenya generates net benefits. In four out of six countries, we find that the local health costs dwarf the global climate benefits of carbon prices.

Cost-to-benefit ratios range from 2 to 127 across countries where carbon pricing generates net costs, with most countries exhibiting costs that are at least an order of magnitude above the benefits generated from domestic carbon pricing.

We also conduct a sensitivity check of our cost-benefit calculations by applying a higher carbon price of US$ 185 per tCO_2 and a correspondingly higher price for methane (approximately 21 times the carbon price) (US$ 3,885 per tCH_4), following [26], in Appendix Table A28. At these higher values, we still find that local health costs exceed the global climate benefits from carbon prices in four out of six countries, with net benefits from carbon pricing observed in two cases. Our findings are thus robust to higher values of the SCC and SCM.

Table 1: Costs and Benefits of 1% Price Increases for Fossil-based Fuels

Country	Fuel	Climate Benefits (Per '000 Persons) (US$)	Climate Costs (Per '000 Persons) (US$)	Health Costs (Per '000 Persons) (US$)	Health Benefits (Per '000 Persons) (US$)	Δ (Costs - Benefits) (Per '000 Persons) (US$)	Cost-Benefit Ratio
Cambodia	Electricity	60	-0.3	-172	28	-260	-2
	LPG	11	38	1,406	-	1,432	127
Ghana	LPG	126	346	10,625	-	10,844	87
Honduras	Electricity	69	20	4,256	62	4,145	33
	LPG	227	17	4,770	-	4,561	21
India	LPG	91	21	8,274	-	8,205	91
Kenya	Kerosene	54	-2	-276	-	-332	-5
	LPG	44	275	2,719	-	2,950	68
Myanmar	Electricity	28	-0.4	105	16	61	2
	LPG	38	2	200	-	164	5

Note: Benefits and costs are calculated for 1% price increases for fossil-based fuels. The carbon price applied is US$ 80 per tCO_2, and the price on methane emissions applied is US$ 1,680 per tCH_4. Detailed calculations for each of the costs and benefits (climate benefits, climate costs, health benefits and health costs) are presented in Appendix A.4.

4 Discussion and conclusion

We find that the local health costs arising from indoor air pollution exceed the global climate benefits of introducing a carbon price in several LMICs. Carbon prices that increase prices for fossil fuel-based cooking energy are thus likely to exacerbate local health costs in countries where households substitute biomass for cooking. Given that nearly 2.5 billion people globally still depend on biomass as a primary cooking fuel [20] and lack access to cleaner fuels and technologies, our results and their policy implications apply to a substantial share of the global population.

Our results bear consequences for the global distribution of climate change mitigation programs. Some argue that the marginal costs of emission abatement are lower in developing countries compared to industrialised countries [2]. Our results suggest that - considering a broader framework of social welfare - the full economic costs of emission abatement would be substantially larger in lower-income countries than previously thought, particularly in the residential energy sector.

Our analysis shows that climate policy design requires taking a broad perspective with respect to welfare. Carbon pricing can produce additional costs and benefits, as we show for the case of increasing indoor air pollution. In addition, carbon pricing could lower the use of coal for electricity generation and thus improve local outdoor air quality in proximity to coal-fired power plants [28]. Nevertheless, we show that the local health costs resulting from increased biomass use following increasing electricity prices exceed the local health benefits of improved outdoor air quality in several countries. Our results suggest that first-best taxes may not generate optimal outcomes in the presence of an additional uncorrected externality in developing countries [29].

The results of these cost-benefit analyses hinge on important assumptions. The method used to evaluate the value of emission reductions or the value of statistical life (VSL) will determine the outcome of the results. By valuing carbon emissions at US$ 80 per tCO_2, we take a conservative approach compared to recent estimates of the social cost of carbon [30, 31]. Instead of these estimates, we draw on realistic carbon price levels, as implemented in the EU ETS [27]. Nevertheless, applying a higher carbon price of US$ 185 per tCO_2 produces robust results that show net costs for most countries [15].

Similarly, we apply a conservative estimate to the value of statistical life (VSL). Following the benefit-transfer approach [32], we account for developing countries' lower per capita incomes and thus, their reduced ability to pay to mitigate mortality risks. Our estimates of VSL are two orders of magnitude below those of richer countries such as the United States. Despite using substantially lower VSL estimates, we find that the introduction of a carbon price produces large health costs that dwarf the climate benefits in several countries.

Importantly, our study highlights that cost-benefit calculations of domestic climate policy, which take into account local externalities, are context-specific and require detailed country-level investigations prior to the introduction of carbon pricing. Furthermore, our analysis primarily looks at residential cooking energy, with coverage of emissions limited to household use of fossil-based fuels such as electricity, LPG, and kerosene. In these analyses, we do not consider the potential effects of carbon prices on industrial and commercial demand for cooking fuels.

Our analyses hold implications for national and international climate policy. While taxes on transport fuels may generate co-benefits through improved local air quality [28], policy design may consider exempting specific household cooking fuels (such as LPG, kerosene and electricity) from carbon pricing in low- and middle-income countries, where households would be likely to substitute these fuels with polluting biomass. To reduce the public health burden from burning biomass in several LMICs, direct subsidies for LPG, electricity derived from renewable energy, and cookstoves may be introduced effectively [33]. Subsidies for cooking fuels would generate small increases in aggregate emissions while contributing to effective implementation of globally efficient climate policy. Emissions from residential energy use (including fossil fuels used for cooking) account for a small share of aggregate CO_2 emissions (approximately 4-6% of total emissions in LMICs) [34].

Our findings rely on sufficient monetary transfers to poor households in LMICs to offset any welfare losses to consumers. Domestic carbon prices are likely to be insufficient to generate these required funds [35, 36]. International climate finance would thus be required to ensure climate action in LMICs. Large-scale income transfers are essential to mitigate the substantial welfare losses generated from carbon pricing. If transfers are difficult to administer effectively, international climate policy design should entail lowering technological barriers to ensure widespread access to affordable clean cooking fuels and technologies in lower income countries to ensure the equity and effectiveness of global climate policy.

5 Methods and data

The demand system used to derive elasticities is presented in section 5.1 and the econometric method used to estimate elasticities is discussed in section 5.2. Data sources are presented in section 5.3, methods for the cost-benefit analyses are outlined in section 5.4, and limitations of the study are discussed in section 5.5.

5.1 The demand system

We estimate the Exact Affine Stone Index (EASI) implicit Marshallian demand system for household cooking fuels for each of six countries in our sample, distinguishing between rural and urban regions [37]. We apply the approximate linear EASI model for J-goods, with the expenditure function $C(p, u, \epsilon)$ expressed in terms of household utility u, a J-vector of log prices p, an L-vector of demographic characteristics and regional controls z, and a J-vector of error terms ϵ, which are interpreted as random utility parameters reflecting preference heterogeneity:

$$C(p, u, \epsilon) = u + p'(b_0 + b_1 u + rz) + \frac{1}{2} p' A p + p' \epsilon \tag{1}$$

Applying Shephard's Lemma to the expenditure function, we obtain the Hicksian demand functions in budget share form:

$$w_j = b_{0j} + b_{1j} y + c_j z + \sum_{k=1}^{J} \alpha_{jk} p_k + \epsilon_j \tag{2}$$

where y is log household total expenditure [37]. Expenditure shares w_j for J goods in the demand system are calculated with respect to total expenditure on cooking fuels, m, assuming multi-stage budgeting - a standard assumption in demand analysis [38]. To relate total household expenditure and household expenditure on cooking fuels, we further estimate a linear regression of log m on y, based on the Working-Leser form [39], as follows:

$$lnm = a_0 + e_{m,y} y + \epsilon \tag{3}$$

where $e_{m,y}$ is the elasticity of household expenditure on cooking fuels with respect to total household expenditure. We impose parameter restrictions on demand derived from consumer theory, which include budget balance, homogeneity of the expenditure function of degree one in prices, and symmetry of the Slutsky matrix, as follows: $1'_J\beta_0 = 1$, $1'_J\beta_1 = 0$, $1'_J c = 0$, $\sum_{j=1}^{J}\alpha_{jk} = 0$ $\forall\ k$, and $\alpha_{jk} = \alpha_{kj}\ \forall\ j,k$ [37]. Although we estimate a demand system only for cooking energy, the parameter restrictions remain unchanged, as these ensure budget balance and Slutsky symmetry for our demand systems. To ensure homogeneity, our restrictions imply that an increase in total household expenditure leads to an increase in household expenditure on cooking fuels by $e_{m,y}$. Hence, we assume the elasticity, $e_{m,y}$, remains unchanged as household total expenditure rises. This is a standard assumption in studies of consumer demand when assuming multi-stage budgeting [38].

From budget share equation 2, we derive the compensated (Hicksian) cross-price elasticity of demand for good j with respect to the price of good k as follows:

$$e^c_{j,k} = \begin{cases} \frac{\alpha_{jk}}{w_j}, & j \neq k \\ \frac{\alpha_{jk}}{w_j} - 1, & j = k \end{cases} \tag{4}$$

The expenditure elasticity of demand for good j with respect to log total household expenditure y is expressed as:

$$e_{j,y} = \frac{b_{1j}}{w_j} + e_{m,y} \tag{5}$$

The uncompensated (Marshallian) elasticity of demand for good j with respect to the price of good k is derived from the Slutsky equation as follows:

$$e^u_{j,k} = e^c_{j,k} - e_{j,y} w_k \tag{6}$$

5.2 Econometric method

To estimate price elasticities of demand, we run regressions of expenditure shares for household cooking fuels on prices and household expenditures. Since a large proportion of households in each country sample reports zero expenditure on specific energy sources, we use a corner solution response model [40]. We estimate the Tobit Type I model, which corrects for the probability of households consuming a specific fuel in the estimation of the regression coefficients.

A demand system requires parameter restrictions across equations, derived from consumer theory. Hence, we estimate the system of expenditure share equations efficiently through the Generalized Method of Moments (GMM), which also allows for cross-equation correlations in error terms [40, 41].

Our statistical model incorporates the Tobit likelihood in the GMM moment equations, following [23], based on the following latent expenditure share equation:

$$w_{ij}^* = b_{0j} + b_{1j}y_i + c_j z + \sum_{k=1}^{J} \alpha_{jk} p_{kr} + \epsilon_{ij} \tag{7}$$

where w_{ij}^* is the latent expenditure share for good j and household i, y_i is the logarithm of total expenditure for household i, p_{kr} is the logarithm of price for commodity k in region r, z is household size, and ϵ_{ij} is a normally distributed error term.

Fuel prices and household-specific variables such as total expenditure and household size are considered plausibly exogenous, and are included as instruments. We include additional instruments such as region-specific dummy variables to capture potential correlations between fuel prices and other unobserved region-specific factors.

The observed expenditure share w_{ij} can be expressed in Tobit Type I form:

$$w_{ij} = \begin{cases} w_{ij}^*, & 0 < w_{ij}^* < 1 \\ 0, & w_{ij}^* \leq 0 \\ 1, & w_{ij}^* \geq 1 \end{cases} \tag{8}$$

In compact form, the latent budget share equation can be expressed as: $w_{ij}^* = X\beta + \epsilon$. The expected value of the observed expenditure share given covariates for the Tobit model is as follows:

$$E(w_{ij} \mid X) = \Phi(\frac{X\beta}{\sigma_\epsilon})X\beta + \sigma_\epsilon \phi(\frac{X\beta}{\sigma_\epsilon}) \tag{9}$$

where $\Phi(.)$ is the standard normal cumulative distribution function and $\phi(.)$ is the corresponding probability density function [40]. We estimate the above Tobit likelihood for each commodity share through the following moment equation in the Generalized Method of Moments estimator:

$$E[g(w, X, \beta)] = E[w_{ij} - E(w_{ij} \mid X)] = 0$$

From the vectors of estimated regression coefficients b_{1j} and α_{jk}, we compute price elasticities of demand as non-linear combinations of regression coefficients and assess the statistical significance of the elasticities. Further details of the GMM estimator are provided in Supplementary Information A.1.

5.3 Data sources

This section discusses data sources pertaining to (i) the expenditure and price data used to estimate elasticities, and (ii) the data on fuel-specific emission intensities to compute benefits and costs.

5.3.1 Expenditure and price data

We draw on household-level data from nationally representative surveys in six lower middle-income countries. These include Cambodia, Ghana, Honduras, India, Kenya and Myanmar, which are broadly representative of lower-middle income countries in South America, Sub-Saharan Africa and Asia. For Cambodia, Honduras and Myanmar, we draw on survey data from the Multi-Tier Framework (MTF) Surveys for 2017. For other countries, we use surveys from national statistical offices, namely the Household Consumer Expenditure Survey (HCES), 2023-24 for India, the Ghana Living Standards Survey (GLSS), 2016-17 for Ghana, and the Integrated Household Budget Survey (IHBS), 2015-16 for Kenya. National statistics on population, gross domestic product per capita, poverty rate, energy access and $CO2$ emissions per capita, are presented in Table A1.

We select these countries due to the prevalence and use of (i) solid fuels (firewood or charcoal), and (ii) at least one fossil-based fuel such as LPG, kerosene or electricity, for cooking, as well as the availability of household consumption and price data. Household surveys for these six countries provide detailed information on energy use, including quantities of fuel consumed monthly and expenditure on various cooking fuels.

To curtail the effects of outliers, we winsorise fuel expenditure and quantities at the 99th percentiles of the respective distributions for each country and rural/urban region. Fuel prices are derived at the household level as ratios of expenditures to quantities. We further winsorise the fuel price distributions at the 99th percentile levels for each country and rural/urban region.

To mitigate concerns of potential simultaneity between household-level fuel prices and fuel consumption, we construct means for fuel prices at the level of the first-stage sampling unit, differentiated by rural and urban areas (villages in rural areas and towns in urban areas, or equivalently, clusters/enumeration areas). Here, we construct the "leave-one-out" means of fuel prices at the household level. Accordingly, each household is assigned the mean fuel price at the level of the primary sampling unit by excluding the particular household in question from construction of the mean fuel price within the primary sampling unit. Thus, fuel prices differ across households within the primary sampling units.

For self-reported fuelwood collection, we impute the expenditure value of collected fuelwood from the reported quantities collected using the mean fuelwood prices at the level of the primary sampling unit.

To estimate price elasticities of demand, we consider solid fuels and fossil-based fuels that are used for cooking by at least 1% of the population in each country, by rural/urban region. Detailed descriptive statistics of fuel use by country and region are presented in Table A2.

5.3.2 Data on emission intensities for cost-benefit analysis

Data on emission intensities are divided into three strands.

First, we draw on CO_2 emission intensities for fossil fuels and fossil-derived energy sources, including (i) the direct emissions intensity of fossil fuels (obtained from the IPCC Emission Factor Database), and (ii) the indirect emissions intensity (resulting from production or extraction and transportation of the fuel), drawn from the Global Trade Analysis Project (GTAP) 11 for the year 2017 [42]. We convert the indirect CO_2 emission intensity (tCO_2 emitted per USD of fuel purchased), obtained from the GTAP database, to physical units (tCO_2 emitted per Kilogram/Litre/kWh of fuel), based on average national fuel prices for the year 2017. Combining the direct and indirect emission intensities, we obtain the aggregate CO_2 emissions intensity per fuel in tCO_2 per physical unit (Kg/L/kWh). These CO_2 emission intensities are used to compute the climate benefits of carbon pricing, discussed in section 5.4.1.

Second, we obtain data on the CO_2 and CH_4 emission intensities for fuelwood (tCO_2 per kg of fuelwood and tCH_4 per kg of fuelwood, respectively) and a conversion factor for charcoal to fuelwood, in order to compute climate costs. We draw the fuelwood emission intensities and the conversion factor from [13], which we apply uniformly across countries.

Third, we apply $PM_{2.5}$ concentration factors to biomass consumption in order to estimate indoor $PM_{2.5}$ concentrations and related health costs. We draw on a field study in rural India that estimated the relationship between increases in woodfuel consumption (measured in kilograms) and observed indoor $PM_{2.5}$ concentrations (measured in $\mu g/m^3$) [24]. We derive a $PM_{2.5}$ concentration factor for firewood of 58.6 $\mu g/m^3$ per kg of fuelwood burned. Following [25], we apply a $PM_{2.5}$ concentration factor for charcoal which is half that of firewood, i.e. 29.3 $\mu g/m^3$ per kg of charcoal burned.

While these $PM_{2.5}$ concentration factors are stylized, they provide us with reasonable approximations of indoor pollution concentrations in relation to biomass consumption. Our baseline estimated $PM_{2.5}$ concentrations for all countries (Appendix Table A.4.4) are in line with region-wise estimates reported in prior field and modeling studies [43, 44].

5.4 Cost-Benefit Analyses

We use our estimated elasticities and parameter values drawn from the literature to conduct cost-benefit analyses of the potential introduction of a carbon price. We compute (i) the global climate benefits generated from reductions in CO_2 emissions from taxing fossil-based cooking fuels, (ii) the global climate costs of increased CO_2 and CH_4 emissions from burning biomass, (iii) the local health benefits of improved air quality from taxing coal used for electricity generation (in countries where electricity is used for cooking)n and (iv) the local health costs of indoor air pollution from burning biomass. All calculations are based on fuel consumption changes in response to 1% increases in the prices for fossil-derived cooking fuels (electricity, LPG and kerosene). The implicit carbon prices that correspond to these percentage fuel price increases are in the range of US$ 2-11 per tCO_2.

5.4.1 Climate Benefits

Global climate benefits of taxing fossil fuels arise from reductions in fossil fuel use and associated CO_2 emissions. The detailed calculations for climate costs, together with data on relevant parameters, are presented in Appendix Table A.4.1.

The global climate benefit from a 1% increase in the price of fossil-based fuel f in a specific country (expressed per thousand persons of that country's population) is:

$$B_f = \left|(e_{f,f} q_f \frac{\Delta p_f}{p_f} c_f SCC\right| + \left|e_{g,f} q_g \frac{\Delta p_f}{p_f} c_g SCC\right| \tag{10}$$

where $\frac{\Delta p_f}{p_f} = 0.01$. The first term in the above equation measures the climate benefit from a reduction in consumption of fossil-based fuel f in response to a 1% increase in its price. The second term measures changes in consumption (and related emissions) from the other fossil fuel g in the consumer demand system. This could result from potential complementarities or substitutions between fossil fuels f and g (e.g. electricity and LPG, or LPG and kerosene).

The compensated price elasticities of demand for fuels f and g are $e_{f,f}$ and $e_{g,f}$, respectively. The respective quantities of fossil fuel consumed (per thousand persons of the country's population), are q_f and q_g (in units, Kg/L/kWh). The CO_2 emissions intensities for fossil fuels, c_f and c_g are expressed in tonnes of CO_2 per unit (Kg/L/kWh) of the fuel. We apply a social cost of carbon of US$ 80 per tonne of CO_2. We calculate climate benefits for each country, by fuel, for rural and urban regions. We then aggregate climate benefits across rural/urban regions by fuel for each country.

5.4.2 Climate Costs

Global climate costs result from biomass-related deforestation and methane emissions due to taxes on fossil fuels. The detailed calculations for climate costs, with data on relevant parameters, are presented in Appendix Table A.4.2.

Deforestation (CO_2 Emissions)

The global climate costs due to deforestation (CO_2 emissions) resulting from a 1% increase in the price of fossil fuel f in a specific country (expressed per thousand persons of that country's population) is:

$$C_{CO_2} = \sum_{b=\{w,c\}} e_{b,f} s_{nb} q_b \frac{\Delta p_f}{p_f} c_b SCC \tag{11}$$

where $\frac{\Delta p_f}{p_f} = 0.01$ and $b = \{w, c\}$ (w for fuelwood and c for charcoal). The compensated price elasticities of demand for biomass with respect to fossil fuel f are $e_{b,f}$ for $b = \{w, c\}$. The quantities of biomass consumed (per thousand persons of the country's population) are q_b for $b = \{w, c\}$, measured in kilograms.

Climate costs arise from increases in unsustainable harvests of woodfuels, i.e. release of CO_2 into the atmosphere in excess of the amount sequestered during plant growth. Thus, s_{nb} is the share of non-renewable fuelwood harvests in the country, obtained from [13]. The CO_2 emissions intensity of fuelwood c_w is obtained from [13]. The CO_2 emissions intensity for charcoal, $c_c = k.c_w$ is a product of c_w and a conversion factor k, which measures the tonnes of fuelwood required to produce 1 tonne of charcoal, obtained from [13]. Here, we apply a social cost of carbon of US$ 80 per tCO_2.

Methane (CH_4) Emissions

The global climate costs from increased methane (CH_4) emissions due to a 1% increase in the price of fossil fuel f in a specific country (expressed per thousand persons of that country's population) is:

$$C_{CH_4} = \sum_{b=\{w,c\}} e_{b,f} q_b \frac{\Delta p_f}{p_f} m_b SCM \tag{12}$$

The parameters are as defined above. The m_b term measures the emissions intensity of methane for biomass (m_w for fuelwood and $m_c = k.m_w$ for charcoal, with the conversion factor k, as defined above), obtained from [13]. We apply a social cost of methane emissions of US$ 1,680 per tonne of CH_4, which is approximately 21 times the applied social cost of carbon, as recommended by [26].

5.4.3 Health Benefits

Taxes on coal used to generate electricity can confer local health benefits in terms of reduced air pollution. The detailed calculations for health benefits in countries where electricity is used for cooking are presented in Appendix Table A.4.3.

The health benefits from a 1% increase in the price of electricity through a tax on coal for a specific country (expressed per thousand persons of the country's population) is:

$$B_c = \frac{e_{c,c}}{s_c} \frac{\Delta p_e}{p_e} q_c D_c VSL \qquad (13)$$

where $e_{c,c}$ is the own-price elasticity of coal consumption, drawn from [45], s_c is the country's share of coal in electricity generation (obtained from Ember - Yearly Electricity Data for 2022), and $\frac{\Delta p_e}{p_e} = 0.01$ reflects a 1% increase in the price of electricity. q_c is annual national coal consumption (per thousand persons of the country's population), obtained from the US Energy Information Administration for 2022. In this calculation, we assume a 1% increase in the price of electricity. We assume complete pass-through from coal to electricity prices in power generation, which results in a $(1/s_c)$ % increase in the price of coal.

D_c is the number of deaths from ambient air pollution per tonne of coal consumed at power plants. This is obtained as a product of (i) the number of deaths per ton of SO_2 emissions and (ii) the amount of SO_2 contained in one tonne of coal. Data on deaths per tonne of SO_2 emissions are obtained from [14] (a value of 20 for China, which we apply to all countries). Burning 1 tonne of coal releases 6 kg of SO_2 in Chinese power plants [46], which we apply to all countries. The VSL is the value of statistical life per country, estimated based on the "benefit-transfer" approach [19].

5.4.4 Health Costs

To quantify the health costs of biomass use, we first estimate $PM_{2.5}$ levels associated with biomass consumption for an average household in each country, by rural-urban region. We estimate $PM_{2.5}$ concentrations associated with observed fuel consumption, both prior to and following 1% increases in the prices for fossil cooking energy. Then, we compute excess premature "non-accidental mortality" from exposure to communicable and non-communicable diseases (including cardio-vascular diseases) linked to rising pollution concentrations and the health costs of excess premature mortality.

To estimate premature mortality, we apply hazard ratios of increased incidence of non-accidental all-cause mortality from an incremental exposure to $PM_{2.5}$ concentrations of 10 $\mu g/m^3$, drawn from the latest cross-country Prospective Urban and Rural Epidemiology (PURE) study [47]. The hazard ratio, or equivalently the relative risk of disease associated with an increase in $PM_{2.5}$ concentrations of 10 $\mu g/m^3$, is drawn from model 5 study results, which incorporate regional fixed effects in the regression models. The reported hazard ratio is 1.08 in the exposed population, relative to the unexposed population. These estimates provide an update to the previous study by [48], which assumes a concave integrated exposure-response function. In contrast, the PURE study [47] suggests linear increases in the relative risk of disease at high concentrations of pollution.

Next, we compute the population-attributable fraction (PAF), i.e. the share of the population which is exposed to the rise in pollution from additional biomass use. The PAF is a function of the relative risks of disease burdens associated with baseline and endline levels of pollution. We then estimate excess premature mortality due to increased indoor pollution concentrations from biomass consumption for each of the five diseases. Here, we apply the disease-specific population attributable fraction (PAF) values to disease-specific mortality levels for each country and rural-urban region. Data on disease-specific mortality rates are obtained from the Global Burden of Disease (2019) database for all countries.

Finally, we calculate the monetary health costs of excess premature mortality by applying the Value of Statistical Life (VSL) for each country, based on [19]. The detailed calculations for these health costs are presented in Appendix Table A.4.4 (Calculations I - III).

I. Estimating indoor air pollution

We estimate $PM_{2.5}$ concentrations for an average household by country and rural/urban region. The literature follows different approaches to estimating indoor pollution levels. For example, [43] simulate $PM_{2.5}$ levels based on fuel-specific cook-stoves from the Global Burden of Disease database, while [25] provide $PM_{2.5}$ emission factors for biomass by weight.

We rely on estimated $PM_{2.5}$ concentration factors (indoor kitchen concentrations in relation to biomass burned by weight), based on field measurements of $PM_{2.5}$ conducted by [24] in a village in rural India. Hence, we apply a $PM_{2.5}$ concentration factor of 58.6 $\mu g/m^3$ per kilogram of dry fuelwood burned. For charcoal, we apply a $PM_{2.5}$ concentration factor of 29.3 $\mu g/m^3$ per kilogram of dry charcoal burned, which is half that of fuelwood, following [25].

Based on these concentration factors, we estimate indoor pollution levels for an average household in a country and rural/urban region, based on the mean observed levels of fuelwood and charcoal consumption from the respective household surveys. The initial $PM_{2.5}$ concentration is measured as follows:

$$PM_{2.5,initial} = 58.6 * q_w + 29.3 * q_c \tag{14}$$

where q_w and q_c are the mean daily quantities of fuelwood and charcoal consumed per household (measured in kilograms) in a country and rural-urban region. Next, we estimate indoor pollution concentrations, applying 1% price increases for fossil-based fuels and the corresponding demand elasticities for fuelwood and charcoal. These inform us of the $PM_{2.5}$ concentrations observed, based on biomass consumption in response to fossil taxes.

The final $PM_{2.5}$ concentration is measured as follows:

$$PM_{2.5,final,f} = 58.6 * q_w \left(1 + e_{w,f}\frac{\Delta p_f}{p_f}\right) + 29.3 * q_c \left(1 + e_{c,f}\frac{\Delta p_f}{p_f}\right) \tag{15}$$

where $e_{w,f}$ and $e_{c,f}$ are the respective price elasticities of demand for fuelwood and charcoal with respect to fossil fuel f, and $\frac{\Delta p_f}{p_f} = 0.01$, reflecting a 1% price increase for fuel f.

We compute the initial and final $PM_{2.5}$ concentrations for all country-region-fuel pairs. The results are presented in Appendix Table A.4.4 (Calculations I).

II. Estimating excess premature mortality

We calculate the population-attributable fraction (PAF), which measures the share of deaths from specific diseases that can be attributed to exposure to higher levels of indoor air population, as a consequence of price increases for fossil fuels. The PAF, expressed in percentage terms, is as follows [20]:

$$PAF_f = \frac{p(RR-1)}{p(RR-1)+1} \times 100 \tag{16}$$

where p is the proportion of the population exposed to solid fuels and RR is the risk of non-accidental all-cause mortality among the exposed population, relative to the unexposed population. In our calculations, this implies: $RR = \frac{RR_{final,f}}{RR_{initial}}$, where $RR_{final,f}$ corresponds to the relative risk of fatal disease cases with the associated $PM_{2.5}$ concentrations, following a 1% increase in the price of fossil fuel f in a specific country and region, and $RR_{initial}$ refers to the baseline relative risk of fatal disease cases at observed baseline pollution concentrations.

Further, the baseline relative risk is defined as follows:

$$RR_{initial} = \frac{(1.08)}{10} * PM_{2.5,initial}$$

and the final relative risk is defined as follows:

$$RR_{final,f} = \frac{(1.08)}{10} * PM_{2.5,final,f}$$

We modify the calculation for the PAF from [20] by imposing $p = 1$. This is because the burning of solid fuel contributes significantly to ambient air pollution, with estimates suggesting up to one-third of ambient air pollution is due to burning biomass indoors [49, 50]. Households that do not consume solid fuels directly may nevertheless be exposed to the smoke generated by neighbouring households from burning solid fuels. Hence, we find it reasonable to assume the entire population is exposed to pollution from burning solid fuels. Thus, we compute the PAF, in percentage terms, as follows:

$$PAF_f = \left(1 - \frac{RR_{initial}}{RR_{final,f}}\right) \times 100$$

From PAF_f, we estimate the excess premature mortality ΔM_f resulting from higher concentrations of indoor air pollution due to a 1% price increases on fossil fuel f, expressed per million persons of the country's regional (rural/urban) population, as:

$$\Delta M_{r,f} = \left(\frac{PAF_f}{100}\right) \times M_r$$

where excess premature mortality (per million persons of the country's regional population) is the product of the population-attributable fraction (expressed in proportions) and the annual mortality from disease M_r in country-region r (per million persons of the country's regional population). Data on annual non-accidental all-cause mortality for each country in our sample are drawn from the IHME, Global Burden of Disease (GBD), 2019. Country-wise population data are drawn from the World Bank Group's database.

Given that our calculations of $PM_{2.5}$ concentrations are differentiated by rural and urban regions within each country, we decompose the annual national mortality burden across rural-urban regions by applying the rural-urban specific shares of the national population to the mortality incidence for each country. Hence, we assume that country-level mortality is distributed in the same proportion as the country's population, across rural and urban areas. Thus, we compute the premature excess mortality for each country-region-fuel pair in our sample. We make this simplifying assumption in the absence of data on mortality incidence at the sub-national and regional levels.

III. Estimating health costs of excess premature mortality

Finally, we compute the health costs of excess premature mortality from disease (expressed in USD per thousand persons of the country's regional population for comparison), by applying the Value of Statistical Life (VSL), to the estimated excess premature mortality. The VSL is estimated for each country using the benefit-transfer approach, following [19]. To do so, we compute the ratio of the per capita income of the country being analyzed relative to the per capita income of the United States. We then multiply this ratio by the VSL for the United States, which is estimated at USD 9.6 million to obtain the country-specific VSL estimates as follows:

$$C_H = VSL \times \left(\frac{\Delta M_{r,f}}{1,000}\right)$$

The VSL measures individuals' willingness to pay to mitigate the risk of mortality from disease [19]. We aggregate health costs across rural-urban regions by applying the respective population shares to obtain country-wide health costs for each fossil fuel f taxed, expressed per thousand persons of the country populations.

5.5 Limitations

The results of the study should be interpreted with a number of caveats. First, our demand system assumes linear demand functions and the price elasticities reflect marginal price changes. Extrapolating demand changes at large carbon price levels using these estimated elasticities may thus be inaccurate. Hence, we compute the costs and benefits of marginal increases in fossil fuel prices and do not attempt to project aggregate costs and benefits for carbon price levels that result in large fuel price increases. More sophisticated methods that account for nonlinear demand responses would be required to estimate costs and benefits resulting from large increases in fossil fuel prices.

Second, our datasets are limited as we rely on cross-sectional price variation from household surveys to estimate elasticities. Hence, estimated elasticities should be interpreted with caution, as the household data may suffer from measurement errors in reported expenditures or consumption levels. This is salient for household reports of self-collected biomass, which may bias cross-price elasticities of demand for biomass with respect to fossil fuel prices.

In all countries except India and Kenya, we observe significant gaps between the share of the country-region population that reports cooking with fuelwood and the share of the respective population which reports positive expenditures on purchased fuelwood or positive quantities of fuelwood gathered (Appendix Table A2. These gaps are especially pronounced in rural areas, suggesting that coverage of fuelwood consumption in these country household surveys is non-representative =. Hence, elasticity estimates for all countries except India and Kenya should be interpreted with caution. In the remaining countries (India and Kenya), we observe a higher share of households reporting expenditure on fuelwood or quantities of collected fuelwood than the share of the population reporting fuelwood use for cooking. This is due to the fact that the household surveys in these countries only inquired about the households' primary cooking fuel.

Further, we make a number of assumptions to compute the external effects of carbon prices. In particular, we apply the social cost of carbon to approximate the net present value of global environmental damage due to climate change. The approximation may underestimate potentially large, catastrophic damage that is imprecisely estimated. Hence, we interpret the climate benefits of carbon taxes as lower-bound values. In addition, we calculate approximate health damage from biomass consumption by relying on parameter values from the existing literature on public health and epidemiology. We calculate health costs for an average household, assuming environmental conditions including kitchen ventilation, kitchen size, type of cook-stove, and exposure to ambient air pollution. Experimental data on measured particulate matter concentrations across countries would be required to undertake granular analysis to explore household heterogeneity in the health impacts of exposure to indoor air pollution.

Moreover, we only compute health costs associated with premature mortality from exposure to indoor air pollution, but do not compute additional health costs due to morbidity from disease, or the economic costs of air pollution associated with a loss in labor productivity and illness. In that sense, our estimates of health costs (or benefits) may be considered lower-bound estimates in magnitudes.

Appendix A

In section A.1, we outline details of the econometric analysis. Summary statistics are presented in section A.2 and estimated elasticities are presented in section A.3. Detailed calculations for cost-benefit analyses are presented in section A.4.

A.1 Econometric Method (Contd.)

We apply the Tobit Type I statistical model and estimate the EASI demand system efficiently through the Generalised Method of Moments (GMM). We integrate the Tobit likelihood in the moment equation for GMM:

$$E[g(w, X, \beta)] = E[w_{ij} - E(w_{ij} \mid X)] = 0 \tag{A1}$$

where $E(w_{ij} \mid X) = \Phi(\frac{X\beta}{\sigma_\epsilon})X\beta + \sigma_\epsilon \phi(\frac{X\beta}{\sigma_\epsilon})$.

We assume weak exogeneity between the vector of covariates X_i for household i and the error terms, $E(\epsilon_{ij} \mid X_i) = 0$. We apply the pooled Tobit estimator, which maximizes the partial likelihood for each expenditure share equation. Given the potential for correlation between error terms across equations, we estimate the equation system efficiently through GMM. Since fuel prices and the household's total expenditure are plausibly exogenous, we use all covariates as instruments, and include dummy variables for region and month as additional instruments.

Identification of the coefficient vector β in the moment equations requires an estimate for σ_ϵ. We obtain a preliminary estimator for σ_ϵ by applying the Tobit Type I regression model to each expenditure share equation, and then derive $\hat{\sigma}_\epsilon$ from the sample. From the Law of Large Numbers, the Continuous Mapping Theorem, and the Slutsky Theorem, $\hat{\sigma}_\epsilon$ consistently estimates σ_ϵ, although $\hat{\sigma}_\epsilon$ is not an efficient estimator for σ_ϵ.

We then implement two-step GMM, which allows for correlations among error terms across the equations, and impose relevant parameter restrictions from consumer theory, to obtain a consistent and efficient estimator for the coefficient vector β, solving the following minimization problem:

$$min_{b \in \Theta} \bar{g}(w, X, b)' W \bar{g}(w, X, b) \tag{A2}$$

where $\bar{g}$ are the sample analogues of the population moment conditions and W is the optimal weight matrix.

A.2 Summary Statistics

We present national statistics on GDP per capita, poverty rates, rates of access to clean cooking fuels, and CO_2 emissions per capita for all countries in the sample in Table A1.

Table A1: Summary statistics

Country	Population (Million)	GDP p.c. (US$)	Poverty rate (%)	Electricity access (%)	CO_2 emissions p.c. (tCO_2)
Cambodia	17	1,875	18	92	1.1
Ghana	34	2,238	23	85	0.6
Honduras	11	3,247	48	94	0.9
India	1,429	2,485	22	99	1.6
Kenya	55	1,950	36	76	0.4
Myanmar	55	1,188	25	74	0.6

Note: This table provides summary statistics for countries in our sample. Statistics include population (in millions), GDP per capita (p.c.), poverty rate (%), electricity access (%), and annual CO_2 emissions per capita (p.c.). Source: World Development Indicators (2023) [22].

Next, we present descriptive statistics of rural-urban samples, cooking fuel choices, and reports of fuel expenditures from the household surveys for all countries and regions in Table A2.

Table A2: Country-level descriptive statistics on sample and fuel consumption

Country	Region	Sample size	HH positive exp. (5)	Cooking fuel	Use of cooking fuel (7)	Positive exp. on fuel (8)
Cambodia	Rural	1,664	100%	Electricity	11%	51%
				LPG	31%	29%
				Charcoal	23%	19%
				Firewood	88%	24%
	Urban	1,626	99%	Electricity	52%	90%
				LPG	84%	82%
				Charcoal	48%	40%
				Firewood	30%	13%
Ghana*	Rural	7,991	98%	Gas	6%	4%
				Charcoal	16%	11%
				Firewood	72%	17%
	Urban	6,018	98%	Gas	35%	24%
				Charcoal	44%	26%
				Firewood	13%	4%
Honduras	Rural	1,574	100%	Electricity	7%	18%
				LPG	13%	12%
				Firewood	95%	13%
	Urban	1,241	100%	Electricity	27%	21%
				LPG	50%	48%
				Firewood	48%	29%
India*	Rural	154,357	100%	LPG	49%	71%
				Firewood	47%	73%
	Urban	107,596		LPG	86%	89%
				Firewood	5%	14%
Kenya*	Rural	13,092	100%	LPG	2%	6%
				Kerosene	2%	61%
				Charcoal	8%	26%
				Firewood	87%	76%
	Urban	8,681	100%	LPG	18%	25%
				Kerosene	17%	59%
				Charcoal	30%	52%
				Firewood	32%	31%
Myanmar	Rural	1,725	100%	Electricity	39%	50%
				LPG	1%	0%
				Charcoal	15%	15%
				Firewood	69%	19%
	Urban	1,721	99%	Electricity	57%	69%
				LPG	10%	10%
				Charcoal	44%	43%
				Firewood	25%	10%

A.3 Estimated Elasticities - The Demand System

We present three sets of elasticities: (i) income elasticities of demand, (ii) compensated price elasticities of demand, and (iii) uncompensated price elasticities of demand.

A.3.1 Income Elasticities of Demand

The income elasticities of demand reflect the percentage change in consumption of a fuel in response to a 1% increase in the household's income (or expenditure) (Table A3).

Table A3: Income elasticity

Country	Urban	Firewood	Charcoal	Kerosene	LPG	Electricity
Cambodia	Urban	0.509***	0.565***	-	0.519***	0.62***
		(0.036)	(0.037)	-	(0.036)	(0.019)
	Rural	0.48***	0.607***	-	0.576***	0.552***
		(0.083)	(0.033)	-	(0.029)	(0.044)
Ghana	Urban	-0.139**	0.244***	-	0.42***	-
		(0.068)	(0.024)	-	(0.014)	-
	Rural	0.024	0.477***	-	0.485***	-
		(0.147)	(0.028)	-	(0.007)	-
Honduras	Urban	0.148	-	-	0.112***	0.356***
		(0.092)	-	-	(0.033)	(0.033)
	Rural	0.227	-	-	0.267***	0.234***
		(0.252)	-	-	(0.037)	(0.043)
India	Urban	0.246***	-	-	0.574***	-
		(0.005)	-	-	(0.003)	-
	Rural	-0.094***	-	-	1.009***	-
		(0.004)	-	-	(0.003)	-
Kenya	Urban	-0.594***	0.732***	0.376***	0.885***	-
		(0.065)	(0.024)	(0.028)	(0.012)	-
	Rural	-0.739***	0.793***	0.424***	0.65***	-
		(0.078)	(0.018)	(0.027)	(0.004)	-
Myanmar	Urban	0.413**	0.965***	-	1.071***	0.79***
		(0.174)	(0.074)	-	(0.002)	(0.055)
	Rural	0.694***	1.244***	-	-	0.687***
		(0.189)	(0.023)	-	-	(0.064)

A.3.2 Compensated and Uncompensated Price Elasticities of Demand

The compensated price elasticity of demand for fuel pair $\{j, k\}$ reflects the percentage change in demand for fuel j in response to a percentage increase in the price of fuel k. These reflect the pure substitution effect. The uncompensated price elasticity of demand for fuel pair $\{j, k\}$ reflects the percentage change in demand for fuel j in response to a percentage increase in the price of fuel k. These account for both substitution and income effects, and are presented in Tables A4 - A27. Each cell (row j, column k) represents the percentage change in demand for fuel j in response to a percentage increase in the price of fuel k.

Table A4: Compensated elasticities of demand in rural Cambodia

	Electricity	LPG	Charcoal	Firewood
Electricity	-1.392***	0.253***	0.164***	-0.026
	(0.082)	(0.066)	(0.039)	(0.022)
LPG	0.104***	-1.251***	0.119***	0.028**
	(0.027)	(0.033)	(0.017)	(0.013)
Charcoal	0.089***	0.158***	-1.324***	0.077***
	(0.021)	(0.023)	(0.02)	(0.015)
Firewood	-0.026	0.067**	0.143***	-1.185***
	(0.022)	(0.031)	(0.027)	(0.042)

Table A5: Uncompensated elasticities of demand in rural Cambodia

	Electricity	LPG	Charcoal	Firewood
Electricity	-1.757***	-0.012	-0.124***	-0.386***
	(0.087)	(0.072)	(0.042)	(0.036)
LPG	-0.278***	-1.527***	-0.182***	-0.348***
	(0.027)	(0.039)	(0.022)	(0.023)
Charcoal	-0.313***	-0.134***	-1.641***	-0.319***
	(0.033)	(0.026)	(0.023)	(0.028)
Firewood	-0.344***	-0.163***	-0.108**	-1.498***
	(0.061)	(0.051)	(0.048)	(0.069)

Table A6: Compensated elasticities of demand in urban Cambodia

	Electricity	LPG	Charcoal	Firewood
Electricity	-1.184***	0.036	0.111***	0.037***
	(0.051)	(0.056)	(0.028)	(0.014)
LPG	0.059	-1.518***	0.507***	-0.048*
	(0.091)	(0.108)	(0.055)	(0.028)
Charcoal	0.127***	0.353***	-1.434***	-0.045*
	(0.032)	(0.038)	(0.038)	(0.027)
Firewood	0.047***	-0.037*	-0.051*	-0.959***
	(0.018)	(0.022)	(0.03)	(0.022)

Table A7: Uncompensated elasticities of demand in urban Cambodia

	Electricity	LPG	Charcoal	Firewood
Electricity	-1.596***	-0.149***	-0.027	-0.188***
	(0.053)	(0.056)	(0.029)	(0.016)
LPG	-0.285***	-1.673***	0.391***	-0.236***
	(0.095)	(0.109)	(0.056)	(0.031)
Charcoal	-0.248***	0.184***	-1.561***	-0.25***
	(0.038)	(0.041)	(0.039)	(0.03)
Firewood	-0.291***	-0.189***	-0.165***	-1.143***
	(0.03)	(0.025)	(0.031)	(0.024)

Table A8: Compensated elasticities of demand in rural Ghana

	LPG	Charcoal	Firewood
LPG	-1.036***	0	0.035***
	(0.007)	(0.003)	(0.007)
Charcoal	0.001	-1.039***	0.038
	(0.029)	(0.045)	(0.034)
Firewood	0.782***	0.09	-1.873***
	(0.161)	(0.082)	(0.173)

Table A9: Uncompensated elasticities of demand in rural Ghana

	LPG	Charcoal	Firewood
LPG	-1.455***	-0.353***	-0.41***
	(0.008)	(0.006)	(0.01)
Charcoal	-0.412***	-1.386***	-0.4***
	(0.037)	(0.047)	(0.046)
Firewood	0.761***	0.073	-1.895***
	(0.187)	(0.132)	(0.237)

Table A10: Compensated elasticities of demand in urban Ghana

	LPG	Charcoal	Firewood
LPG	-1.081***	0.042***	0.04***
	(0.016)	(0.01)	(0.011)
Charcoal	0.135***	-1.17***	0.034
	(0.034)	(0.04)	(0.03)
Firewood	0.252***	0.067	-1.319***
	(0.069)	(0.058)	(0.069)

Table A11: Uncompensated elasticities of demand in urban Ghana

	LPG	Charcoal	Firewood
LPG	-1.461***	-0.286***	-0.2***
	(0.016)	(0.017)	(0.016)
Charcoal	-0.086**	-1.36***	-0.105***
	(0.035)	(0.049)	(0.031)
Firewood	0.377***	0.175*	-1.24***
	(0.079)	(0.091)	(0.079)

Table A12: Compensated elasticities of demand in rural Honduras

	Electricity	LPG	Firewood
Electricity	-1.119***	0.057**	0.062
	(0.048)	(0.027)	(0.048)
LPG	0.009**	-1.044***	0.035***
	(0.004)	(0.016)	(0.013)
Firewood	0.073	0.266***	-1.339***
	(0.057)	(0.099)	(0.079)

Table A13: Uncompensated elasticities of demand in rural Honduras

	Electricity	LPG	Firewood
Electricity	-1.323***	-0.125***	-0.119**
	(0.065)	(0.045)	(0.053)
LPG	-0.223***	-1.252***	-0.171***
	(0.033)	(0.032)	(0.033)
Firewood	-0.125	0.09	-1.514***
	(0.238)	(0.208)	(0.211)

Table A14: Compensated elasticities of demand in urban Honduras

	Electricity	LPG	Firewood
Electricity	-1.122***	-0.032	0.154***
	(0.038)	(0.034)	(0.038)
LPG	-0.012	-1.005***	0.017
	(0.013)	(0.029)	(0.022)
Firewood	0.202***	0.06	-1.262***
	(0.049)	(0.076)	(0.073)

Table A15: Uncompensated elasticities of demand in urban Honduras

	Electricity	LPG	Firewood
Electricity	-1.385***	-0.319***	-0.09**
	(0.045)	(0.044)	(0.044)
LPG	-0.095***	-1.096***	-0.06*
	(0.027)	(0.038)	(0.033)
Firewood	0.094	-0.059	-1.364***
	(0.089)	(0.102)	(0.096)

Table A16: Compensated elasticities of demand in rural India

	LPG	Firewood
LPG	-1.274***	0.274***
	(0.003)	(0.003)
Firewood	0.345***	-1.345***
	(0.004)	(0.004)

Table A17: Uncompensated elasticities of demand in rural India

	LPG	Firewood
LPG	-2.028***	-0.348***
	(0.004)	(0.004)
Firewood	0.415***	-1.286***
	(0.005)	(0.005)

Table A18: Compensated elasticities of demand in urban India

	LPG	Firewood
LPG	-1.134***	0.134***
	(0.003)	(0.003)
Firewood	0.187***	-1.187***
	(0.004)	(0.004)

Table A19: Uncompensated elasticities of demand in urban India

	LPG	Firewood
LPG	-1.686***	-0.131***
	(0.004)	(0.003)
Firewood	-0.049***	-1.3***
	(0.006)	(0.004)

Table A20: Compensated elasticities of demand in rural Kenya

	LPG	Kerosene	Charcoal	Firewood
LPG	-1.021***	0.005***	0.004***	0.012***
	(0.002)	(0.001)	(0.001)	(0.002)
Kerosene	0.165***	-1.205***	0.087***	-0.046***
	(0.022)	(0.029)	(0.021)	(0.014)
Charcoal	0.048***	0.035***	-1.107***	0.023**
	(0.011)	(0.008)	(0.013)	(0.01)
Firewood	0.239***	-0.031***	0.038**	-1.246***
	(0.035)	(0.009)	(0.016)	(0.04)

Table A21: Uncompensated elasticities of demand in rural Kenya

	LPG	Kerosene	Charcoal	Firewood
LPG	-1.37***	-0.195***	-0.296***	-0.498***
	(0.003)	(0.001)	(0.002)	(0.003)
Kerosene	-0.063***	-1.335***	-0.109***	-0.379***
	(0.024)	(0.031)	(0.024)	(0.026)
Charcoal	-0.378***	-0.209***	-1.473***	-0.599***
	(0.015)	(0.011)	(0.015)	(0.018)
Firewood	0.635***	0.197***	0.379***	-0.667***
	(0.058)	(0.025)	(0.039)	(0.069)

Table A22: Compensated elasticities of demand in urban Kenya

	LPG	Kerosene	Charcoal	Firewood
LPG	-1.146***	0.092***	0.033***	0.021***
	(0.008)	(0.006)	(0.004)	(0.004)
Kerosene	0.423***	-1.418***	0.008	-0.013
	(0.028)	(0.031)	(0.018)	(0.011)
Charcoal	0.121***	0.006	-1.152***	0.025**
	(0.016)	(0.014)	(0.016)	(0.01)
Firewood	0.11***	-0.014	0.035**	-1.131***
	(0.021)	(0.013)	(0.013)	(0.02)

Table A23: Uncompensated elasticities of demand in urban Kenya

	LPG	Kerosene	Charcoal	Firewood
LPG	-1.805***	-0.281***	-0.5***	-0.573***
	(0.01)	(0.009)	(0.009)	(0.01)
Kerosene	0.143***	-1.577***	-0.218***	-0.265***
	(0.03)	(0.036)	(0.025)	(0.023)
Charcoal	-0.424***	-0.302***	-1.593***	-0.467***
	(0.02)	(0.019)	(0.022)	(0.02)
Firewood	0.552***	0.236***	0.392***	-0.732***
	(0.051)	(0.03)	(0.042)	(0.049)

Table A24: Compensated elasticities of demand in rural Myanmar

	Electricity	Charcoal	Firewood
Electricity	-1.081***	0.044**	0.037*
	(0.026)	(0.019)	(0.02)
Charcoal	0.004**	-1.008***	0.004
	(0.002)	(0.004)	(0.004)
Firewood	0.031*	0.033	-1.064***
	(0.017)	(0.034)	(0.038)

Table A25: Uncompensated elasticities of demand in rural Myanmar

	Electricity	Charcoal	Firewood
Electricity	-1.545***	-0.391***	-0.544***
	(0.044)	(0.045)	(0.063)
Charcoal	-0.836***	-1.796***	-1.048***
	(0.016)	(0.016)	(0.02)
Firewood	-0.438***	-0.406***	-1.651***
	(0.13)	(0.13)	(0.158)

Table A26: Compensated elasticities of demand in urban Myanmar

	Electricity	LPG	Charcoal	Firewood
Electricity	-0.9***	0.095***	-0.196***	0.001
	(0.049)	(0.019)	(0.053)	(0.04)
LPG	0.001***	-1.002***	0.002***	-0.001
	(0)	(0.001)	(0.001)	(0.001)
Charcoal	-0.118***	0.212***	-1.141***	0.047
	(0.032)	(0.07)	(0.109)	(0.051)
Firewood	0.001	-0.081	0.06	-0.98***
	(0.031)	(0.059)	(0.065)	(0.063)

Table A27: Uncompensated elasticities of demand in urban Myanmar

	Electricity	LPG	Charcoal	Firewood
Electricity	-1.443***	-0.275***	-0.679***	-0.642***
	(0.075)	(0.032)	(0.048)	(0.059)
LPG	-0.736***	-1.504***	-0.652***	-0.871***
	(0.001)	(0.001)	(0.001)	(0.001)
Charcoal	-0.782***	-0.24***	-1.73***	-0.737***
	(0.07)	(0.085)	(0.102)	(0.087)
Firewood	-0.283**	-0.274***	-0.192*	-1.315***
	(0.13)	(0.102)	(0.106)	(0.164)

A.4 External effects of fossil taxes

In this section, we present detailed calculations for the cost-benefit results from Table 1. First, we present calculations for global climate benefits in Table A.4.1. Next, we present calculations of global climate costs in Table A.4.2. Then, we present calculations for local health benefits in Table A.4.3. Finally, we present calculations for local health costs in Table A.4.4.

Lastly, we also present a sensitivity check of our cost-benefit analyses, where we apply a higher social cost of carbon of US$ 185 per tCO_2 and corresponding social cost of methane of US$ 3,885 per tCH_4, in Table A28.

Table A.4.1. Climate Benefits: Calculations

Country	Region	**1% Price Increase for Fuel *f***	Compensated Price Elasticity of Demand for Electricity	Compensated Price Elasticity of Demand for LPG	Compensated Price Elasticity of Demand for Kerosene	Per capita annual fuel consumption, Electricity (kWh)	Per capita annual fuel consumption, LPG (Kg)	Per capita annual fuel consumption, Kerosene (L)	CO2 emissions intensity, Electricity (Kg CO2 per kWh)	CO2 emissions intensity, LPG (Kg CO2 per Kg)	CO2 emissions intensity, Kerosene (Kg CO2 per L)	**Climate Benefits (USD per thousand persons)**
Cambodia	Rural	Electricity	-1.39	0.10		53	4		0.6	2.8		35
	Urban	Electricity	-1.18	0.06		356	16		0.6	2.8		200
	Rural	LPG	0.25	-1.25		53	4		0.6	2.8		5
	Urban	LPG	0.04	-1.52		356	16		0.6	2.8		48
Ghana	Rural	LPG		-1.04			9			2.8		22
	Urban	LPG		-1.08			86			2.8		208
Honduras	Rural	Electricity	-1.12	0.01		242	94		0.2	2.8		41
	Urban	Electricity	-1.12	-0.01		505	103		0.2	2.8		93
	Rural	LPG	0.06	-1.04		242	94		0.2	2.8		219
	Urban	LPG	-0.03	-1.01		505	103		0.2	2.8		234
India	Rural	LPG		-1.27			25			3.3		83
	Urban	LPG		-1.13			35			3.3		106
Kenya	Rural	Kerosene		0.09	-1.42		27	25		2.8	2.6	69
	Urban	Kerosene		0.01	-1.20		18	9		2.8	2.6	23
	Rural	LPG		-1.15	0.42		27	25		2.8	2.6	47
	Urban	LPG		-1.02	0.16		18	9		2.8	2.6	39
Myanmar	Rural	Electricity	-1.08			291			0.1	2.8		25
	Urban	Electricity	-0.90	0.00		485	67		0.1	2.8		35
	Urban	LPG	0.10	-1.00		485	67		0.1	2.8		146

Note: The proportionate price increase, $\frac{\Delta p_f}{p_f} = 0.01$ and the SCC is US$ 80/tCO2. These calculations are based on eqn. 10 in section 5.4.1 (Climate Benefits):

$$B_f = \left|(e_{f,f} q_f \frac{\Delta p_f}{p_f} c_f SCC\right| + \left|e_{g,f} q_g \frac{\Delta p_f}{p_f} c_g SCC\right|$$

Table A.4.2. Climate Costs: Calculations

Country	Region	**1% Price Increase for Fuel *f***	Compensated Price Elasticity of Demand for Charcoal	Compensated Price Elasticity of Demand for Firewood	Per capita annual fuel consumption, Charcoal (Kg)	Per capita annual fuel consumption, Fuelwood (Kg)	Share of Non-renewable Fuelwood	Climate Costs (CO2 Emissions), USD per '000 persons	Climate Costs (CH4 Emissions), USD per '000 persons	**Total Climate Costs, USD per '000 persons**
Cambodia	Rural	Electricity	0.09	-0.03	34	775	0.38	-3	-0.1	-4
	Urban	Electricity	0.13	0.05	60	61	0.38	17	0.4	17
	Rural	LPG	0.16	0.07	34	775	0.38	36	1	37
	Urban	LPG	0.35	-0.04	60	61	0.38	42	1	43
Ghana	Rural	LPG	0.00	0.78	81	2582	0.28	709	19	728
	Urban	LPG	0.14	0.25	204	42	0.28	45	1	46
Honduras	Rural	Electricity		0.07		120	0.64	7	0.2	7
	Urban	Electricity		0.20		188	0.64	31	1	32
	Rural	LPG		0.27		120	0.64	26	1	26
	Urban	LPG		0.06		188	0.64	9	0.2	9
India	Rural	LPG		0.34		257	0.23	25	1	26
	Urban	LPG		0.19		217	0.23	12	0.3	12
Kenya	Rural	Kerosene	0.01	-0.01	423	463	0.63	4	0.1	4
	Urban	Kerosene	0.04	-0.03	238	1758	0.63	-15	-0.4	-15
	Rural	LPG	0.12	0.11	423	463	0.63	214	6	220
	Urban	LPG	0.05	0.24	238	1758	0.63	374	10	384
Myanmar	Rural	Electricity	0.00	0.03	97	270	0.07	1	0.0	1
	Urban	Electricity	-0.12	0.00	92	65	0.07	-4	-0.1	-4
	Urban	LPG	0.21	-0.08	92	65	0.07	7	0.2	7

Note: Conversion factor from charcoal to fuelwood = 4.24. The CO2 emission intensity (tCO2 per tonne fuelwood) = 1.584 and CH4 emission intensity (tCH4 per kilotonne fuelwood) = 2. The SCC is 80 US$/ton and the SCM is 1,680 US$/ton. These calculations are based on eqns. 11 & 12 in section 5.4.2. (Climate Costs):

$$C_{CO_2} = \sum_{b=\{w,c\}} e_{b,f} s_{nb} q_b \frac{\Delta p_f}{p_f} c_b SCC \qquad C_{CH_4} = \sum_{b=\{w,c\}} e_{b,f} q_b \frac{\Delta p_f}{p_f} m_b SCM$$

Table A.4.3. Health Benefits: Calculations

Country	**1% Price Increase for Fuel**	Share of Coal in Electricity Generation	Per capita annual coal consumption (Kg)	Own-Price Elasticity of Coal Consumption	No. of deaths per tonne of coal consumed at power plants	Value of Statistical Life (USD)	Health Benefits (USD per '000 persons)
Cambodia	Electricity	0.42	0.13	-0.25	0.12	298,381	**28**
Honduras	Electricity	0.05	0.02	-0.25	0.12	516,721	**62**
Myanmar	Electricity	0.10	0.03	-0.25	0.12	188,981	**16**

Note: Deaths per tonne of coal consumed at power plants are determined by the product of (i) number of deaths per tonne of SO2 emissions and (ii) the SO2 emission content of coal (i.e. tonnes of SO2 released per tonne of coal consumed at power plants). Data on deaths per tonne of SO2 emissions are taken to as '20' (Black et al. 2023) and data on the SO2 emissions content of coal are taken as "6" (kg SO2 per tonne coal) (Qian et al. 2020). These calculations are based on equation 13 in section 5.4.3 (Health Benefits):

$$B_c = \frac{e_{c,c}}{s_c} \frac{\Delta p_e}{p_e} q_c D_c VSL$$

Table A.4.4. Health Costs

Country	Region	Average household daily charcoal consumption (Kg)	Average household daily fuelwood consumption (Kg)	PM 2.5 (Initial), μg/m³	**1% Price Increase for Fuel *f***	Compensated Price Elasticity of Demand for Charcoal	Compensated Price Elasticity of Demand for Firewood	Change in PM 2.5 concentration (Final - Initial), μg/m³	PM 2.5 (Final), μg/m³	PAF (%)	Mortality, by region	Excess Mortality, by region	VSL (USD)	**Health Costs (USD per '000 persons)**
Cambodia	Rural	0.34	7.66	458.67	Electricity	0.09	-0.03	-0.11	458.56	-0.02	95,144	-22	298,000	-461
	Urban	0.66	0.76	63.63	Electricity	0.13	0.05	0.05	63.68	0.07	17,439	12	298,000	1,404
	Rural	0.34	7.66	458.67	LPG	0.16	0.07	0.32	458.98	0.07	95,144	66	298,000	1,371
	Urban	0.66	0.76	63.63	LPG	0.35	-0.04	0.05	63.68	0.08	17,439	14	298,000	1,593
Ghana	Rural	0.70	32.04	1,897.76	LPG	0.00	0.78	14.68	1,912.44	0.77	97,275	747	356,000	18,591
	Urban	1.83	0.58	87.77	LPG	0.14	0.25	0.16	87.93	0.18	123,906	224	356,000	4,371
Honduras	Rural		1.17	68.37	Electricity		0.07	0.05	68.42	0.07	28,664	21	517,000	2,197
	Urban		2.10	123.15	Electricity		0.20	0.25	123.40	0.20	31,631	64	517,000	6,121
	Rural		1.17	68.37	LPG		0.27	0.18	68.55	0.27	28,664	76	517,000	8,043
	Urban		2.10	123.15	LPG		0.06	0.07	123.22	0.06	31,631	19	517,000	1,805
India	Rural		2.79	163.27	LPG		0.34	0.56	163.83	0.34	6,751,118	23,184	396,000	9,771
	Urban		2.16	126.70	LPG		0.19	0.24	126.94	0.19	3,410,107	6,365	396,000	5,311
Kenya	Rural	3.46	5.40	417.87	Kerosene	0.01	-0.01	-0.04	417.83	-0.01	204,784	-19	310,000	-165
	Urban	1.96	20.05	1,232.00	Kerosene	0.04	-0.03	-0.34	1,231.66	-0.03	102,977	-29	310,000	-496
	Rural	3.46	5.40	417.87	LPG	0.12	0.11	0.47	418.34	0.11	204,784	231	310,000	2,020
	Urban	1.96	20.05	1,232.00	LPG	0.05	0.24	2.83	1,234.83	0.23	102,977	236	310,000	4,108
Myanmar	Rural	0.98	2.91	199.14	Electricity	0.00	0.03	0.05	199.20	0.03	331,989	91	189,000	434
	Urban	1.08	0.69	71.87	Electricity	-0.12	0.00	-0.04	71.83	-0.05	117,922	-61	189,000	-822
	Urban	1.08	0.69	71.87	LPG	0.21	-0.08	0.03	71.90	0.05	117,922	57	189,000	764

Note: These calculations are based on formulae in section 5.4.4 (Health Costs):

$$PAF_f = \left(1 - \frac{RR_{initial}}{RR_{final,f}}\right) \times 100 \qquad \Delta M_{r,f} = \left(\frac{PAF_f}{100}\right) \times M_r \qquad C_H = VSL \times \left(\frac{\Delta M_{r,f}}{1,000}\right)$$

Table A28: Costs and Benefits of 1% Price Increases for Fossil-based Fuels: Sensitivity Check

Country	Fuel	Climate Benefits (Per '000 Persons) (US$)	Climate Costs (Per '000 Persons) (US$)	Health Benefits (Per '000 Persons) (US$)	Health Costs (Per '000 Persons) (US$)	Δ (Costs - Benefits) (Per '000 Persons) (US$)	Cost-Benefit Ratio
Cambodia	Electricity	139	-1	28	-172	-340	-1
	LPG	26	88	-	1,406	1,467	57
Ghana	LPG	292	800	-	10,625	11,132	39
Honduras	Electricity	159	46	62	4,256	4,081	19
	LPG	524	40	-	4,770	4,287	9
India	LPG	210	49	-	8,274	8,113	40
Kenya	Kerosene	124	-5	-	-276	-405	-2
	LPG	102	636	-	2,719	3,253	33
Myanmar	Electricity	64	-1	16	105	24	1
	LPG	89	4	-	200	116	2

Note: Benefits and costs are calculated for 1% price increases for fossil-based fuels. The carbon price applied here is US$ 185 per t$CO2$ [15, 16], and the price on methane emissions applied is US$ 3,885 per t$CH4$ [26].

A sensitivity check of the cost-benefit calculations, applying a higher social cost of carbon of US$ 185 per tCO_2 and social cost of methane of US$ 3,885 per tCH_4, is presented in Table A28. The results show that costs of small domestic carbon prices outweigh the benefits in four out of six countries. These net costs range from US$ 24 - 11,132 per thousand persons of the countries' populations. In two cases (electricity taxation in Cambodia and kerosene taxation in Kenya), small carbon prices generate net benefits in the range of US$ 340 - 405 per thousand persons of the countries' populations.

Recent studies present a wide range of estimates of the social cost of carbon (SCC). While the mean estimate across studies corresponds to US$ 185 per tCO_2, estimates range from US$ 32 to US$ 874 per tCO_2 (5%-95% confidence interval of SCC estimates) [16]. We briefly discuss how our results would modify when applying an SCC value at the upper end of the range of estimates. When applying a significantly higher SCC (SCM) of US$ 874 (US$ 18,354), we still find that a carbon price produces net costs in three out of six countries. In three cases (electricity taxation in Cambodia, kerosene taxation in Kenya, and electricity and LPG taxation in Myanmar), we now find net benefits resulting from carbon prices, with global climate and local health benefits exceeding the global climate and local health costs. In these three cases, net benefits range from US$ 198 - 887 per thousand persons of the countries' populations. In all other cases, we continue to find that net costs are produced by carbon prices, ranging from US$ 1,698 - 13,023 per thousand persons of the countries' populations.[1]

Our results suggest that local health costs remain salient in most lower middle-income countries, even when applying very high values to the social cost of carbon. In a few countries, the benefits from climate change mitigation begin to outweigh the local health costs of increased pollution if damages from climate change are valued at sufficiently high levels.

[1] These detailed calculations are available upon request.

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