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Distributional Effects of Climate Policy & the Interaction with Energy Access Policies

A report prepared by

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0 Contents

1 OBJECTIVES & BACKGROUND

Three billion people globally burn solid fuels such as firewood, charcoal, coal, dung, and crop residues in open fires and traditional stoves for cooking and heating [1]. Household air pollution (HAP) from the combustion of these fuels prematurely kills 4.3 million each year globally. In South Asia alone, over 1.7 million deaths can be attributed to solid fuel use, exceeding the burden of disease from any other energy-related or environmental risk factor [1-4]. Solid fuel use also perpetuates income and gender inequality by forcing users, mostly poor women and children, to spend long hours collecting fuels and to suffer from adverse health effects.

Numerous intervention efforts have focused on distributing more efficient and cleaner burning biomass stoves, but these programs have had relatively little demonstrable impact on health outcomes [5]. In India, the nation with the largest population of solid fuel users globally [2], government interventions have also sought to make petroleum-based fuels such as kerosene and LPG more affordable through subsidy. These subsidies are estimated to have cost over $6 billion per year [8, 9] and yet over 72% of the population continues to rely on solid fuels today [2, 7]. In a recent policy shift, the government has introduced a direct benefits transfer scheme for households consuming LPG in an effort to prevent diversions, and reduce the fiscal burden of subsidies [9]. Poor progress in expanding access to clean cooking globally has also prompted efforts such as the United Nations Secretary-General's Sustainable Energy for All (SE4All) initiative and the explicit inclusion universal access to modern energy services by 2030 as one of the global Sustainable Development Goals (SDG) just approved in September 2015 [6, 10].

Previous research has explored the impact on modern fuel use of both climate policy [13-16] and cooking fuel subsidy [11, 17] at an aggregate scale. The literature suggests that greenhouse gas (GHG) emissions reductions efforts in Asia [13, 14] and Africa [16] would increase the cost of kerosene and LPG and thereby hamper the spread of these cooking fuels. However gaps remain in our understanding of 1) the distributional impacts of climate mitigation policies, specifically on the energy poor; and 2) how social support or energy access policies can counteract or shield the poor from potential price rises. The Intergovernmental Panel on Climate Change (IPCC) states in its 5th Assessment Report (AR5) that the impact of climate change mitigation policy on access to modern energy services is understood with only low confidence and that the policy mechanisms needed to counteract these impacts are understood with only medium confidence [12]. Here we aim to provide new insights on both these issues.

In the study, we explore the impact of increasingly stringent climate policies and a range of compensatory fuel and stove price support (access policies) on solid fuel reliance in four urban and rural South Asian socio-economic groups using the MESSAGE-Access household fuel-choice model [19-20][see Methods]. For each combination of climate and access policy, we quantify the cost of access policy and the associated health outcomes.

2 SCENARIO DESCRIPTION

We carry out the analysis by employing the MESSAGE-Access household fuel-choice model (see next section and Appendix). We focus our analysis on the MESSAGE South Asia region [23] as it has a greater number of solid-fuel users than any other region [2]. Our model differentiates the South Asian population into 4 distinct demographic groups split on 1) rural-urban location to account for differences in the availability of cooking fuels and 2) daily per-capita expenditure in purchasing power parity dollars to account for differences in the affordability of fuels. These groups include: rural households spending <$2/capita/day (R1), rural household spending >$2/capita/day (R2), urban households spending <$5/capita/day (U1), and urban households spending >$5/capita/day (U2). The difference in income thresholds reflects the fact that average expenditure of urban households in India has historically been roughly double that of rural households and continues to grow [24].

The Global Energy Assessment's Mix scenario (GEA-M) [23] serves as a baseline scenario for this analysis, which we refer to as the no new policy scenario (NNP). We then explore a range of carbon mitigation scenarios that are consistent with increasing probability of achieving a 2°C world [26, 27]. We use an economy-wide carbon price as a proxy for a hypothetical increase in energy prices that may actually result from any number of policy mechanisms but all assumed to target fossil fuels among other sectors. These are defined as global carbon price scenarios of $10 (C10), $20 (C20), $30 (C30), and $40 (C40) per ton CO_2 equivalent in the year 2020 and applied through the end of the century. Our most stringent scenario has a 66% chance of meeting the UNFCCC target to limit global temperature increase to 2°C by 2100 [27-31]. These taxes are applied uniformly throughout the economy, meaning there is no shielding of specific energy carriers or sectors from policy.

For each carbon price scenario, we also test a range of access policies and evaluate for clean cooking uptake and policy cost. Here we model a range of price support policies on fuel (0%-75%) and stoves (0%-100%), which may in practice be implemented through a range of policy instruments. We present only policies supporting LPG as we found this to be the cheapest Tier 1 fuel-stove option, on average, across the range of scenarios tested in this analysis. We assume LPG and LPG stoves become universally available by 2020. We assume no administrative capacity to target specific population subsets on the basis of household income. This is consistent with existing trends in the region. Even the new direct benefit transfer scheme for LPG consumers in India does not specifically target any household group [32].

3 METHODS & MODELS

We developed a new version of the MESSAGE-Access model applied to the South Asia MESSAGE region for use in this study. Rather than represent household fuel-choice decisions within the broader societal optimization function of MESSAGE as in previous versions [18-20, 25], here our household fuel-choice model ("Access") is exogenous to MESSAGE. These two models are run iteratively: the Access model reads in fuel prices from MESSAGE and returns aggregate residential demand for five cooking fuels over the period from 2005 to 2100. MESSAGE then optimizes the least-cost energy supply pathway to meet these demands and returns new prices. Iteration continues until results converge to within 2% of the results from the previous iteration.

We present a baseline "no-new-policies" (NNP) scenario using the input assumptions described in the Global Energy Assessment "Mix" scenario (GEA-M) [23]. In addition, we test four climate change mitigation scenarios, which differ from the NNP only in that they include carbon prices. Carbon prices start in the year 2020 at values (in 2010 USD) of $10, $20, $30, and $40 per ton CO_2 and are scaled up through 2110 such that they discount to the same value in each period using a discount rate of 5%. Carbon prices were included in the fuel costs passed to the Access model in all scenarios.

The Access model splits the South Asian population into four demographic groups separated on rural/urban location and daily per-capita expenditure. Expenditure divisions are defined in 2005 purchasing power parity USD of less than and greater than $2 per day and $5 per day in rural and urban areas respectively. Average household fuel preferences are determined for each expenditure group for a base year of 2005 using India's National Sample Survey Organization (NSSO) Household Consumer Expenditure Survey [7]. Population, expenditure, and electricity access level is estimated for each group in future periods based on down-scaling projections of future GDP and population by rural and urban South Asian sub-populations from the GEA-M scenario [23].

We represent eight fuel-stove options to meet household cooking energy demand: liquefied petroleum gas (LPG), piped gas, electric induction, kerosene, traditional biomass stoves, and improved biomass stoves with either natural or forced draft. Fuel-stove options are grouped into two "fuel tiers" with clean and easy-to-use fuels in Tier 1 (LPG, piped gas, and electricity), and dirtier or more time-consuming fuels in Tier 2 (biomass and kerosene). We assume that consumers prefer to use Tier 1 fuels as their primary cooking source, but will shift to Tier 2 when the cost of cooking with Tier 1 fuels is too high. We estimate the total cost to cook with each fuel-stove combination in terms of service unit delivered (gigajoules of useful energy). Stove costs are annualized using household discount rates calculated as a function of expenditure (see Appendix).

Demand for Tier 1 fuel-stove options is estimated using an expenditure-group specific demand curve derived from a regression of the household expenditure on a given fuel-stove system vs. the energy demand met with that fuel, as reported in the survey, across all households in the expenditure group. Due to the very small number of reported electricity and piped gas users in the household survey, we lacked adequate data to derive demand curves for these fuel-stove options. We assumed that the service provided by these fuel-stove options is equivalent to that provided by LPG and thus used the LPG demand curve for all three fuel-stove options. Households are assumed to choose the least-cost Tier 1 option in each period.

Cooking energy demand unmet by clean fuels is met by the least-cost combination of Tier 2 options. Households in rural areas are assumed to have the ability to collect biomass free of cost; meaning traditional stoves using biomass are the cheapest option. In urban areas, we assume households are unable to collect biomass, meaning kerosene and purchased biomass fuel-stove options compete on cost. Each expenditure group's average energy demand is adjusted over time as a function of expenditure and household size using a regression from the household survey data. Similarly, we adjust demand curves for future periods based on a regression of total expenditure on cooking fuels and stoves as a function of total household expenditure.

Price support policies were implemented as percent reductions in each period off fuel and stove prices. Fuel price support policy costs were calculated as the quantity of fuel used multiplied by the fuel price and the percentage of fuel subsidized for each period. Stove price support policy costs were calculated as the supported cost of the stove annualized with a discount rate of 5% and multiplied by the number of households using the stove in each period. Health impacts were assessed for each scenario using methods consistent with IHME (see Appendix and ref 38). Global mean temperature outcomes were computed with the reduced complexity carbon cycle and climate model MAGICC in a probabilistic set-up, which is consistent with the climate sensitivity assessment of the IPCC's Fifth Assessment Report [29].

4 Carbon Policy Impacts on Emissions & Solid Fuel Use

Without any change in policy relative to the present (NNP), South Asian GHG emissions rise rapidly throughout our model timeframe roughly doubling every 20 years (Fig. 1a). Meanwhile, the same GDP growth and urbanization that drives these increasing emissions also enables almost 1 billion people (63% of the population) to transition to clean cooking fuels over the period from 2010 to 2050 (Fig. 1b). Although this rapid transition away from solid fuels is quite promising, significant additional measures are required to achieve the SE4All goal of universal clean cooking in 2030. We estimate that 727 million South Asians (35% of the population) continue to rely on solid fuels in the NNP scenario in 2030, leading to about 1.35 million premature deaths per year (see Appendix).

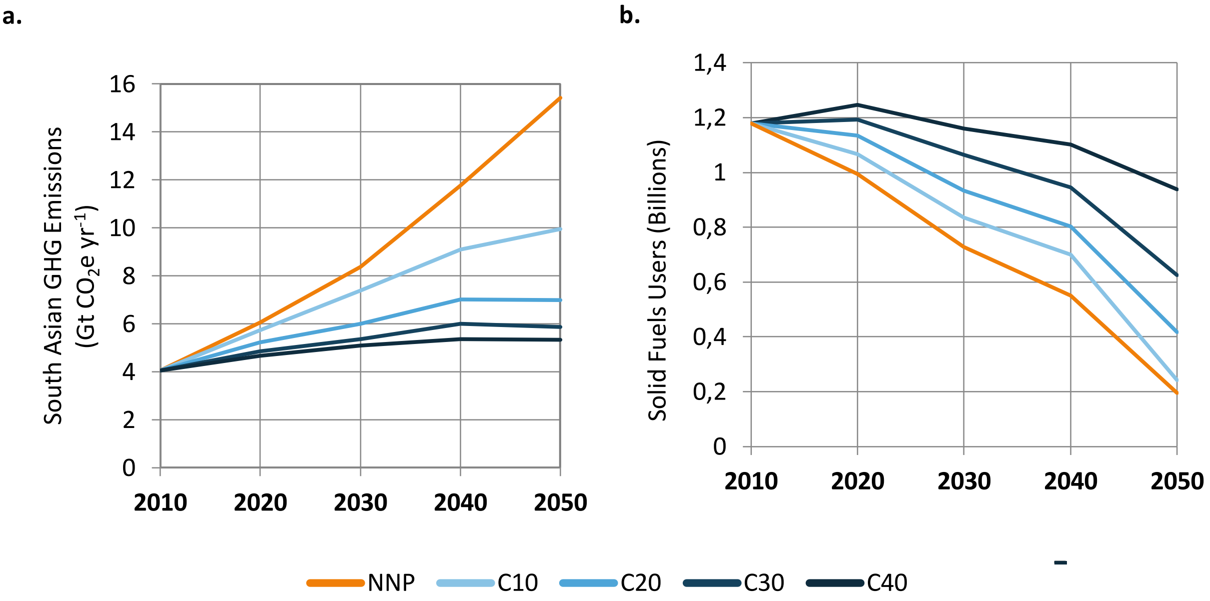

Figure 1. Emissions and solid fuel use outcomes for climate mitigation policy scenarios. a. GHG emissions from the MESSAGE South Asia region, and **b.** solid fuel users in billions from 2010-2050, for a baseline (NNP) and four increasingly stringent climate mitigation policy scenarios.

The implementation of an economy-wide carbon price without any compensatory access policy mechanisms significantly slows both regional GHG emission growth and the transition to clean cooking fuels. In the C30 and C40 scenarios, South Asian GHG emissions remain within 148% and 132% of 2010 levels respectively, peaking in 2040 in both cases. For each $10 of carbon price, however, an additional 110 million people are unable to afford clean cooking fuel in 2030 relative to the NNP scenario. A carbon price of $30/T CO2eq increases the average perceived cost to cook with LPG in 2030 by 28%, causing 336 million additional people (14% of the population) to be unable to afford clean fuels relative to the NNP scenario. This results in over 320,000 additional premature deaths attributable to the increased dependence on solid fuels each year. This is equivalent to forfeiting the projected transition achieved as a result of GDP growth in the NNP scenario over the period from 2015 to 2030. The C40 scenario sets back clean cooking even further resulting in what amounts to almost no change in the total number of households reliant on solid fuels from 2010 to 2030 and almost quadrupling solid fuel users in 2050 relative to the NNP.

5 ACCESS POLICY COST-EFFECTIVENESS ACROSS CLIMATE MITIGATION POLICY SCENARIOS

In principle, households can be shielded from high energy prices using the same types of instruments that the governments would in any case have in place to accelerate clean cooking uptake. However, our analysis reveals that the choice of access policy instrument has a significant impact on the cost of expanding clean cooking uptake (Fig. 2a & 2b). Policies that reduce stove costs shift more households to clean fuels per dollar invested than policies to reduce fuel costs. In the C30 scenario, a 100% stove rebate increases the population share able to afford cooking with clean fuels in 2030 from 49% to 72% at a cost of $3.48 billion per year. In contrast, investing the same value in fuel price support alone improves total clean cooking uptake to only 56%. This is because although stoves represent only a small share of the actual cost of cooking with clean fuels, they represent a much larger barrier to clean cooking for many poor households without adequate liquidity to make the large one-time purchase associated with most clean stoves. Current budget estimates from the Government of India earmark $3.5 billion for LPG subsidies for its new Direct Benefit Transfer (DBT) scheme for households in 2015-16 [35]. By our estimates, this level of annual subsidy will enable only 80% of the population to achieve clean cooking by 2030.

We identify the lowest tested policy cost needed to extend clean cooking to any given share of the population for each carbon price scenario (Fig. 2a marked lines). Comparing the difference between the NNP and C30 "least-cost" policy lines, we can see the level of fuel price support needed to achieve a given clean cooking target increases with stringency of the mitigation policy. In the NNP scenario, only 5% fuel price support is needed in combination with 100% stove rebate to enable over 90% of the South Asian population to afford clean fuels in 2030 at a cost of $6.34 billion per year. In the C30 scenario, fuel price support must be increased to 25% to achieve the same level of access, increasing the total policy cost by $11.1 billion per year. Achieving 100% clean cooking in the C30 scenario in 2030 requires roughly the same additional policy cost relative to the NNP scenario.

However, we find that the impact of stringent climate policy on clean cooking uptake is well within the uncertainty of what may be achieved otherwise from access policies. For example, to achieve 90% clean cooking uptake by 2030 in the absence of climate policy, access policy costs can range from $6.34 to $30.01 billion USD per year depending on the chosen access policy mechanism. Meanwhile, the increase in policy cost necessary to maintain the same access uptake with a $40 carbon price is $15.5 billion per year.

An equity-based international climate policy regime could provide a potential means to bridge the access finance gap critical to achieving a universal clean cooking goal by 2030, even under stringent mitigation (for instance, in the C30 scenario, in which the estimated cost of achieving universal access is estimated at $42 billion per year). That is, if mitigation policies are part of an international climate policy regime that differentiates mitigation efforts among countries, India may be a net recipient of monetary flows from carbon trading. For instance, in a per capita emissions allocation regime, trade flows to South Asian countries could range from -$34 billion to $166 billion (the range representing different model results from Ref. 36, with most models reporting large positive flows with a median value of $71 billion to South Asia) in 2030 from the purchase/sale of allowances in an international carbon market [36].

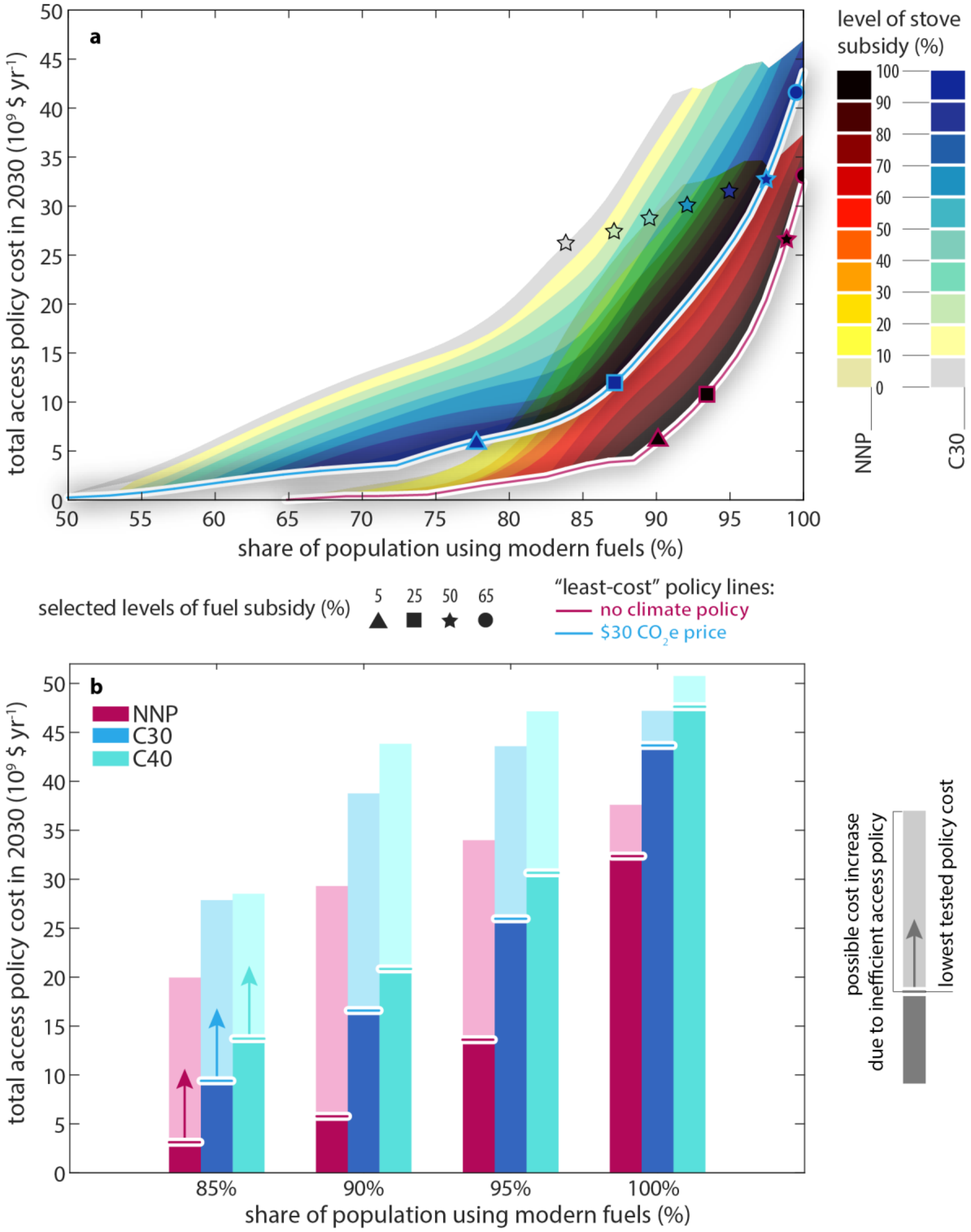

Figure 2. Access policy cost-effectiveness under a baseline and climate mitigation scenarios. a, Fuel and stove price support combinations for the no climate policy (NNP) and $30 CO2e price (C30) in 2030. An additional representation of fuel price support level can be viewed in Appendix Figure 2.1. "Least-cost" policy lines are highlighted at the lower end of each of the areas; **b**, Total access policy costs in 2030 for the achievement of an 85, 90, 95, and 100% share of population having access modern fuels, respectively. Dark shaded bars show the lowest policy costs for the respective level of modern fuel access (corresponding to the level indicated by the "least-cost" policy lines in panel a). Lighter shaded areas show the possible cost increase due to inefficient access policy (illustrated by the arrows). Results are shown for the NPP, C30 and C40 scenarios.

6 Distributional Impacts of Policies

Low-income urban households and moderate-income rural households are likely to be the most affected by carbon price (Fig. 3) and access policies (Fig. 4). The population share reliant on solid fuels in 2050 rises by 19% in U1 and 30% in R2 in the C30 scenario from the NNP baseline, compared to just 2% and 10% in R1 and U2 respectively.

In rural areas, most households have the ability to collect biomass (firewood, dung, or crop residues) at no monetary cost. Rural households at very low income levels (R1) cannot afford to cook with clean fuels even in the absence of climate policy (NNP), so the addition of a carbon price has little impact on the number of solid fuel users in this group. This group therefore requires substantial fuel and stove support to reach even 50% clean cooking in 2030 regardless of the stringency of the carbon mitigation scenario.

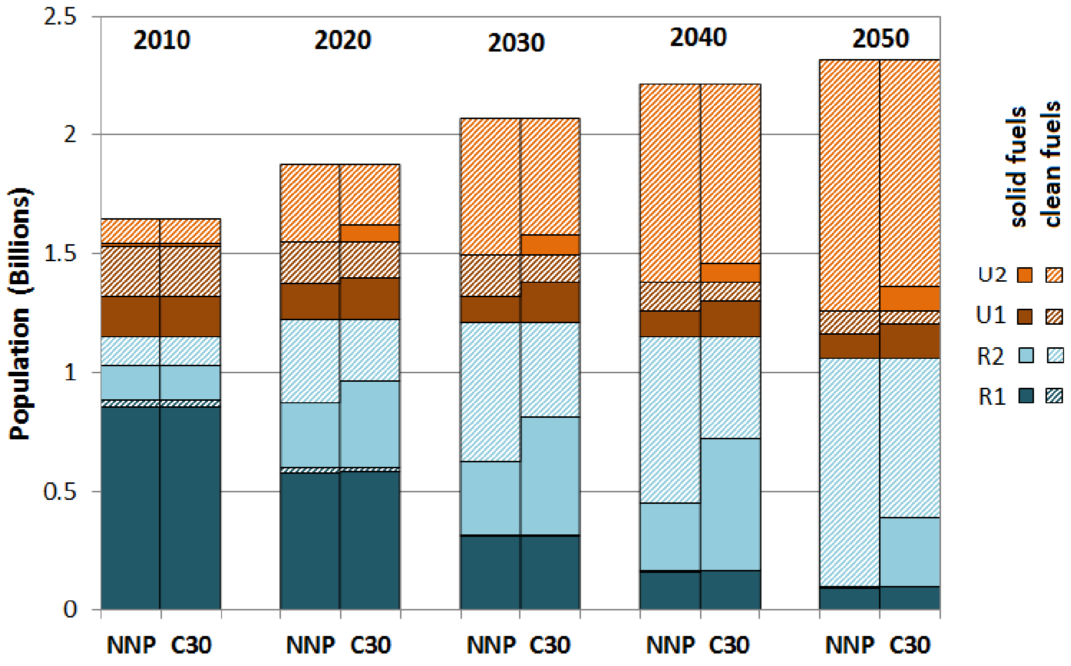

Figure 3. Solid and clean cooking in four population groups over time for the NNP and C30 scenarios.

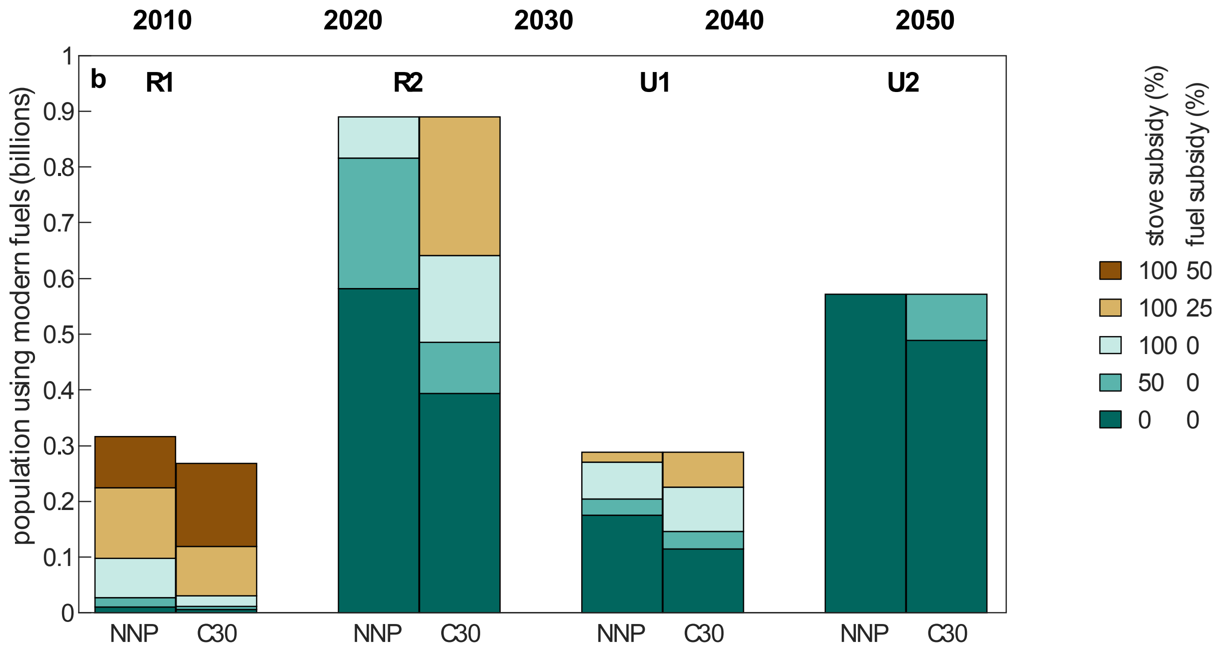

Figure 4. Impacts of selected stove and fuel price support polices on four expenditure groups in 2030 in the NNP and C30 scenarios.

Wealthier rural households (R2) become increasingly able to afford clean fuels over the course of the model timeline in the NNP scenario and achieve 0% solid fuel use by 2050. However, the increase in fuel price modeled in the C30 scenario prompts a larger share of households in R2 to remain reliant on solid fuels than in any other group (15-30% from 2020 to 2050). This can be explained by the ready availability of cheap or even free solid fuel substitutes to clean fuel for this group. Stove cost reductions are sufficient to enable all of R2 to use clean fuels in 2030 in the NNP, but additional fuel price support is needed to achieve the same level of energy access for this group in the C30 scenario.

Households in urban areas are frequently unable to collect solid fuels from their environment and must instead purchase the solid fuels they use. Some urban households also do not have access even to purchased wood or are faced with wood prices that exceed the cost of subsidized kerosene [37]. For this reason, many poor urban households (U1) rely on kerosene, rather than biomass, as a fuel of last resort. This explains why, even at an average per person expenditure of $1.83/day in 2050, only 50% of households in U1 use solid fuels for cooking.

Under carbon mitigation, however, the cost of petroleum-based fuels such as kerosene and LPG increase to the point at which they are no longer affordable for many households in this group or to where they exceed the cost of purchased biomass. As a result, 19% more households in U1 rely on solid fuels for cooking in the C30 scenario in 2050 than in the NNP scenario. Similar to the R2 expenditure group, U1 households need only stove support to afford 100% clean cooking in 2030 in the NNP scenario, but require additional fuel support to compensate for the higher fuel prices under carbon mitigation.

Urban households spending over $5/day per person are able to afford to meet all cooking energy needs with clean fuels starting in 2020 in the NNP scenario, but in the C30 scenario roughly 10% of this group continues to cook with solid fuels through 2050. This group therefore requires no cooking cost support to achieve 100% clean cooking in 2030 in the NNP scenario and requires only a partial (50%) stove price support in the C30 scenario.

7 DISCUSSION & IMPLICATIONS

This analysis makes the novel contribution of systematically modeling a range of access policy mechanisms across increasingly stringent climate mitigation scenarios and differentiating impacts across multiple socioeconomic groups. Even in the absence of climate policy, we find that significant intervention efforts will be needed beyond the policies in place today to achieve the SE4All target of universal clean cooking by 2030. Our results show that economy-wide carbon prices would intensify this need, but that the cost of successful intervention varies more with the choice of access policy mechanism than with the stringency of the carbon price. In other words, the mechanism chosen to implement access policy will have a larger impact on the number of households reliant on solid fuels than will climate policy. The impact of climate policy on access to clean cooking fuels is therefore not a justification to forestall climate policy implementation, but rather an additional incentive to hone the institutions in place to more efficiently help the poor.

We find that a well-designed climate policy could even help mobilize additional resources to bridge the access finance gap. Policy costs for achieving a universal clean cooking goal by 2030 even under stringent climate mitigation could be well within the range of financial transfers that may result from efforts-sharing international climate regimes. Clean cooking may be a good policy option to direct such transfers given its clear development benefits.

There are some caveats to our analysis. While we account for fuel price induced macroeconomic feedback effects, our model does not capture other general equilibrium feedbacks via labor or productivity changes, or the effect of non-ideal institutions. We assume idealized institutions in this analysis for which there is neither wasted investment nor leakage of fuel and stove price support to other economic sectors. In reality, both of these factors would necessitate additional measures to be in place to ensure access policies are effective.

On the other hand, real-world policy makers also have a number of policy tools at their disposal to reduce access policy costs relative to the estimates in this analysis, such as through the use of microfinance to accomplish fuel and stove price support rather than through subsidy. Furthermore, our analysis illustrates that the need for intervention varies widely among different population groups. Consequently, efforts to target access policy to more vulnerable population groups could significantly increase policy efficiency.

Finally, climate policy could be implemented so as to better shield the poor from the burden of GHG emission reduction or even to finance access policy. Revenues generated from carbon pricing could be recycled to help fund access policies. For example, the additional cost needed to achieve universal access to clean cooking with a $30 carbon price relative to no carbon price would be less than 5% of the revenue generated by such a price.

By systematically modelling a range of access policy mechanisms across increasingly stringent climate mitigation scenarios, our analysis differentiates the impacts of climate and access policies across multiple population sub-groups, and offers insights on achieving an ambitious clean cooking target with stringent climate mitigation.

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9 Methods Appendix

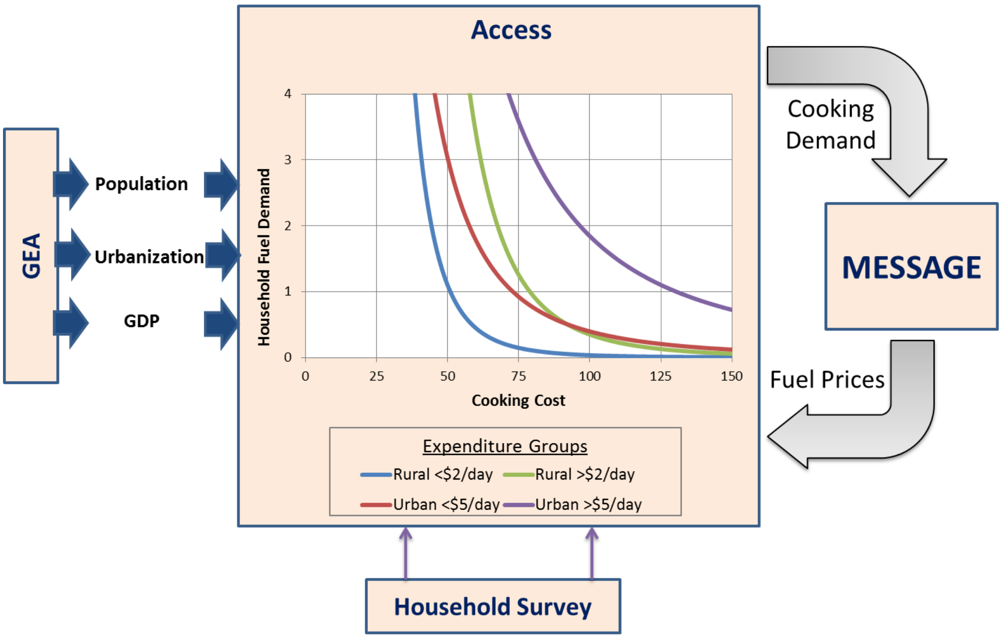
9.1 MESSAGE-Access Model Overview

"MESSAGE-Access" describes the linkage of two separable models: a global energy system model: MESSAGE and (2) a residential fuel and technology choice model: Access.

MESSAGE (Model for Energy Supply Strategy Alternatives and General Environmental Impact)[1,2] is a bottom-up least-cost optimization energy supply model that is used by numerous international research bodies including the International Panel on Climate Change (IPCC) and the World Energy Council (WEC). MESSAGE represents energy flows from resource extraction to end-use consumption. Demands are exogenously defined for 11 world regions across multiple sectors (residential, industrial, commercial, and transportation) and demand types (thermal, lighting, kilometers traveled, etc.). Demand levels respond to changes in price through iteration with the macroeconomic model MACRO[3]. For this study, we use the model version and associated input assumptions defined in the Global Energy Assessment's "Mix" scenario (GEA-M)[4]. MESSAGE is calibrated to historical data in 5 year periods from 1990-2010, then optimizes freely over the period from 2020 to 2100 in decadal time steps.

The Access model reads in prices for five fuels from MESSAGE over the period from 2005 to 2100 and determines demand for each fuel in multiple heterogeneous population sub-groups. In this study, Access is implemented only for the MESSAGE South Asia region and represents only demand for cooking fuels. The Access model requires data inputs in three categories: 1) household characteristics and fuel preferences for each population sub-group calculated from nationally representative household surveys, 2) regional projections of population, GDP, urbanization, and electrification source and 3) cooking technology attribute data. When used in conjunction with MESSAGE, the two models iterate to account for the impact of changing household energy demands on fuel prices. MESSAGE-Access iterates until the output of the Access model from a given run is within 2% of its output from the previous run. This process is visualized in Supplementary Figure A1.

Figure A1. Diagram of the MESSAGE-Access model



9.2 HOUSEHOLD SURVEY DATA INPUTS

The Access model is customized for the region it represents using data from nationally representative household surveys. India's population today comprises over 75% of the population of the South Asia region represented in MESSAGE. Our projections indicate it will make up roughly 70% of the South Asian population in 2050. It is therefore assumed that a nationally representative household survey for India can be scaled up to accurately represent household preferences across the region. We use India's National Sample Survey Organization Household Consumer Expenditure Survey (NSSO 2007) as this is the largest survey to report data on both household fuel expenditure and quantity purchased[5]. The surveys are conducted annually. However, a larger nationally representative round is conducted every five years. The 2004/05 survey year was chosen for this analysis because of non-availability of a full data set from the subsequent large survey round for 2009/10, on account of that being a draught year in India. The 2004/05 survey covers a sample of 79,298 rural and 45,346 urban households. Block 6 of the survey on fuel and light contains information on household expenditures and quantities consumed of different fuels and electricity for a reference period of the last 30 days. Imputed values for expenditures on non-commercial biomass fuels (firewood and dung) are also provided based on self-reported consumption and locally available market price estimates. The data file pertaining to Block 6 of the survey for the 2004/05 round has 124,222 household observations. For 422 of the sampled households, data on fuel and light expenditures and consumption are missing. In addition, for another 511 observations, data on total household expenditures (used as a proxy for income) and expenditures on cooking fuels is missing. We perform standard data cleaning procedures to exclude missing values and extreme values after which we were left with 118,349 household observations with complete data on household cooking expenditures and consumption.

9.3 POPULATION GROUPING

We divide the population into four heterogeneous groups to account for differences in the availability and affordability of fuel-stove combinations. To represent differences in fuel-stove *availability*, we split the population into rural and urban sectors using reported household sector from the survey. Rural and urban sectors were each divided into 2 groups based on total household expenditure to represent differences in the *affordability* of fuel-stove combinations. Household expenditure divisions were chosen to represent significant poverty benchmarks but also to maintain approximately even population between groups in the start year of the model. Due to differences in mean wealth between the two sectors, expenditure divisions differ between rural and urban sectors [6]. Expenditure group definitions can be seen in Table A1.

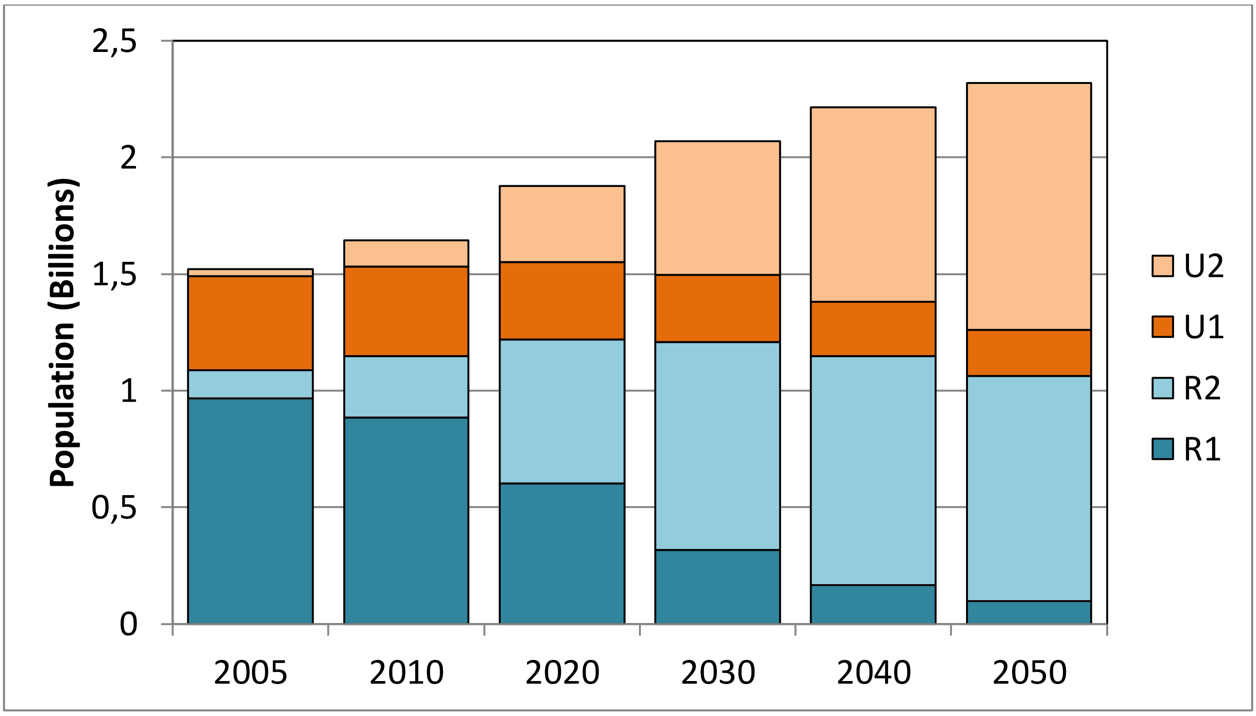
Table A1. Population group expenditure levels in 2005 purchasing power parity (PPP) Dollar per capita per day

Label	Expenditure ($/cap-day)
R1	< 2
R2	> 2
U1	< 5
U2	> 5

9.4 Population and Income Projections

Population, GDP, and urbanization projections for the South Asia region are taken from the Global Energy Assessment's "Mix" scenario ("GEA-M")[4]. We use methods developed for the GEA to downscale the aggregate rural and urban population and GDP projections to the four population subgroups, as described in Pachauri et al (2013)[7]. The method assumes that the rate of change of GDP is proportional to that of total household expenditure or income. With GDP growth over time, populations shift from lower income groups to higher income groups within the rural and urban sector, respectively. The GDP per capita of only the highest income groups is assumed to change to reflect the overall economic growth patterns of the respective sectors. The Gini coefficients are also kept constant at the base year level. Future work could consider exploring alternative future growth rates and distributions of income, but this is not explored in this analysis. Figure A2 illustrates population dynamics and Supplementary Table **A2** presents the projections of average income per capita per day for the four different population subgroups till 2050.

Figure A2. Population projections by expenditure group from 2005 to 2050.



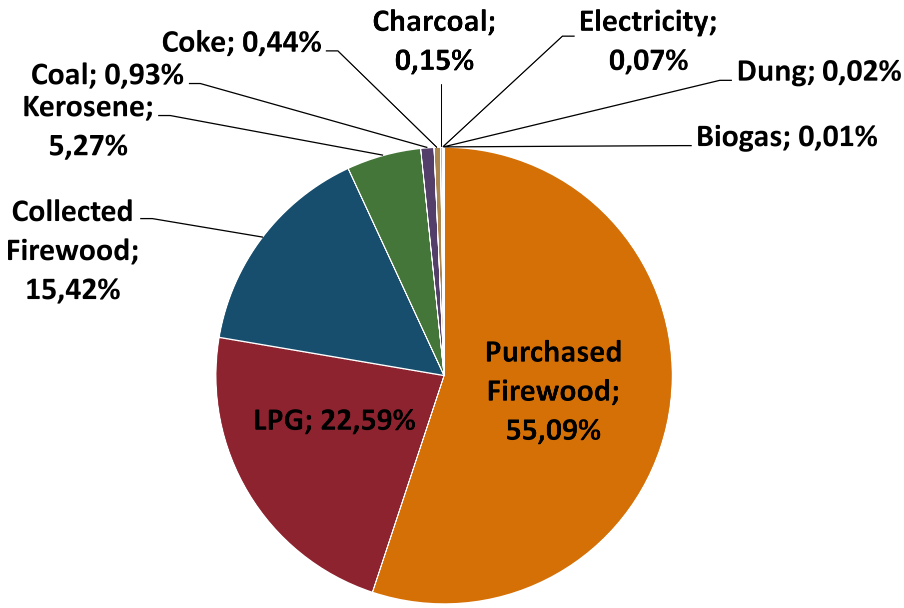
Supplementary Table A2. Income projections by expenditure group in $PPP/cap-day.

	2005	2010	2020	2030	2040	2050
R1	1.05	1.09	1.15	1.13	1.13	1.12
R2	3.32	3.87	4.85	6.99	11.34	17.88
U1	1.95	1.90	1.80	1.82	1.83	1.84
U2	8.37	7.08	8.20	11.73	17.82	26.12

9.5 Modeled Cooking Fuels

The household survey reports 9 fuel types used for cooking in 2005: biogas, charcoal, coal, coke, dung, electricity, firewood, kerosene, and liquefied petroleum gas (LPG). Figure A3 illustrates the relative shares in the household survey of each fuel in meeting national cooking energy demand.

Figure A3. Mean share of useful cooking energy in India [5]



Charcoal, coke, coal, and dung combine to just 1.5% of all demand in the survey year, making distinctions between these fuels insignificant. We therefore group these fuels together with firewood and represent them as one aggregate solid fuel category for our analysis. Biogas ("gobar gas" in the survey) refers to gas sourced from small-scale manure digesters that can supply single families or small communities. Although these digesters are subsidized through the Government of India's National Biogas and Manure Management Programme (NBMMP), gobar gas is unlikely to be scalable to a significant share of the South Asian population [8,9]. In contrast, electricity has a far greater potential to supply clean cooking energy to large segments of the population in the future as it does in much of the developed world. We therefore choose to exclude small-scale biogas but to include electricity for this analysis. Finally, we include piped gas (PNG) in spite of its absence from the survey because of its growing share of the cooking market in South Asia [10]. This leaves a total of 5 modeled fuel options: electricity, kerosene, LPG, PNG, and solid fuels.

9.6 Modeled Cooking Stoves

No information is provided in the survey on what type of stove is used with these fuels. We include seven fuel-stove options for household cooking in the MESSAGE-Access model. The model requires inputs for three stove attributes: price, efficiency, and lifetime. We describe each stove and list stove price (in 2010 USD) and attribute assumptions in Table A3.

1. **Traditional Stoves:** Cooking in its simplest form uses an open biomass fire as a heat source. Pots and pans can be positioned over the fire by balancing them on three stones or cinderblocks placed around the fire in a triangular formation. In South Asia, traditional cooking is also performed on a chulha – a U-shaped mud structure built around a fireplace to support cookware over an open fire. For our analysis, we do not distinguish between three-stone stoves, chulhas,

or other traditional stove types and refer to these in aggregate as "traditional stoves." We make the assumption that these stoves can be created or assembled for free, making the stove lifetime attribute irrelevant for this stove as there is no cost to replace it. Estimates of combustion efficiency for traditional stoves range from 7 – 15% [11-13]. We assume the efficiency to be at the high-end of this spectrum at 15% so that we do not overestimate potential efficiency gains from alternative biomass cooking systems.

2. **Improved Cooking Stoves:** "Improved" biomass cooking stoves are purchased devices for more efficiently combusting solid fuels. They come in a myriad of shapes, sizes, and costs. Some of the manufacturers with large market-share include Philips, Servals, and Envirofit. We represent just two generic categories of improved biomass stoves for simplicity:
    a. **Natural Draft Improved Cooking Stoves (ICS-N)** contain heat from biomass combustion to more efficiently direct it toward the cookware, drawing air naturally.
    b. **Forced Draft Improved Cooking Stoves (ICS-F)** use an electric fan to force air through the system to increase combustion efficiency.

    Cost estimates for ICS stove options range enormously from \$9 – \$90 [11,14,15]. We assume moderate prices for both stove categories at \$30 and \$50 respectively. Stove lifetime estimates range from 2-4 years – we assume 3. Finally, efficiency estimates in literature range from 20 – 40% [11,13,15,16]. We assume efficiencies of 25% and 35% respectively.

3. **Kerosene Stoves:** We assume a cost of \$20, a lifetime of 5 years, and an efficiency of 45% [13,14,17].

4. **LPG Stoves:** Standard propane cooking systems include both the stove itself and a large canister to store LPG. Both components of this cooking system are included in the stove cost for this analysis. We assume a cost of \$78 (roughly \$60 for the stove and \$18 for the canister), a lifetime of 10 years, and an efficiency of 60% [12-14,16,17].

5. **Piped Gas Stoves:** We assume the same type of gas range used for LPG can also be used for piped gas. Piped gas does not require a cylinder, so the stove cost is reduced to \$60.

6. **Electric Stoves:** Electric cooking has historically been performed with a radiant heat system which generates heat by running electricity through heating elements. This system is slower than cooking with LPG. We model a newer electric stove technology: the induction stove. Induction stoves operate by inducing heat in specialized cookware using magnetic current rather than in the stove coils. This process is both faster and more efficient than radiant heat technology and has already begun to penetrate the market in some regions of India [10]. Because the stove itself does not heat, the system as a whole discharges less heat into the home, resulting in a cooler kitchen environment. These advantages will make induction stoves a more attractive alternative to LPG relative to radiant heat stoves in the future. We assume an average price of \$95 including specialized cookware, a lifetime of 15 years, and an efficiency of 80% [18].

Table A3. Stove costs and attributes

Stove System	Fuel	Price (2015$)	Efficiency (%)	Lifetime (yrs)
Traditional	Biomass	0.00	15	3
Natural Draft ICS	Biomass	30.00	25	3
Forced Draft ICS	Biomass	50.00	35	3
Kerosene Stove	Kerosene	20.00	45	5
Gas Stove	Piped Gas	60.00	60	10
Gas Stove, Canister	LPG	78.00	60	10
Electric Induction	Electricity	95.00	80	15

ICS, piped gas, and electric induction cooking systems are not presently in wide use throughout most of South Asia. We therefore restrict the use of these technologies either partially or completely until the 2030 model time period to allow for infrastructure development for delivery of the stoves at which point we assume all technologies can reach all households given adequate demand. For both ICS stove options, we assume unrestricted stove availability starting in the year 2020. Use of electricity is assumed partially restricted through the 2020 model time period based on estimated rates of electrification in the South Asia region from the Global Energy Assessment [4]. Piped gas is assumed unavailable until 2030.

9.7 SURVEY COOKING COSTS

Each household in the survey reported expenditure and quantity consumed for one or multiple fuels. We estimate the total cost to cook with each fuel when accounting for both stove and fuel costs per service unit delivered (gigajoules of useful energy). To do so, we annualize stove costs and divide by total demand for that fuel. Annual stove cost is calculated with Equation 1:

Equation 1. Annualized stove cost formula

$$\boldsymbol{A_e} = \frac{\boldsymbol{P_s} * \boldsymbol{r_e}}{1 - (1 + \boldsymbol{r_e})^{-\boldsymbol{L_s}}}$$

where ***A*** = Annualized stove cost, ***P*** = price, ***r*** = household discount rate, ***L*** = stove lifetime, ***s*** = stove type, and ***e*** = expenditure group.

Household specific discount rates are calculated as a function of total household expenditure using Equation 2[19]:

Equation 2. Discount rate formula

$$\boldsymbol{r_e} = -\mathbf{0.162} \times \boldsymbol{ln}\ \boldsymbol{X_e} + \mathbf{1.9558}$$

where ***r*** = implicit discount rate (%), ***X*** is household expenditure per year in 2005 PPP$, and ***e*** is expenditure group.

Based on these inputs, we calculate total cooking cost per unit useful energy for each group in each year using Equation 3:

Equation 3. Cooking cost formula

$$\boldsymbol{C_{e,s}} = \frac{\boldsymbol{P_f}}{\boldsymbol{E_s}} + \frac{\boldsymbol{A_s}}{\boldsymbol{D_e}}$$

where ***C*** = cooking cost in \$/gigajoule useful energy, ***P*** = price, ***A*** is annualized stove cost, ***E*** = stove efficiency, ***D*** = total household demand for cooking energy in gigajoules of useful energy, ***f*** = fuel type, ***s*** = stove type, and ***e*** = expenditure group.

9.8 DEMAND CURVE DERIVATION

Demand curves are used to estimate how each income group's fuel and technology preferences change under varying price scenarios (Figure A4). Demand curves are derived from the household survey by regressing a best-fit power function of the log of household demand for a fuel against the log of household and fuel-stove specific cooking cost (as calculated in the preceding section) weighted by the survey household multiplier. The power curve is chosen over other regressions because we assume that observed price elasticity is constant. To use a power curve, we must exclude survey respondents reporting zero fuel use. If the curve were estimated this way without any further adjustment, we would create a curve that reflects the preferences of only those households that use the fuel and thereby overestimate demand for that fuel. We adjust accordingly to account for households not using the fuel by multiplying fuel demand by the mean share of total useful cooking energy met with that fuel across the entire expenditure group. The resulting curve describes the preferences of an expenditure group's average household, which when multiplied by the number of households in that group reflects the total demand of that group for the fuel. Derived coefficient values for the LPG demand curves for each of the four household groups are presented in Table A4.

Figure A4. Example demand curve for LPG in expenditure group U2

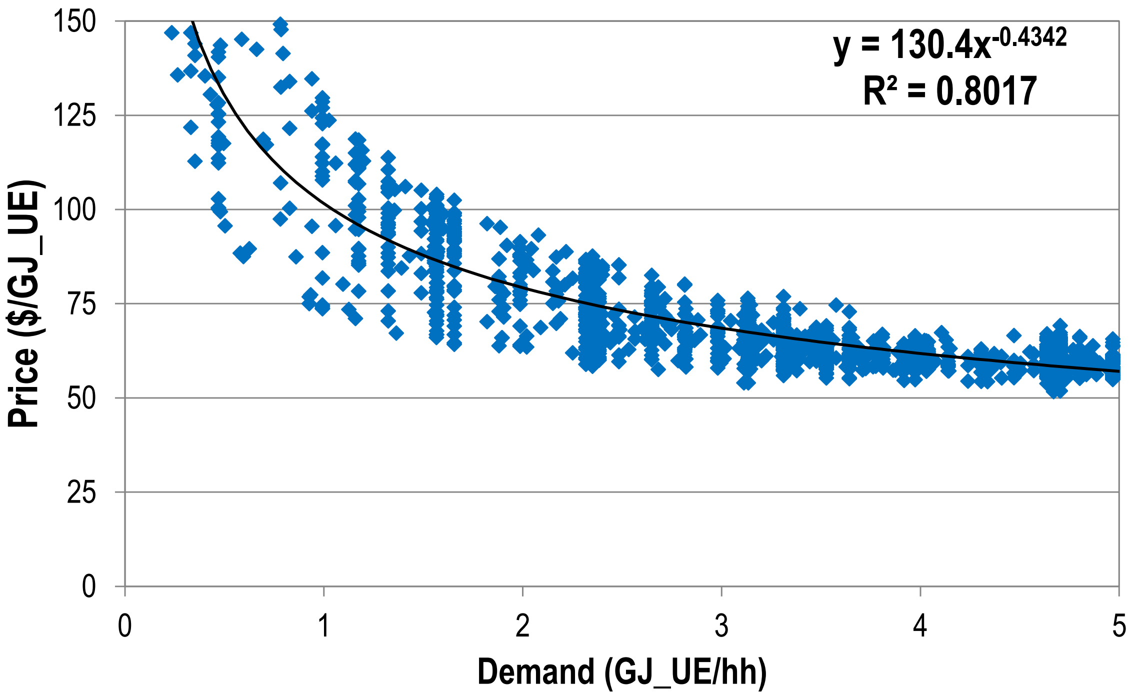


Table A4. Derived demand curve coefficients for LPG fuel-stove combination

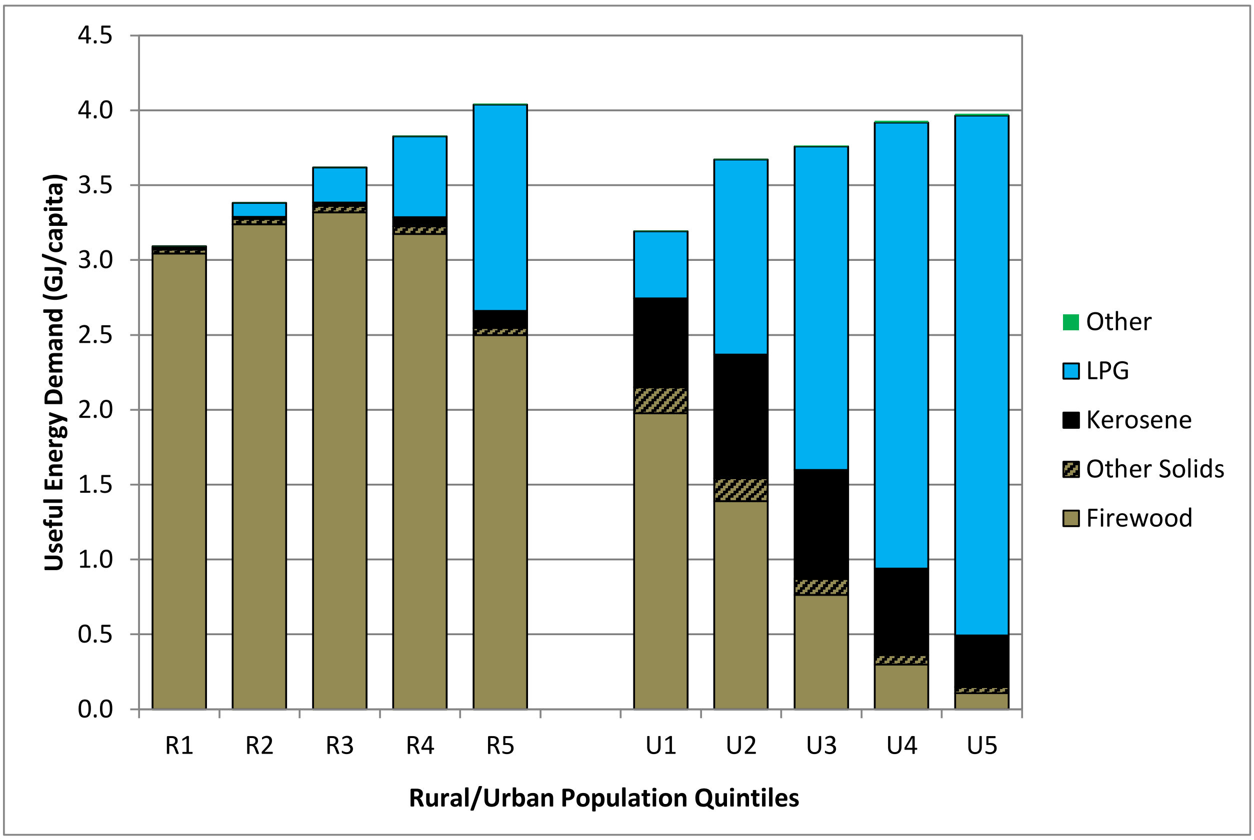
Population Group	Coefficient a	Coefficient b
R1	50.88	-0.2017
R2	78.87	-0.2248
U1	72.89	-0.3412
U2	130.38	-0.4342

9.9 FUEL-STOVE CHOICE ALGORITHM

Households usually do not use just one fuel, but instead "stack" multiple fuel options to meet different cooking needs or by using different fuels at different times in response to changes in fuel availability and price [10,12,20]. Therefore, groups cannot be assigned a single fuel according to their income. Instead, we need a method to determine how households choose which fuels to use and in what amounts.

If we consider the mean demand for each fuel across expenditure quintiles in the household survey (Figure A5), we observe that as households get wealthier (from R1-R5 and U1-U5) and are provided greater access to liquid fuels (from rural to urban groups), use of liquid fuels increases and use of solid fuels decreases as a share of total cooking energy use. It is also clear that the wealthier groups choose LPG over kerosene. These same preferences have been documented in other research and are in line with evidence that households ascend a metaphorical "energy-ladder" as they get richer [10,20]. We therefore assume that consumers prefer to meet their cooking needs with clean, easy-to-use fuels such as LPG, but will shift to dirtier and more time-consuming fuels such as kerosene and firewood when the cost of cooking with more desirable fuels is too high.

Figure A5. Fuel use by rural and urban expenditure quintiles [5]



An additional challenge is that many of the fuel-stove options we represent in our model are a) not distinguished in the survey (ICS-N, ICS-F), or b) were not widely available at the time of the survey (piped gas and electric induction). For this reason, it is not possible to draw conclusions from the survey about the relative preference for these fuel-stove options over those presently in wide use. In addition, we lack the necessary data to derive demand curves specific to those fuels. We address this issue by assuming that each modeled fuel-stove option not presently in wide use can provide cooking service that is equivalent to that provided by one of the existing stoves.

Piped gas and electric induction both offer LPG-like cooking service in that they are very clean, fast, and easy to use. We therefore group these fuels into a single "modern fuel" service category. One could make the argument that, in reality, households may prefer PNG or electric induction over LPG due to the inconvenience of refilling the LPG canister and in keeping with the norm of higher income regions such as North America and Europe. On the other hand, reliability issues with both of these infrastructure-dependent distributed fuels may deter would-be consumers in the immediate future in South Asia, whereas LPG offers a tested system. We ultimately discard these factors as outside the scope of our analysis.

Similar to our grouping of modern fuels, we group ICS together with traditional stoves. Although conventional thinking assumes ICS would be preferred to traditional stoves, slow real-world uptake of ICS indicates this assumption may be faulty [10,21]. We assume ICS stoves offer the same quality of cooking service as traditional stoves given that all three options are slow to start-up, require effort and attention to maintain, and produce smoke.

Based on these groupings, we are left with three fuel-stove categories or "fuel tiers":

- **Tier 1:** LPG, Piped Gas, Electricity
- **Tier 2:** Kerosene
- **Tier 3:** Traditional Cook Stoves, ICS-N, ICS-F

Given the assumption of service equivalence within tiers, we assume the demand curve for one fuel in a tier can also be used to describe the demand for other fuels in that tier. Thus, a demand curve derived from the household survey for LPG can also describe household demand for piped gas or electric induction. The only remaining difference between fuels of the same tier is price.

The model assumes households will use the cheapest fuel within each tier either to the extent specified by the demand curve for the given price or up to the point at which the fuel is no longer available due to model constraints (described in section "Modeled Cooking Stoves"). If the cheapest fuel-stove option in a given tier is constrained, the income group then moves to the second cheapest fuel-stove option in that tier and so on until all fuel-stove options from that tier have been exhausted. We assume that household demand for cooking service is fixed: households do not cook excessively when fuel prices are low nor can they make do by cooking less when fuel prices are high. Thus, if the cooking cost for a fuel drops well below the price needed to meet all of a household's demand, we assume no additional fuel is used.

If the income group cannot afford to meet all its cooking energy demand with tier 1 fuels, the model moves to tiers 2 (kerosene) and tier 3 (biomass). Kerosene in India is subsidized and distributed to households through the Public Distribution System (PDS) according to quotas determined by a proxy indicator of poverty and household size. This means that the majority of survey data reflect purchases of subsidized kerosene at nearly the same price and in set increments according to quotas. As a result, demand curves for kerosene derived from this survey reflect little relationship between cost and demand and could not be used for this analysis.

Although conventional thinking suggests kerosene would be preferred over biomass for cooking, some primary research indicates that many households may actually prefer to use biomass if it is cheaper. Kerosene is then used when biomass prices exceed kerosene's or when biomass is unavailable such as in urban slums or during monsoons[20]. This is further evidenced by the household survey itself – rural households with access to kerosene report low or nearly negligible use of kerosene for cooking, using biomass instead, whereas a sizeable share of urban households of the same income level cook with kerosene. This suggests kerosene use for segments of the urban population may be driven by a lack of access to firewood.

In light of this behavior, we treat kerosene as a fuel of last resort. Lacking data on which households have access to biomass, we assume kerosene will be used by a fixed percentage of those households unable to use tier 1 fuels. We determine the percentage for each expenditure group as the share of non-tier 1 households using kerosene in the household survey. This subset of households using kerosene is nearly negligible for rural households, but makes up a more sizeable fraction of households in poor urban expenditure groups. Using this algorithm, the total number of households using kerosene for cooking will grow when tier 1 fuel use drops and decrease as tier 1 fuel use grows. All remaining demand not met by tiers 1 and 2 is met by the cheapest available tier 3 fuel.

9.10 Future Fuel Prices and Access Representation in MESSAGE

Fuel prices in future periods are estimated from MESSAGE shadow prices for each fuel. Shadow prices reflect the system cost to produce an additional unit of fuel. MESSAGE shadow prices are thus a proxy for the cost to supply the fuel, but do not capture market and distribution costs such as retail profits that alter the price seen by household consumers from the cost of production. For this reason, it is necessary to adjust MESSAGE prices to match the consumer prices seen in the household survey. We assume this difference is best captured by a fixed-margin adjustment, rather than a percentage price increase. In other words, we assume LPG distributors and other businesses in this sector do not double their profits when LPG prices double but instead maintain even profit margins.

Non-commercial biomass is not represented in sufficient detail in the GEA version of MESSAGE to be useful for this analysis. Instead, we use commercial biomass at the primary energy level in MESSAGE as a proxy for the price of non-commercial biomass in the Access model. This represents our assumption that even biomass purchased by households is likely to become more expensive if demand for biomass increases throughout the economy more broadly. Biomass demands in Access, however, are assumed not to impact commercial biomass prices, so we do not include a demand feedback from Access biomass to MESSAGE commercial biomass.

Sourcing for the other four Access fuels is more obvious: kerosene and propane are both sourced on light oil, PNG is sourced on gas, and electricity on electricity. The difference in prices between LPG and kerosene is then purely accounted for through the shadow-price add-on calculated from the survey. The only complication arises from that fact that the survey does not provide a price for PNG. We therefore take consumer prices for PNG from the PNG rate card for major utilities in India [22]. Global energy system price feedbacks in response to energy demands in the Access model are accounted for through aggregating demand for each Access fuel and including these in the MESSAGE model.

MESSAGE prices in historical model time-steps, such as 2005 and 2010, are constrained to most accurately model energy use in that time period. Constraints on MESSAGE distort the model's fuel prices in the year they are active. MESSAGE fuel prices for years 2005 and 2010 are therefore not reliable. Consequently, we hold the 2005 survey prices constant for model year 2010. The fixed-margin adjustment for each fuel is calculated as the difference between the mean 2005 survey price of the fuel and the 2020 MESSAGE price of that fuel and used starting in 2020 and then for each subsequent period.

Household survey data also demonstrates that the fuel prices seen by consumers vary across income groups and between urban and rural regions. Biomass prices are considerably cheaper in rural areas than in urban areas, presumably due to the greater biomass availability and the greater ease with which rural residents can collect biomass for free. In contrast, LPG prices are lower in urban areas relative to poor areas due to the greater costs of distribution in less dense rural areas. Kerosene prices become more expensive as households get wealthier because poorer households meet a larger share of their kerosene demand with PDS kerosene relative to wealthier households. In contrast, we see a slight decrease in LPG fuel prices as consumers become wealthier. This may be in part due to the ability of wealthier households to purchase fuels in bulk and thereby achieve savings, while poorer households can only afford smaller containers of fuel at any given purchase time.

For PNG, we lacked the survey data to directly calculate differences in fuel prices between groups. However, we assumed that PNG would most closely resemble the pricing structure of LPG in that distribution would become more expensive as homes became more remote. We therefore assumed identical fuel price adjustment factors for PNG as for LPG. For electricity, we looked at the mean total electric demand for each household group (not just demand for cooking) to give a basis for the electricity rate that household group is charged on average. We then assumed that this average electricity usage would increase by roughly 60 kilowatt-hours per month if that family were to begin using electricity for cooking (2 hours of cooking per day on a 1 kilowatt stove for 30 days per month). With this additional electricity demand, all expenditure groups would most closely resemble the total monthly electricity demand of what is currently the wealthiest tier: U4. We therefore assigned the electricity fuel price adjustment factor for U4 to all groups given that this is likely the price households would pay if they began cooking with electricity. Table A5 shows the derived and assumed fuel price adjustment factors for each income group.

Table A5. Fuel price adjustment factors to account for retail costs, derived from surveys. Columns highlighted in grey contain assumed price adjustment factors.

	Biomass	Kerosene	LPG	PNG	Electricity
R1	0.90	0.99	1.01	1.01	1.01
R2	0.88	1.02	1.01	1.01	1.01
U1	1.12	0.96	0.99	0.99	1.01
U2	1.12	0.98	0.99	0.99	1.01

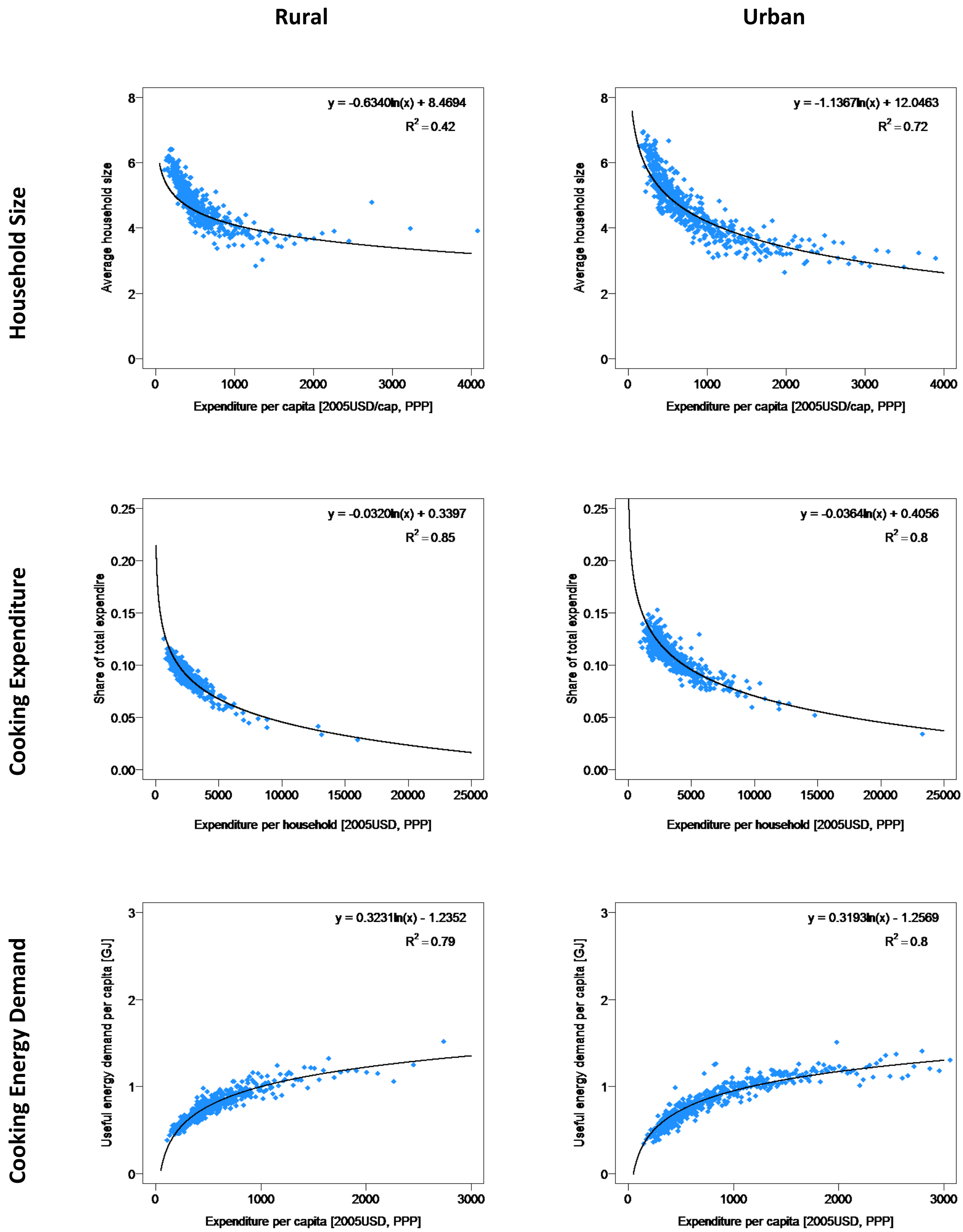
9.11 Population Characteristics in Future Years

We adjust four household attributes in future model time steps to account for changes in household energy demand and fuel preferences with increasing income (Figure A6). These attributes are discount rate, household size, per capita demand for cooking energy, and the Tier 1 fuel share of cooking energy demand. We adjust the Tier 1 share by allocating all additional cooking expenditure from increasing income to Tier 1 fuels. Whereas for the top rural and urban groups R2 and U2 expenditure increases in every period, for the bottom expenditure groups in both sectors (R1 and U1) income remains static throughout the model time horizon. For this reason, only groups R2 and U2 are assumed to change in the above-mentioned attributes.

Future discount rates are calculated according to equation 2 (see section "Survey Cooking Costs") for each future time period. Discount rates decrease as households become wealthier. To estimate the effect of changing income on household size, useful energy demand, and the Tier 1 fuel share, we use survey data to regress these attributes against household income over 500 household groups of equal size and in ascending order of income. The regressions can be seen in Supplementary Figure 6.

Household size tends to decrease as households get wealthier, while per capita energy demand increases. Finally, total expenditure on cooking fuel and stoves increases with increasing wealth, but decreases as a share of total expenditure. We assume that all cooking fuel and stove expenditure that is additional in future years relative to the base year (2005) will be spent on tier 1 fuel-stove systems. This adjustment accounts for the increase in preference for Tier 1 fuels that we observe as households get wealthier.

Figure A6. Regressions of household income against household size, cooking expenditure, and energy demand for rural and urban groups.



9.12 Carbon Price Scenarios

We present a baseline "no-new-policies" (NNP) scenario using the input assumptions described in the Global Energy Assessment "Mix" scenario (GEA-M) [22], namely with respect to policies, technological change, and regionally specific socio-economic and demographic developments from now to 2100. In addition, we test four climate change mitigation scenarios, which differ from the NNP only in that they include increasing stringent climate mitigation policy that start in the year 2020 with implied values (in 2010 USD) of $10, $20, $30, and $40 per ton CO_2e and are scaled up through 2110 such that they discount to the same value in each period using a discount rate of 5% (see Figure A7). These values factor in to the fuel costs passed to the Access model in all scenarios, depending on the carbon intensity of each fuel type (see Figure A8 for an example with LPG).

Figure A7. Implied carbon equivalent values for the base case (NNP) and four increasingly stringent climate change mitigation scenarios.

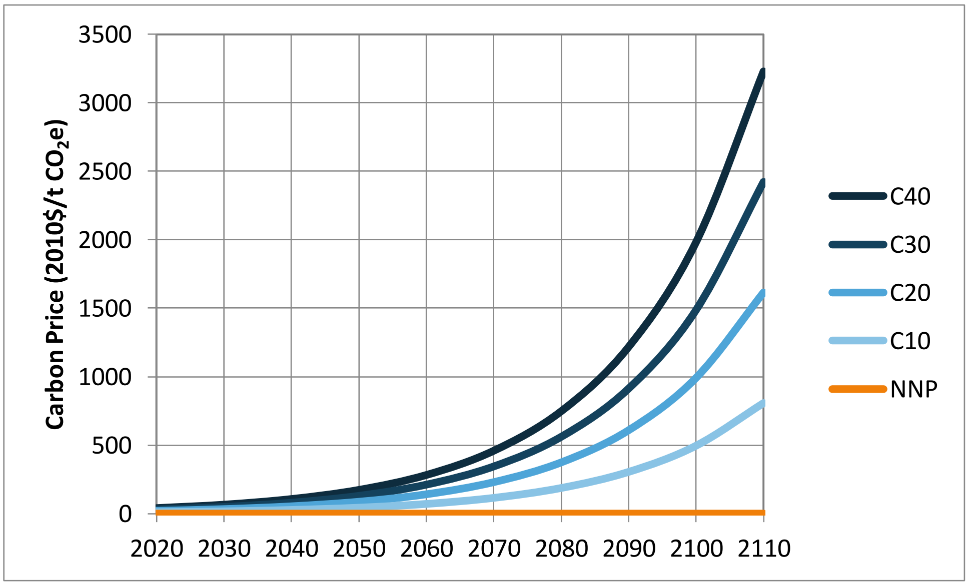
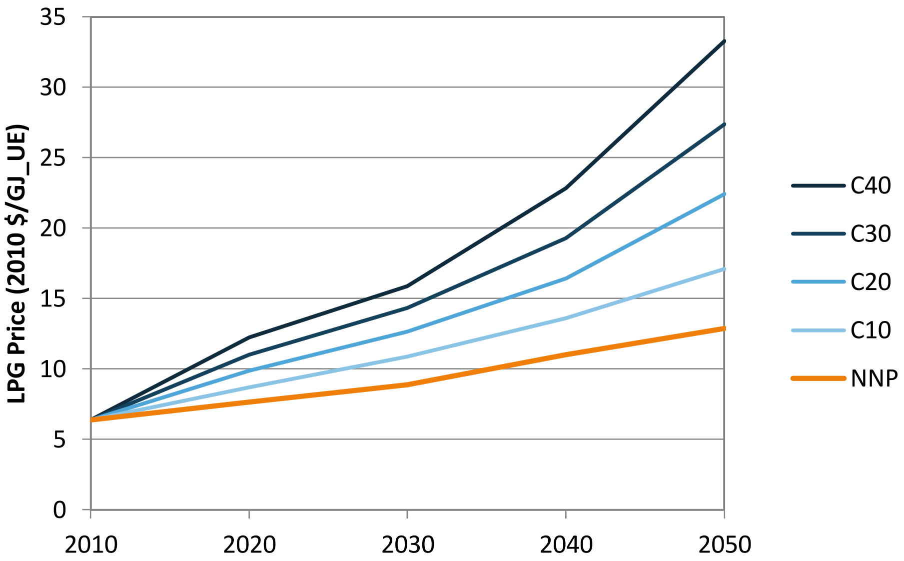


Figure A8. LPG fuel prices (2010 USD/gigajoule final energy) for the five scenarios. Values represent only fuel prices and do not include annualized stove costs. Therefore, price increases reflected here are larger than the LPG cost increase cited in the main text.

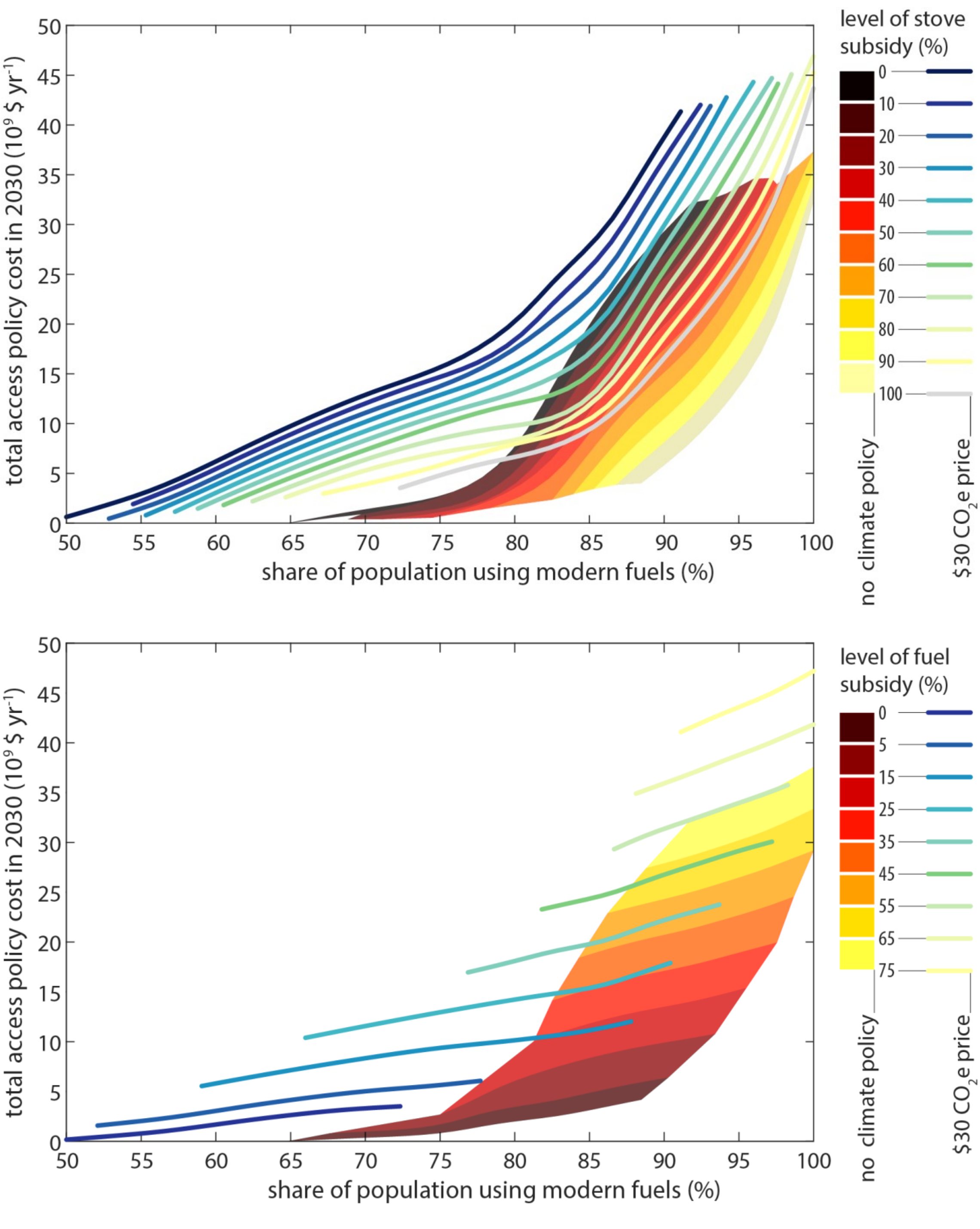


9.13 Access Policy Scenarios and Policy Costs

For the no climate policy scenario and each climate policy scenario, we also test a range of access policies. Here we model price support policies on fuel from 0%-75% and stoves from 0%-100%, which may in practice be implemented through various policy instruments. Fuel price support above 75% was unnecessary to achieve 100% modern fuel access, so no scenarios were run that exceed the 75% support level. Stove price support was used to full capacity (100%) given that investments in stove support were more cost effective than fuel support. We present only policies supporting LPG as we found this to be the cheapest Tier 1 fuel-stove option, on average, across the range of scenarios tested in this analysis. We assume LPG and LPG stoves become universally available by 2020. We assume no administrative capacity to target specific population subsets on the basis of household income. This is consistent with existing trends in the region. Even the new direct benefit transfer scheme for LPG consumers in India does not specifically target any household group [23]. Support policies were implemented in the access model by reducing LPG fuel or stove prices by the specified percent for each household group. For example, 75% fuel support means that demand for LPG was estimated for only 25% of the price generated by MESSAGE in each period.

Policy costs for fuel price support were calculated as the quantity of fuel used in a given period multiplied by the fuel price and the percentage of fuel subsidized for each period. Stove price support policy costs were calculated as the cost of the stove, annualized with a discount rate of 5%, and multiplied by the number of households using the stove in each period (see Figure A9 for an illustration of the cost-effectiveness of access policies under the NNP and C30 scenarios).

Figure A9 Scenarios of access policy cost-effectiveness under the NNP and C30 scenarios. **a**, Access policies by stove price support level; **b**, Access policies by fuel price support level.



9.14 Health Impacts

Health impacts were assessed for each scenario using methods consistent with 2010 Global Burden of Disease,[24] which has also been applied elsewhere.[25] This method combines the population attributable fraction (PAF) for health outcomes associated with exposures to household pollution from solid fuel cooking with the latest relative risk estimates[26] for diseases associated with exposure to pollution from solid fuel combustion.

The policy scenarios explored in the report affect the overall health impacts by effectively modifying the proportion of the population exposed i.e. depending on solid fuels. In order to estimate the future health impacts for the exposed population in 2030, we project the background disease deaths using age-specific data on deaths attributable to each disease for the years 1990, 1995, 2000, 2005, and 2010 from the Institute for Health Metrics and Evaluation, and population by age and sex data from the UN. The historical data on background deaths are then extrapolated to 2030, adjusting for population growth. This is done by (1) dividing historic deaths for each age and sex category by corresponding population size; (2) projecting the per-capita death trend; (3) then multiplying by the projected future population to arrive at future deaths. A similar methodology has previously been employed by Murray et al. (2007).[27]

Table A6 **Error! Reference source not found.**presents results of our estimates of health impacts for 2010, 2020 and 2030 under alternative climate/access policy scenarios. There is a significant drop in the number of child deaths attributable to solid fuel use in homes between 2010 and 2030 even in the absence of any new access policies. This is because of general improvements in health due to rising incomes and better infrastructure overall. By 2030, with no new access policies and in the absence of climate policies, we estimate between 0.45 and 1.31 million deaths occur due to solid fuel dependence. In the C30 climate policy scenario if no compensatory access policies are implemented, we estimate a higher range between 0.63 and 1.66 million deaths in 2030. Implementing access policies could eliminate many of these deaths and lead to significant improvements in the health of the population by 2030.We also estimate the uncertainties in health impact arising from household fuel/stove "stacking" (meaning using multiple fuel/stove options for different tasks) as well as potential benefits from ICS use, under alternative assumptions regarding their future technological development and emissions characteristics.

We categorize consumers' use of stoves and fuels as "heterogeneous behavior" or "uniform behavior," which would give rise to different estimates of population at risk of health impacts. We stylize each household income group as a 'representative' household with particular shares of fuel use (stacking). However, this may in reality manifest as a homogenous set of households with the same stacking pattern ("uniform behavior"), or as 'heterogeneous behavior,' where some households transition fully away from solid fuels, while others continue to use them. In the 'uniform behavior' scenario, since all households use a mix of clean and solid fuels, health benefits of reducing solid fuels only manifest if solid fuel use is sufficiently low. In particular, we assume health benefits are zero unless solid fuel use is less than a third of total fuel use. This would yield a conservative estimate of health benefits. In contrast, in the heterogeneous behavior case, health benefits accrue in full to the share of households that transition fully to clean fuels. Thus, the health benefits accrue to the population share equivalent to the share of clean fuel use for the particular household group.

We also explore varied assumption regarding the future health impacts accrued from use of ICS. The "conservative ICS benefits" assumption credits ICS with no health benefits relative to traditional stove use following the most recent evidence in the literature[28-30]. In contrast, the "optimistic ICS benefits" scenario assumes technology will develop to a level that ICS stove use will provide up to 50% of the benefits provided by LPG stoves today.

Figure A10 presents total deaths in 2030 under all four combinations of behavior and ICS benefits. The range of health impacts estimated under these alternative assumptions lies largely within the range of the confidence bounds of estimates presented in Table A6.

Figure A11 presents the fuel-stove technology portfolio in 2030 under the NNP and C30 climate scenarios combined with two access policy alternatives used as the basis for these health estimations.

Table A6 Attributable deaths (millions) associated with the No New Policy (NNP) scenario, climate policy scenarios (C10-C40), and two access policy scenarios. Main columns use mean relative risk rates (RR). Right-most column uses confidence bounds for the RR.

Policy Scenario		Disease	ALRI	COPD	Lung cancer	IHD	Stroke	Total	Confidence Interval	
Climate	Access	Sex/Age	M/F <5	M/F>15	M/F>15	M/F>15	M/F>15		Low RR	High RR
NNP	NA	2010	0.11	0.44	0.02	0.54	0.32	1.44	0.73	1.79
		2020	0.03	0.30	0.02	0.59	0.34	1.28	0.60	1.60
		2030	0.00	0.17	0.02	0.53	0.31	1.03	0.45	1.31
C10	NA	2010	0.11	0.44	0.02	0.54	0.32	1.44	0.73	1.79
		2020	0.03	0.31	0.02	0.61	0.36	1.34	0.64	1.66
		2030	0.00	0.19	0.02	0.59	0.34	1.14	0.51	1.44
C20	NA	2010	0.11	0.44	0.02	0.54	0.32	1.44	0.73	1.79
		2020	0.03	0.32	0.03	0.64	0.37	1.39	0.67	1.72
		2030	0.00	0.20	0.03	0.64	0.37	1.24	0.56	1.54
C30	NA	2010	0.11	0.44	0.02	0.54	0.32	1.44	0.73	1.79
		2020	0.03	0.33	0.03	0.66	0.38	1.43	0.70	1.76
		2030	0.00	0.22	0.03	0.70	0.40	1.35	0.63	1.66
C40	NA	2010	0.11	0.44	0.02	0.54	0.32	1.44	0.73	1.79
		2020	0.04	0.34	0.03	0.68	0.39	1.47	0.72	1.80
		2030	0.00	0.23	0.03	0.74	0.42	1.43	0.67	1.75
NNP	s100f5	2010	0.11	0.44	0.02	0.54	0.32	1.44	0.73	1.79
		2020	0.01	0.11	0.01	0.21	0.12	0.45	0.18	0.62
		2030	0.00	0.06	0.01	0.18	0.11	0.35	0.14	0.48
C30	s100f25	2010	0.11	0.44	0.02	0.54	0.32	1.44	0.73	1.79
		2020	0.01	0.09	0.01	0.18	0.11	0.40	0.16	0.55
		2030	0.00	0.06	0.01	0.18	0.10	0.35	0.14	0.47

Figure A10 Range of total deaths attributable to solid fuel use in 2030 under alternative assumptions on stove use and benefits. The bars on the blue column represents confidence bounds using low and high relative risks

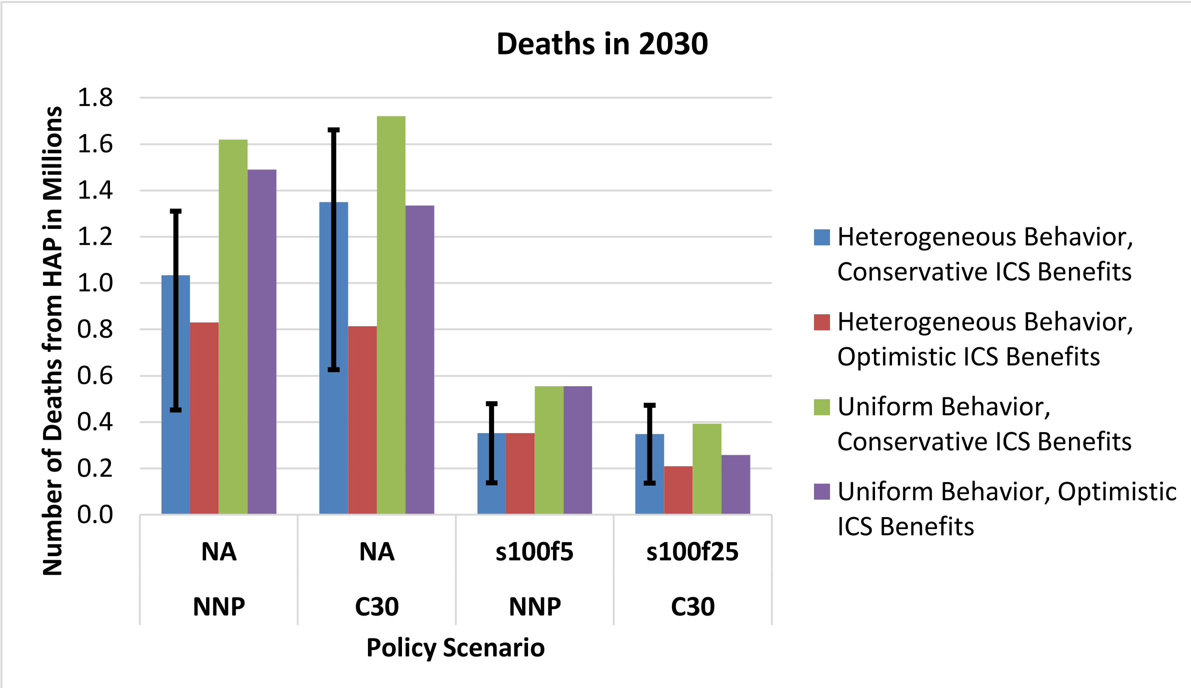
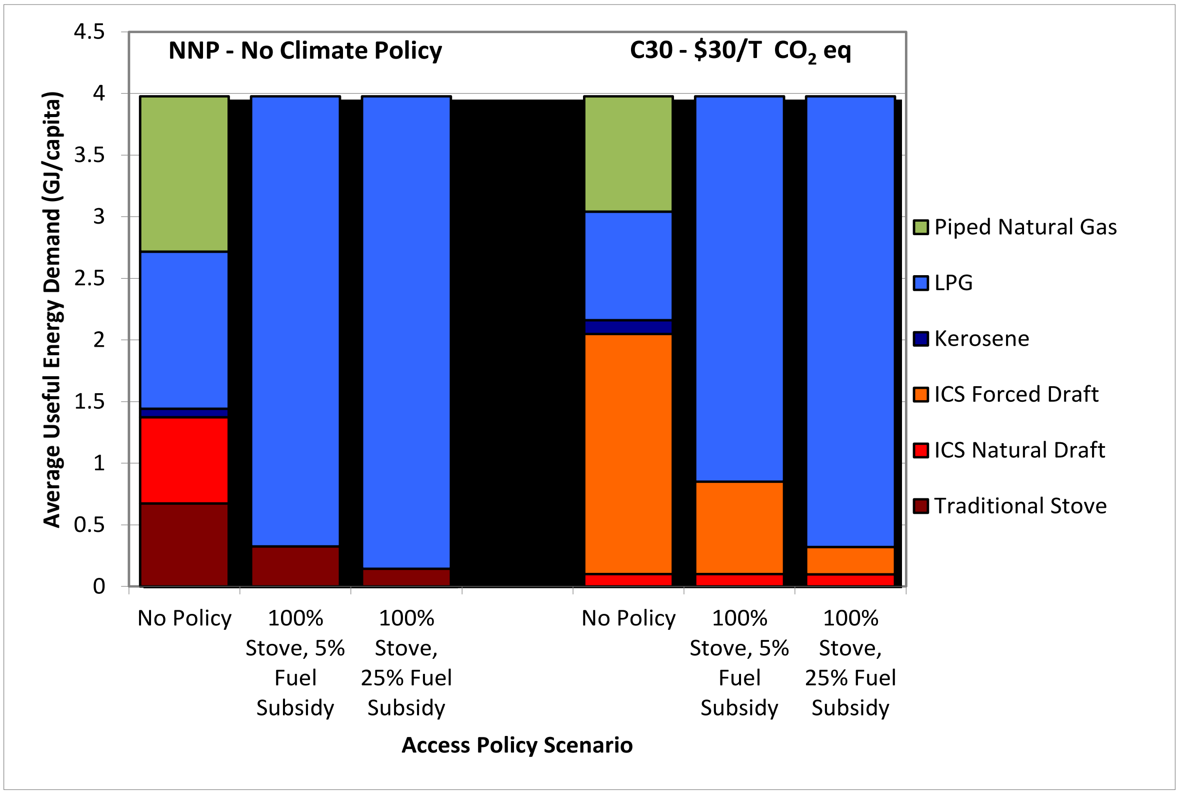


Figure A11 Distribution of average useful energy demand for cooking in 2030 under alternative climate and access policy scenarios



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10 LINKS TO MODEL CODE & DATASETS

The "Access" household fuel-stove choice model code is available at – http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-Access.en.html

If you are referencing this work, please do cite:

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The dataset on residential thermal energy use in South Asia that is the basis for calibration of the model used in this work is available in the ADVANCE Residential database.