nature energy

SUPPLEMENTARY INFORMATION

ARTICLE NUMBER: 15010 | DOI: 10.1038/NENERGY.2015.10

Policy trade-offs between climate mitigation and clean cook-stove access in South Asia

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Supplementary Methods

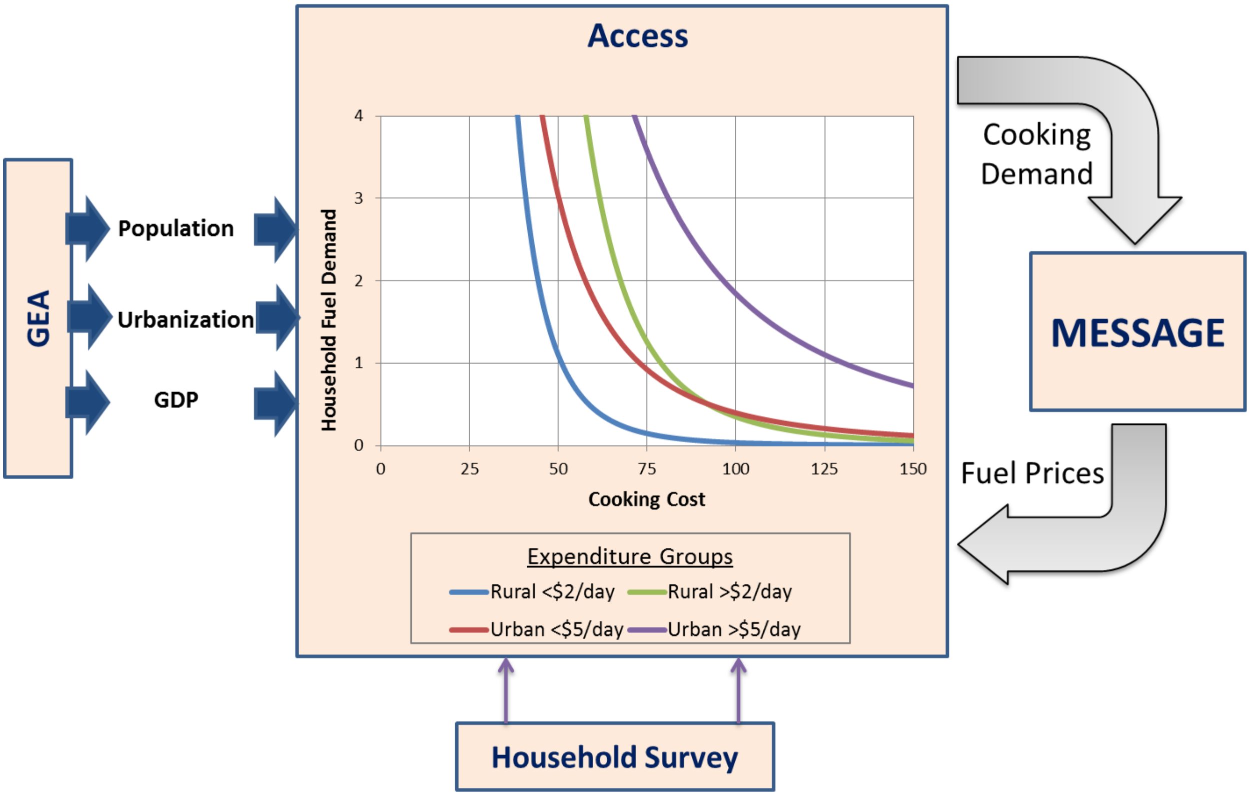
MESSAGE-Access Model Overview

“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 1.

Supplementary Figure 1. Diagram of the MESSAGE-Access model



Household Survey

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.

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 Supplementary Table 1.

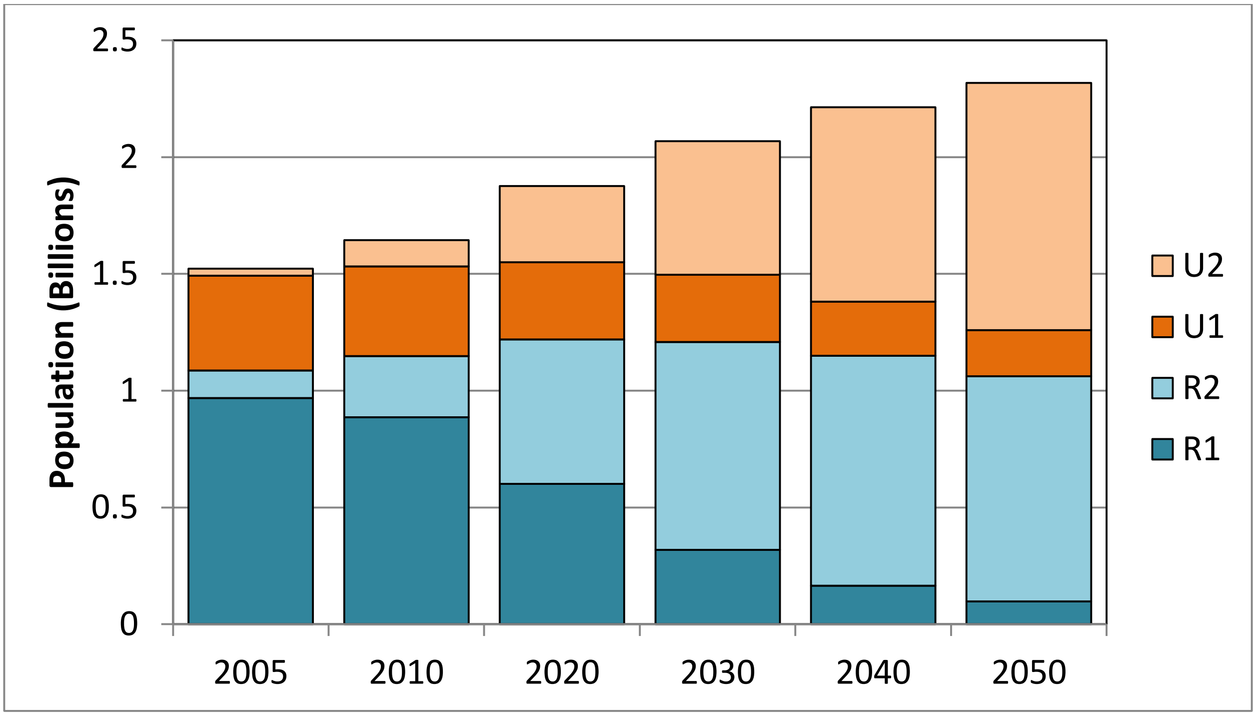
Supplementary Table 1. Population group expenditure levels in 2005 purchasing power parity (PPP) Dollar per capita per day

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

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. Supplementary Figure 2 illustrates population dynamics and Supplementary Table 2 presents the projections of average income per capita per day for the four different population subgroups till 2050.

Supplementary Figure 2. Population projections by expenditure group from 2005 to 2050.



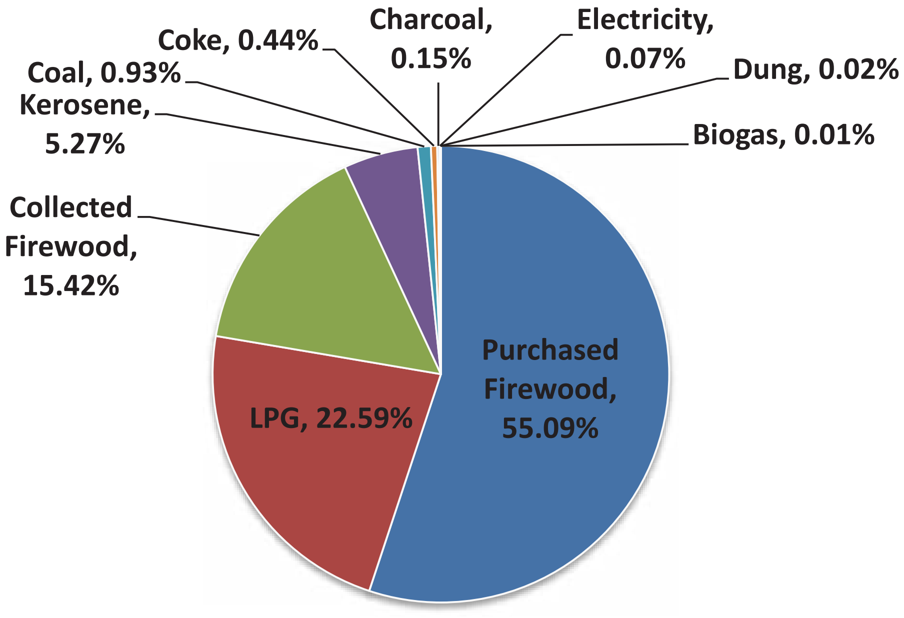
Supplementary Table 2. Income projections by expenditure group in $PPP/cap-day.

	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

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). Supplementary Figure 3 illustrates the relative shares in the household survey of each fuel in meeting national cooking energy demand.

Supplementary Figure 3. 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.

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 Supplementary Table 3.

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].

Supplementary Table 3. 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.

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 $\boldsymbol{A}$ = Annualized stove cost, $\boldsymbol{P}$ = price, $\boldsymbol{r}$ = household discount rate, $\boldsymbol{L}$ = stove lifetime, $\boldsymbol{s}$ = stove type, and $\boldsymbol{e}$ = expenditure group.

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

Equation 2. Discount rate formula

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

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

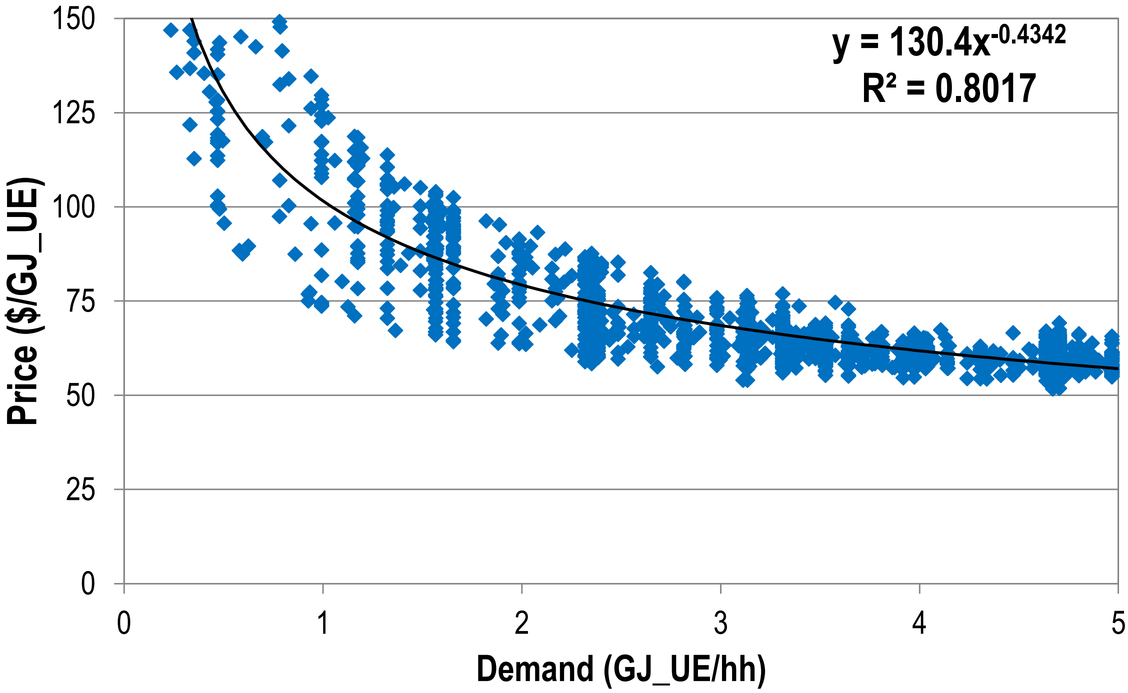
$$\boldsymbol{C_{e,s} = \frac{P_f}{E_s} + \frac{A_s}{D_e}}$$

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.

Demand Curve Derivation

Demand curves are used to estimate how each income group's fuel and technology preferences change under varying price scenarios (Supplementary Figure 4). 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 Supplementary Table 4.

Supplementary Figure 4. Example demand curve for LPG in expenditure group U2



Supplementary Table 4. Derived demand curve coefficients for LPG fuel-stove combination

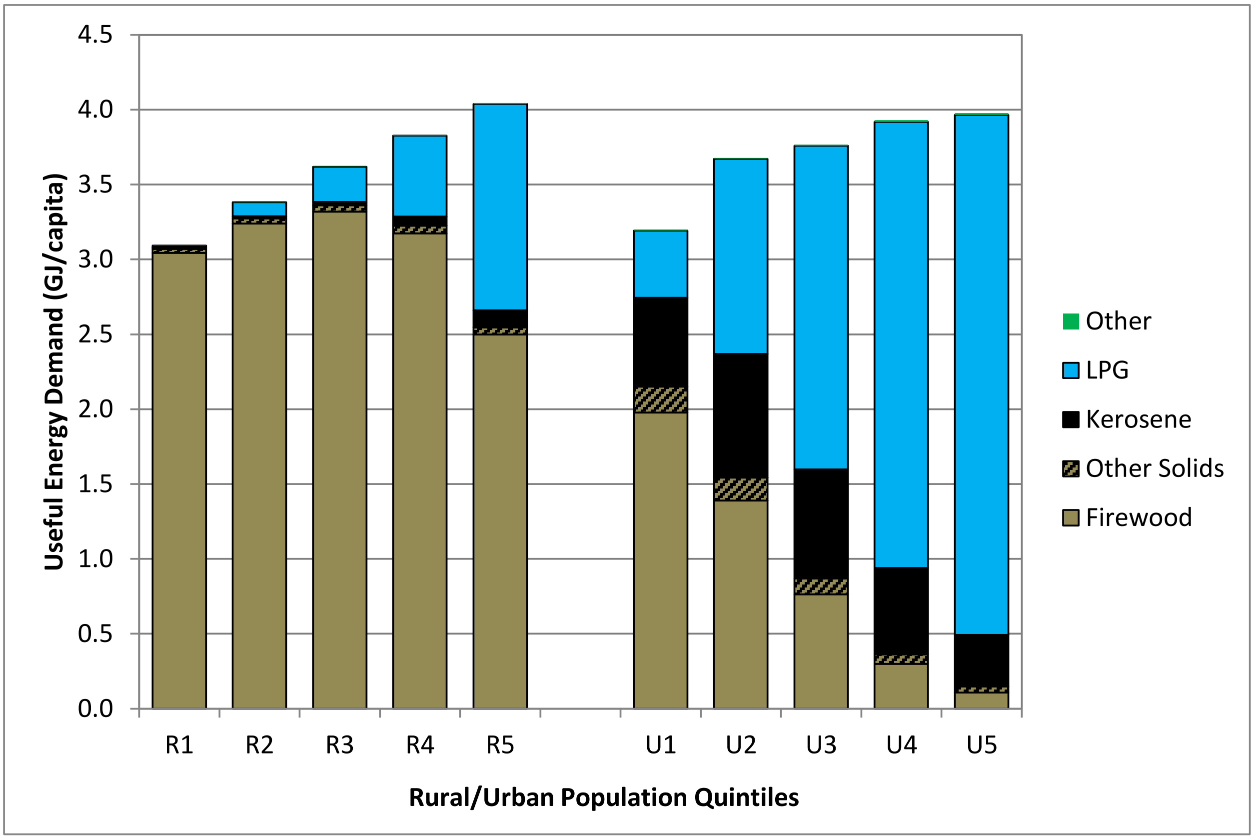
Population Group	Coefficient a	Coefficient b
R1	50.88	-0.2017
R2	78.87	-0.2248
U1	72.89	-0.3412
U2	130.38	-0.4342

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 (Supplementary Figure 5), 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.

Supplementary Figure 5. 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.

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. Supplementary Table 5 shows the derived and assumed fuel price adjustment factors for each income group.

Supplementary Table 5. 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

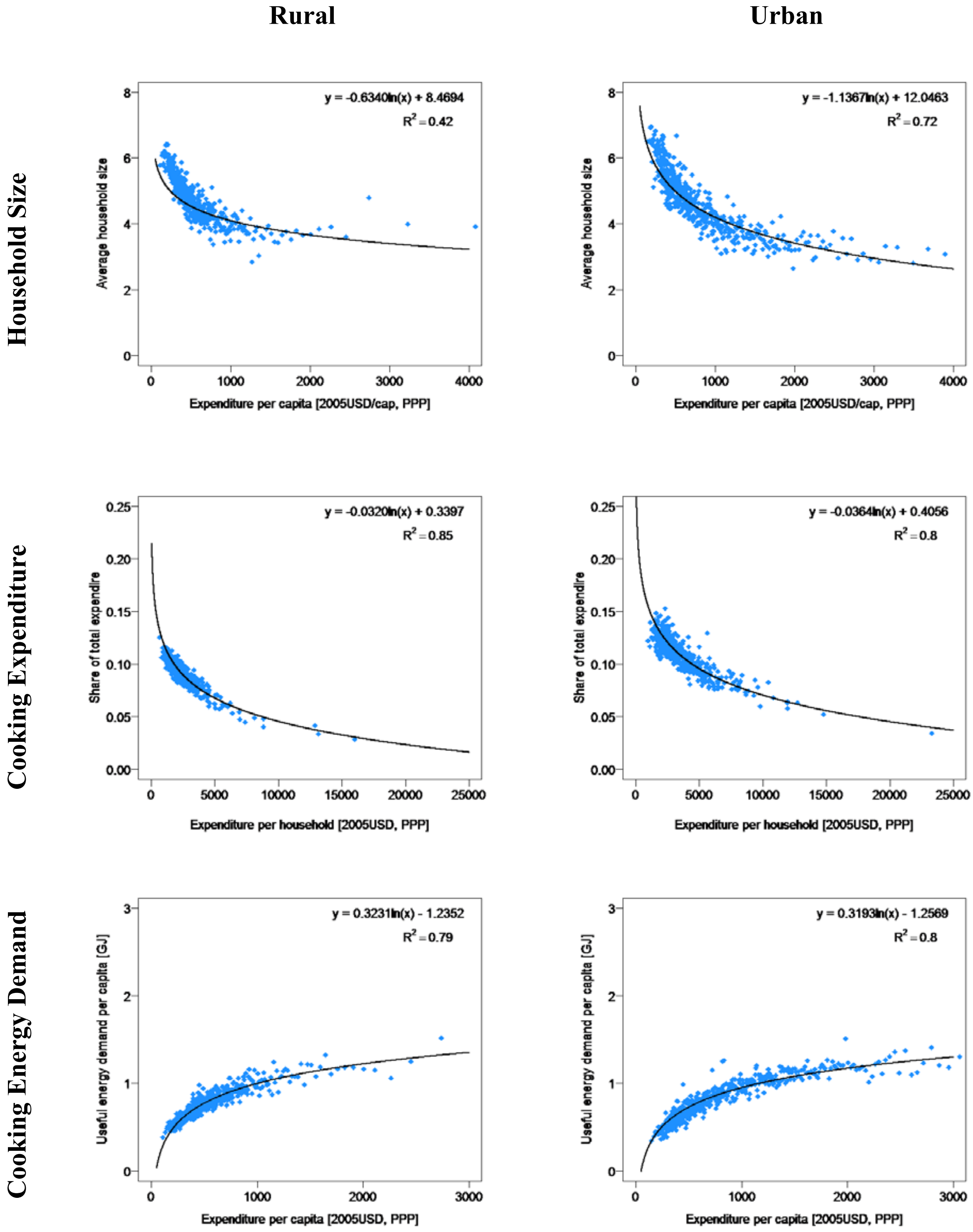
Population Characteristics in Future Years

We adjust four household attributes in future model time steps to account for changes in household energy demand and fuel preferences with increasing income. 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.

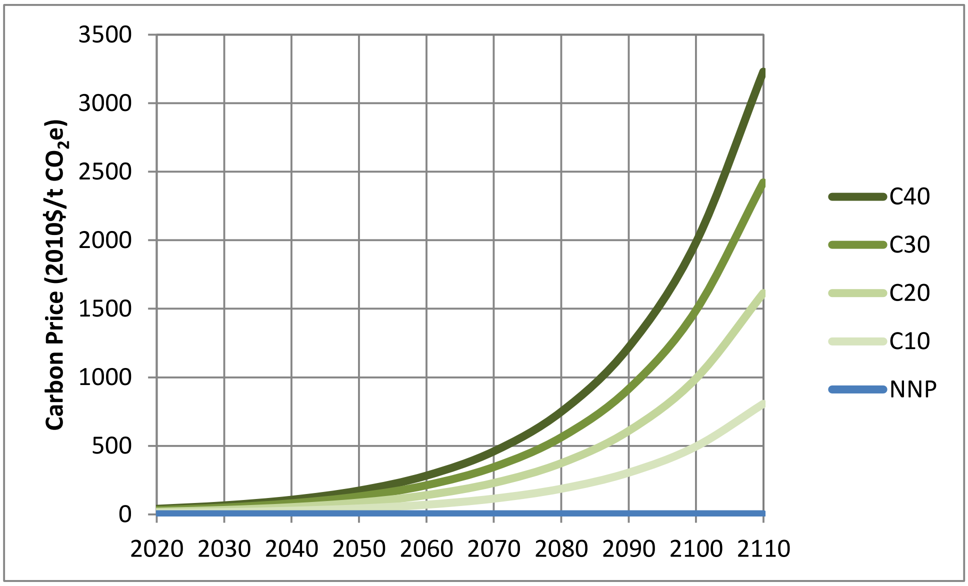
Supplementary Figure 6. Regressions of household income against household size, cooking expenditure, and energy demand for rural and urban groups.



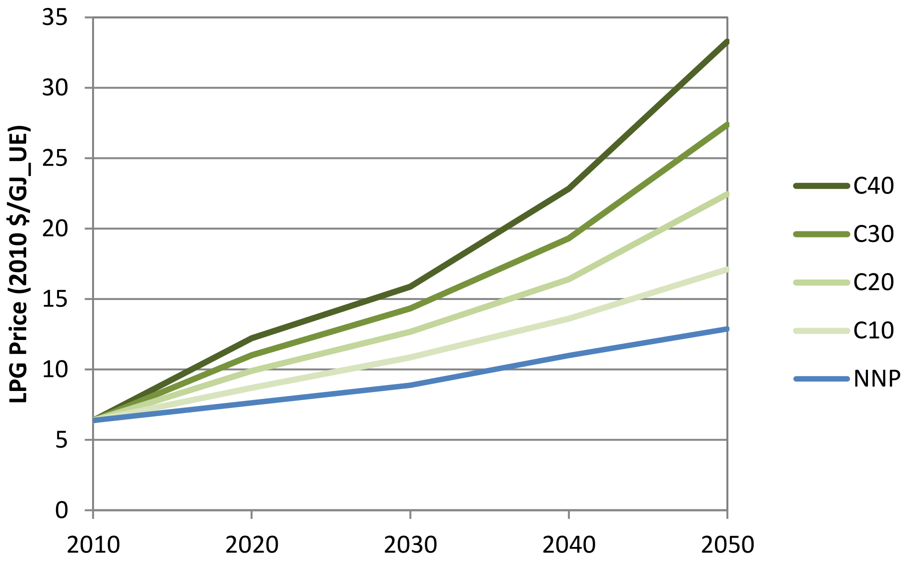
Carbon Price Scenarios

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 Supplementary Figure 7). 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 Supplementary Figure 8 for an example with LPG).

Supplementary Figure 7. Implied carbon equivalent values for the base case (NNP) and four increasingly stringent climate change mitigation scenarios.



Supplementary Figure 8. 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.



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.

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]

Supplementary Table 6 **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.

Supplementary Figure 9 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 Supplementary Table 2.1.

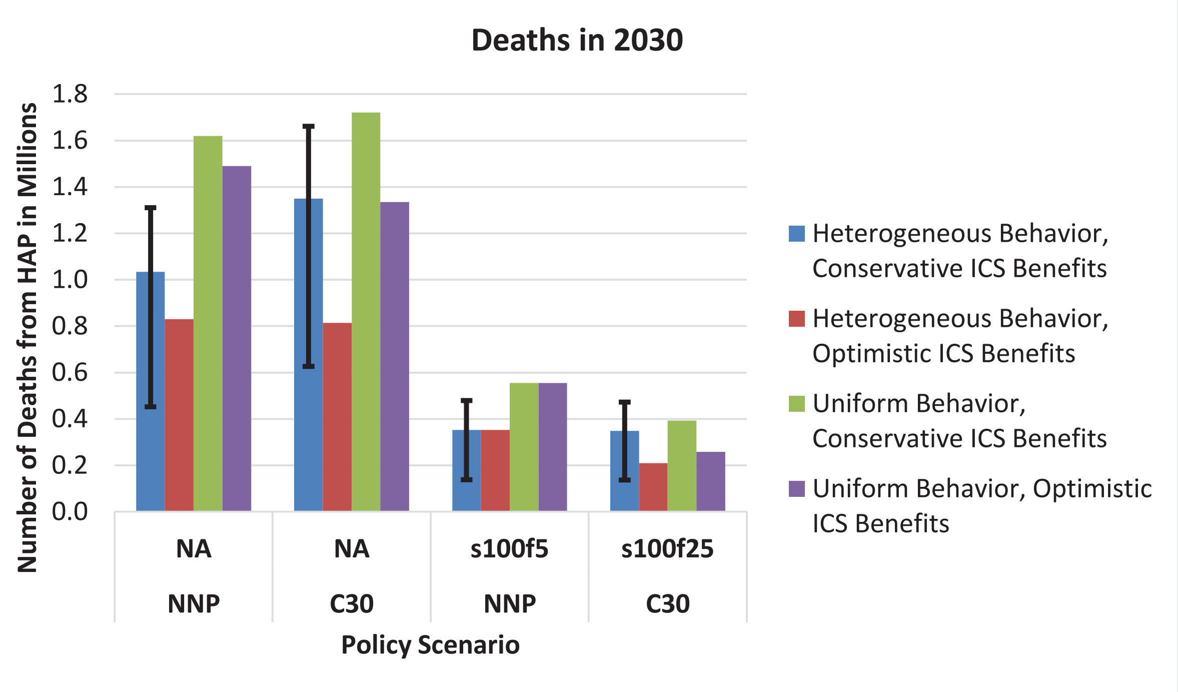
Supplementary Figure 10 presents the fuel-stove technology portfolio in 2030 under the NNP and C30 climate scenarios combined with two access policy alternatives used as the basis for these health estimations.

2. Supplementary Results

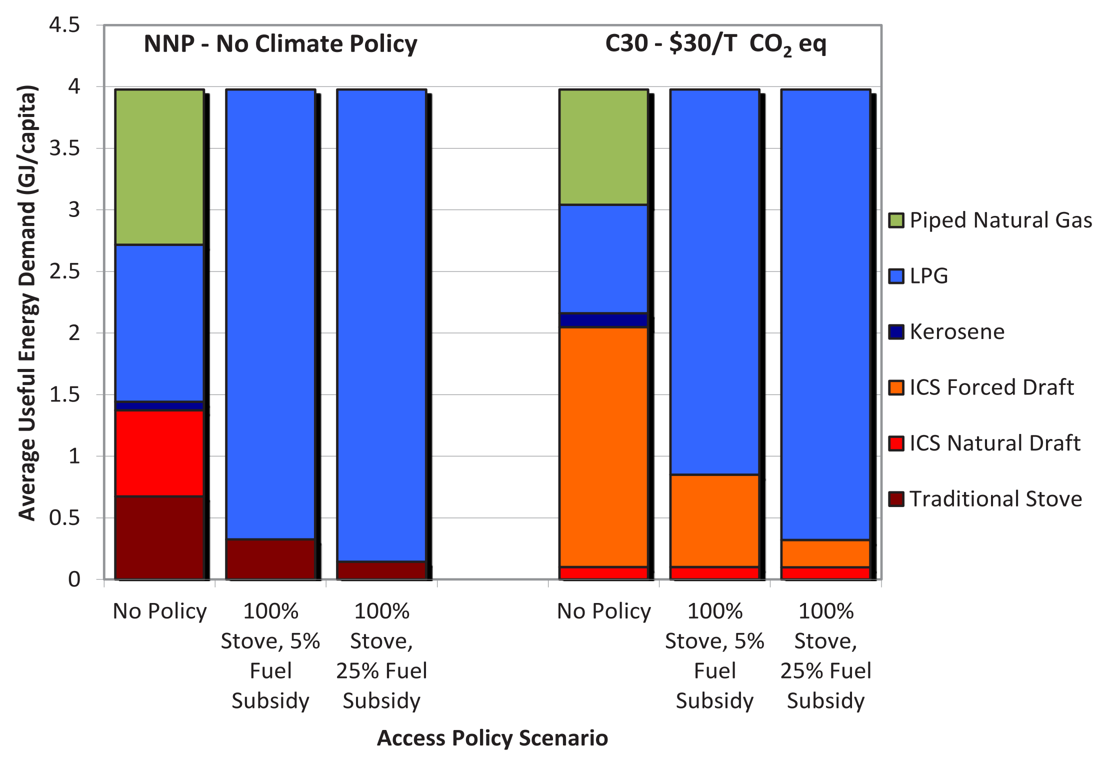
Supplementary Table 6 Attributable deaths (millions) associated with the No New Policy (NNP) scenario, climate policy scenarios (C10-C40), and two access policy scenarios. Main columns use mean relative risk rates (RR). Right-most column uses confidence bounds for the RR.

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

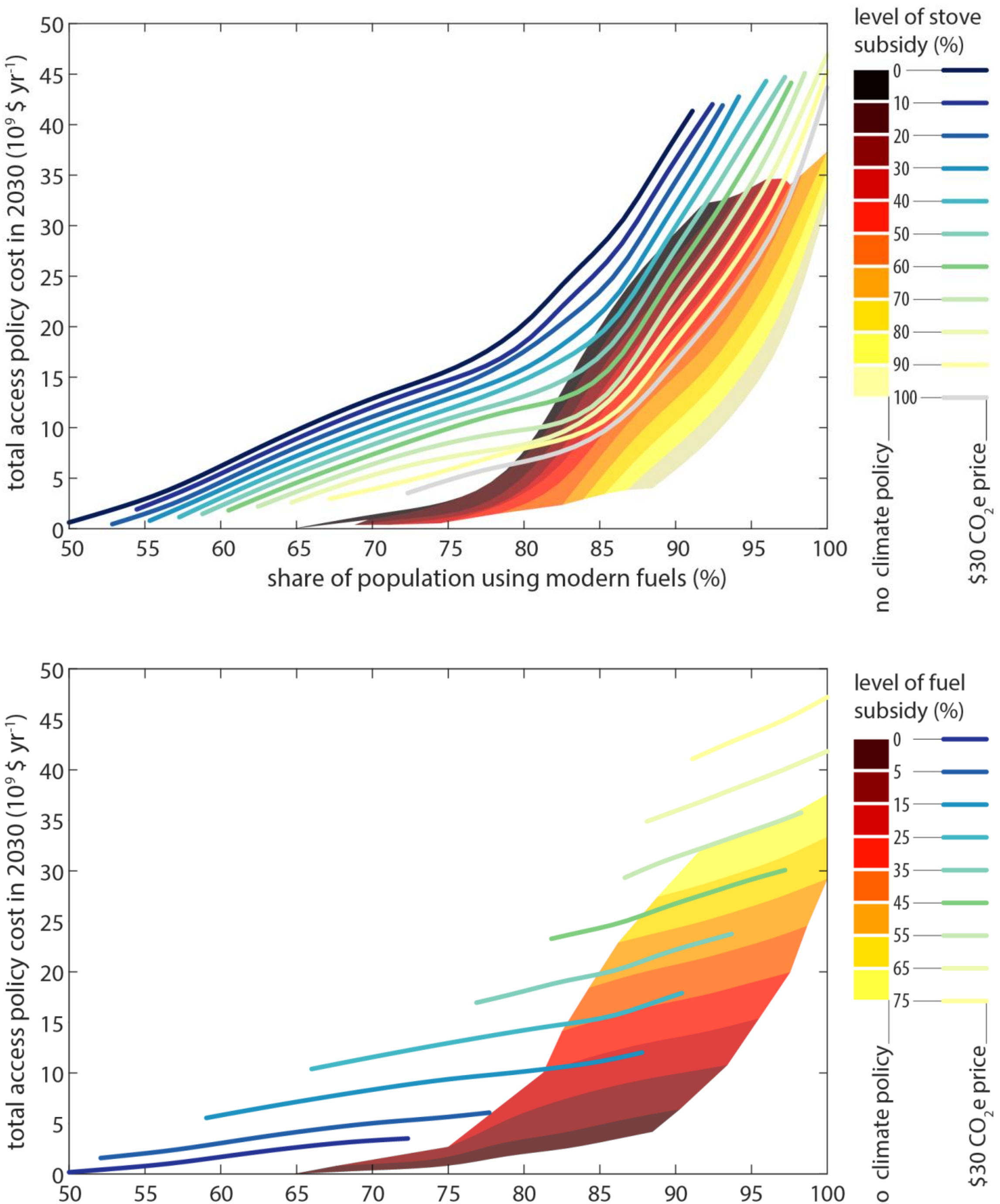
Supplementary Figure 9 Range of total deaths attributable to solid fuel use in 2030 under alternative assumptions on stove use and benefits**.** The bars on the blue column represents confidence bounds using low and high relative risks



Supplementary Figure 10 Distribution of average useful energy demand for cooking in 2030 under alternative climate and access policy scenarios



Supplementary Figure 11 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.



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