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**The Causal Impact of Solid Fuel Use on Mortality:
A Cross-Country Panel Analysis**

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Abstract

In this paper, we examine the relationship between biomass fuel consumption and measures of life expectancy and infant and child mortality. We hypothesize that solid fuel consumption at the country-level causes higher infant and child mortality, and lower male and female life expectancy at birth. Importantly our empirical strategy, using 13 years of cross-country panel data covering 101 countries at all levels of development over the period 2000-2012, allows us to obtain the causal impacts of solid fuel use on health outcomes. To obtain causal estimates, we use as instruments the proportion of the land area that is forested, and the total quantities of country-level oil and gas production. All three instruments are strong and plausibly exogenous to the determination of mortality at the country level. In our preferred instrumental variable specification, we find that solid fuel combustion causes increases in child mortality and decreases in male and female life expectancy. Our findings have important policy implications and suggest that governments, particularly of developing and middle-income countries, should focus efforts to reduce solid fuel use and encourage cleaner fuel use, in order to improve the health and well-being of their populations.

Keywords

solid fuels
indoor air pollution
child mortality
life expectancy

JEL Classification

I15; Q53; O13

1. Introduction

Today, pollution is chiefly responsible for more deaths than AIDS, tuberculosis, obesity, malaria, child and maternal malnutrition, alcohol, road accidents, or wars. Globally in 2015, an estimated nine million premature causalities and 14 million years lived with disability were attributed to pollution (Landrigan *et al.* 2017). Furthermore, millions are facing serious diseases such as lung infection, asthma, tuberculosis (TB), sinus problems, cardiovascular diseases, and cancer (Kim, Jahan and Kabir 2011, Lakshmi *et al.* 2012, Mishra 2003b). The consumption of solid fuels remains higher in rural areas than urban areas (Irfan, Cameron and Hassan 2018) and higher in lower and middle income countries than in developed countries, and the causalities due to indoor air pollution are therefore highest in rural areas of lower and middle income countries (Landrigan *et al.* 2017). Apart from overall premature deaths due to indoor air pollution, adverse health effects are concentrated among women and children, because women usually cook food for their families and children under age five usually accompany their mothers (Edwards and Langpap 2012). Children and infants are particularly vulnerable because of their underdeveloped immune system is less able to fight against infections. Moreover, infants have limited energy stores that may be insufficient to compensate for the reduced feeding that accompanies respiratory illness (Berman 1991).

Premature deaths and diseases due to indoor air pollution place a great burden on national budgets, increase medical expenditures, and reduce the overall productivity of the economy (Landrigan and Fuller 2014). Pollution also damages the environment, and forests are depleting because of the excessive use of firewood as a cooking source (Arnold, Köhlin and Persson, 2006). Worryingly, the overall consumption of solid fuel at household level is also expected to continue increasing until 2030 (Edwards and Langpap 2012). Currently, almost three billion people in lower income and middle income countries do not have access to clean or modern energy sources, and hence depend upon solid fuels such as firewood, biomass, crop residues, coal, and charcoal (Landrigan *et al.* 2017). When these solid fuels are burned, they emit a multitude of complex chemicals including formaldehyde, nitrogen dioxide, carbon monoxide, cilia toxic, polycyclic aromatic hydrocarbons (PAH), and other inhalable particulates (Cooper 1980, Torres-Duque *et al.* 2008), leading to adverse effects on health and the environment.

Despite the substantial collective and individual damages of indoor air pollution, the use of solid fuels is common, especially in developing countries. The prevention of indoor air pollution has not gained the urgency it deserves in international forums. A possible reason of this lack of attention is the lack of awareness of the scope of the problem (Landrigan and Fuller, 2014). Although a positive association between solid fuel consumption and child mortality (or, more generally, a negative association between solid fuel consumption and health) has been found in many studies (for example, Mishra (2003), Bloom *et al.* (2005) and Acharya *et al.*

(2014)). These earlier studies have failed to establish causal effects, as they have been based on cross-sectional or panel data only. The main objective of this paper is to fill this significant research gap by investigating the causal relationship between indoor air pollution and both mortality and life expectancy. This investigation is important so that policy makers can get better understanding about the adverse health effects of solid fuel consumption and form appropriate policies to reduce the consumption of solid fuels.

The rest of the paper is structured as follows. Section 2 discusses the relevant literature, Section 3 discusses the data and variables, and Section 4 presents the methodology. In Section 5 we discuss the results, and Section 6 concludes the paper.

2. Literature Review

An extensive literature is available regarding the impacts of indoor air pollution on health, including review articles such as Bruce, Perez-Padilla, and Albalak (2000), Ezzati and Kammen (2002), Kim *et al.* (2011), Larson and Rosen (2002), Oluwole, Otaniyi, Ana, and Olopade (2012), Pandey, Smith, Boleij, and Wafula (1989) and Smith (2002). Despite these numerous reviews, there remains a severe lack of cross-country empirical research in particular.

Among studies at the individual level, Edwards and Langpap (2012) investigated the impact of firewood consumption on the health of women and of children aged under five years in Guatemala, as well as the consequences of cooking inside the home. They applied probit and Two-Stage Least Squares (2SLS) regression analysis on Living Standards Measurement Survey data (for the year 2000), and found that firewood consumption was positively associated with the probability that a child had a respiratory disease.

Similarly, Mishra (2003b) examined the effect of biomass combustion on children aged under five years in Zimbabwe. They used Zimbabwe Demographic and Health Survey 1999 data, and logistic regression on the probability of suffering from Acute Respiratory Infections (ARI). They concluded that fossil fuel combustion was significantly and negatively associated with children's health. Likewise, in Nepal (Acharya *et al.* 2014) and in South Africa (Barnes *et al.* 2009) found positive associations between ARI and solid fuel consumption among children under five years. Using panel data from India, Upadhyay *et al.* (2015) similarly found a negative association between solid fuel consumption and children's health.

In a study in Bangladesh using primary data from 49 households, Khalequzzaman *et al.* (2007) first measured the amount of harmful gases (carbon dioxide, carbon monoxide, nitrogen dioxide, dust, and volatile organic compound) that were emitted from the energy sources used for cooking. They found that solid fuels such as fuelwood and crop residues were the main

emitters of harmful gases, and then they concluded that these gases are affecting children's health negatively. In other words, consumption of solid fuels (fuelwood, crop residues) were putting children's health at risk.

Cross-country investigations of these relationships are much less common, as are investigations of the relationship between life expectancy and solid fuel consumption. Pope, Ezzati and Dockery (2009) found a negative relationship between air pollution and life expectancy in the United States. The impact of solid fuel consumption on the health of elderly people (>60 years) was examined by Mishra (2003a) in India. He found that the probability of being an asthma patient was two times higher for elderly people living in households using solid fuels than those residing in homes that used clean cooking fuels. Imelda (2018) used a quasi-experiment to establish the causal relationship between kerosene use and infant mortality in Indonesia. They used three rounds of the Indonesian Demographic and Health survey for the years 2002, 2007, and 2012. Having segregated the regions on the basis of subsidy given on LPG, they found that the infant mortality rate was lower in regions where households had shifted from kerosene to LPG use. The study concluded that the LPG subsidy program saved 600 infants death annually in Indonesia. However, the study data was based on repeated cross-sections rather than panel data, and only considered the impact of kerosene consumption on health.

The study bearing the most similarity to our paper is Bloom *et al.* (2005), who used cross-country data for 162 countries to investigate the health impacts of solid fuel combustion on life expectancy and child mortality. They concluded that biomass combustion was positively associated with child mortality and negatively associated with life expectancy. Our study builds on Bloom *et al.* (2005), by using panel data and adopting an instrumental variables approach to demonstrate causal, rather than correlational, effects. Although our results do not differ qualitatively from those of the earlier study, their robustness and the attribution of causality makes them more suitable for policy applications, as suggested by Barnes *et al.* (2009) and Landrigan *et al.* (2017).

3. Data and Variables

Panel data has many advantages over time series and conventional cross-sectional data (Hsiao, Hammond and Holly 2003). Panel data or longitudinal data usually gives the researcher a larger number of data points (N by T), increasing the degrees of freedom and reducing the collinearity among explanatory variables. It allows models to be employed that will control for the impact of time-invariant omitted variables, potentially uncovers dynamic relationships, and generates more accurate predictions. Because of these advantages panel data models have become increasingly popular among applied researchers due to their heightened capacity for capturing the complexity of human behavior, compared with cross-sectional data models (Hsiao *et al.*

2003). Most studies of the relationship between indoor air pollution and health outcomes have used cross-sectional data, whereas only a handful studies have used panel data.

Annual data on GDP, education, population, forest area, and countries' profile variables were obtained from the World Bank's World Development Indicators (WDI),¹ and child and infant mortality rates data were obtained from the World Health Organization (WHO).² Data on household fuel consumption and production at country level, including both clean and solid fuels, were obtained from the UN Statistics Division Energy Statistics Database.³ The energy sources data were available only for the period 2000 to 2012, which restricts our analysis to that time period. The nature and structure of the variables can be seen in Table 1. We have unbalanced panel data on fuel consumption and health for 157 countries, although this falls to 101 in our preferred Instrumental Variables (IV) specification due to lower availability of oil and gas production and forest cover data, which are our instruments (described below).

The main independent variable, 'percentage of solid fuel consumption', was constructed as the proportion of total energy consumption that was consumed by households of fuelwood, charcoal, and dry animal dung. Annual household energy consumption data were not all expressed in the same units; therefore, we first converted them into terajoules.⁴ In the IV regression (described in the following section), we include the percentage of forested area, total production of liquefied natural gas (LNG), liquefied petroleum gas (LPG), and natural gas in terajoules, and the production of fuel and crude oil (in metric tons) as instrumental variables. The proportion of energy derived from solid fuel consumption was treated as the endogenous variable.

Table 1 shows the summary statistics of the variables in total, as well as separately for poor, lower middle income, upper middle income, and high-income countries.⁵ As anticipated, household consumption of solid fuel is higher in poor and lower middle-income countries, and the rates of infant mortality and child mortality are also higher in those countries. Per capita GDP and the exploration of oil and gas are also lower in poor and lower middle-income countries, as is the percentage of the population living in urban areas.

¹ <https://data.worldbank.org/data-catalog/world-development-indicators>

² <http://www.who.int/gho/en/>

³ <https://unstats.un.org/unsd/energy/edbase.htm>

⁴ We used an online calculator for this conversion, namely, <https://www.convertunits.com/from/tons/to/terajoule>

⁵ The World Bank classifies these categories based on mainly Gross National Income (GNI). For details see: <https://datahelpdesk.worldbank.org/knowledgebase/articles/378833-how-are-the-income-group-thresholds-determined>.

Table 1: Summary Statistics by Country Income Class

Variables	Country Income Class									
	Poor	n	Lower Middle	n	Upper Middle	n	Rich	n	All Countries	n
Percentage of Solid Fuel Consumption	30.71 (19.03)	299	10.09 (17.02)	505	1.82 (6.88)	599	0.32 (0.63)	619	7.69 (15.69)	2022
Infant Mortality Rate Per Thousand (0-27 Days)	74.00 (21.28)	299	44.72 (22.44)	506	24.37 (18.96)	606	7.02 (5.51)	624	31.40 (28.56)	2035
Child Mortality Rate Per Thousand (1-59 Months)	118.94 (40.86)	299	61.05 (36.07)	506	31.1 (29.46)	606	8.31 (6.49)	624	44.48 (46.64)	2035
Female Primary School Enrolment (Gross)	75.96 (42.25)	299	89.84 (35.92)	506	84.20 (42.74)	606	91.72 (31.74)	624	86.69 (38.24)	2035
Male Primary School Enrolment (Gross)	87.78 (42.91)	299	93.42 (93.42)	506	86.13 (43.86)	606	92.37 (32.03)	624	90.09 (38.64)	2035
Log of GDP Per Capita (USD)	5.95 (0.50)	297	7.03 (0.69)	500	8.31 (0.65)	601	10.02 (0.75)	617	8.16 (1.60)	2015
Total Population (Millions)	15.54 (15.60)	298	59.90 (186.43)	506	48.84 (190.62)	606	14.60 (24.51)	624	36.20 (141.63)	2034
Percentage of Urban Population	26.99 (10.25)	298	41.24 (17.01)	506	59.77 (15.12)	606	75.70 (18.71)	624	55.24 (23.72)	2034
Percentage of Forest Area of Total Area	21.86 (15.30)	299	29.92 (23.90)	506	38.27 (25.09)	606	28.33 (22.27)	624	30.73 (23.35)	2035
Log of LNG, LPG and Natural Gas Production (Terajoule)	4.55 (4.57)	73	7.24 (7.15)	301	9.49 (5.64)	428	9.45 (5.50)	499	8.68 (6.07)	1301
Log of Fuel Oil and Crude Oil Production (Metric Tons)	5.58 (2.04)	40	7.60 (2.10)	344	8.92 (2.36)	438	8.90 (1.87)	487	8.47 (2.23)	1297

Standard deviations are in parenthesis.

4. Methodology

Our hypothesis is that increasing solid fuel consumption at household level causes indoor air pollution and is therefore a source of higher infant and child mortality and lower life expectancy at birth. We do not have cross-country data on indoor air pollution, and so our models are a reduced form specification that links solid fuel consumption directly to health impacts. Hence, in order to examine the impact of using biomass fuels on child mortality and life expectancy, we applied panel data models. In total we ran five models with different dependent variables: (1) infant mortality per thousand; (2) child mortality per thousand; (3) life expectancy at birth for both sexes combined; (4) female life expectancy at birth and (5) male life expectancy at birth. Explanatory variables included the proportion of energy derived from solid fuel consumption, male and female primary school enrolment (gross), log of gross domestic product per capita, and proportion of the population living in urban areas.

The general panel specification of our models is:

$$y_{it} = \beta_1 x_{it} + a_i + u_{it}, \quad t = 1, 2, 3, \dots, T \quad (1)$$

where:

y_{it} dependent variable for country i in time period t (in our case, the dependent variable is one of infant mortality, child mortality or life expectancy for the whole population or for one of the genders);

x_{it} independent variables;

a_i unknown intercept for each country;

β_1 coefficient for the independent variables;

u_{it} idiosyncratic error term.

A particular issue for our reduced form specification is that solid fuel consumption may depend on household income, education level, access to the fuels, and other demographic variables that are also included in the regression model (Jan, Khan and Hayat 2012, Lee 2013, Irfan, Cameron and Hassan 2017). Thus, the independent variable will be correlated with the error term in the panel regression model, leading to an endogeneity problem. To overcome this, we apply an IV approach. Our selected instruments are: (1) percentage of forest area in the country; (2) annual production of natural gas; and (3) annual production of crude and fuel oil. Our instrumental variables model, with instruments denoted by z_{it} , is shown in Equation (2):

$$y_{it} = \beta_1 x_{it1} + \beta_2 x_{it2} + \beta_3 z_{it3} \dots + \beta_k x_{itk} + a_i + u_{it}, \quad t = 1, 2, 3, \dots, T \quad (2)$$

where k is the number of explanatory variables.

Each of these variables can be expected to affect the endogenous variable (solid fuel consumption), and is plausibly exogenous (that is, has no direct effect on infant and child mortality or life expectancy). Households located near to forested areas are expected to

consume more of firewood (Jumbe and Angelsen, 2011), while forested areas are not expected to directly affect mortality or life expectancy in a material way. In 2015, the total number of fatalities due to forest fire across 31 countries⁶ are only 18,400, which is certainly too small to have an appreciable impact on country-level mortality (World Fire Statistics, n.d.). Moreover, casualties due to wildfire or forest fire are reducing significantly due to better equipment for firefighting and advancements in weather forecasting (Doerr and Santín 2016).

Similarly, a country that has oil and gas reserves is expected to consume less solid fuels because of the increased availability of natural gas, LNG, LPG, and kerosene oil. Production of oil and gas is not expected to have an appreciable direct effect on mortality or life expectancy. The global data related to number of fatalities due to oil and gas extraction occupation are not available; however, some studies have tried to estimate the number of deaths at a regional level. The total number of deaths from 1969 to 1996 due to oil and gas related occupation in seven countries⁷ were 8,386 (Hirschberg *et al.* 2004) and in the United States of America from 2003 to 2013 were 1,189 (Mason *et al.* 2015). Thus, this is again too small to have an appreciable impact on country-level mortality. Moreover, wildfire and especially oil and gas extraction related mortality are more likely to affect adults than children. Therefore, we argue that our instruments are plausibly exogenous.

There could be some cause for concern that our instruments are influenced by GDP and are therefore not exogenous in that way. To allay these concerns, we checked the correlation between the instruments and the log of GDP per capita. Table A4 in the appendix shows that only one instrument (log of gas production) is significantly and positively associated with log of GDP per capita. We ran the first stage regression without log of GDP per capita, and the results are presented in Table A5. The results are not sensitive to the exclusion of log of gas production. Furthermore, the suitability of the instruments was further tested for over-identification and under-identification, as well as for weak instruments.

Finally, we also anticipate medicinal and technological improvements over time could significantly affect mortality rates. Therefore, time fixed effects were included by introducing time dummies for each year in each model:

$$y_{it} = \beta_1 x_{it1} + \beta_2 x_{it2} + \beta_3 z_{it3} + \beta_4 D_{it4} \dots + \beta_k x_{itk} + a_i + u_{it}, \quad t = 1, 2, 3, \dots, T \quad (3)$$

⁶ Armenia, Austria, Belarus, Bulgaria, Croatia, Czech Republic, Estonia, Finland, France, Great Britain, Hungary, Italy, Kazakhstan, Kyrgyzstan, Latvia, Liechtenstein, Lithuania, Moldova, Mongolia, Netherlands, New Zealand, Poland, Romania, Russia, Singapore, Slovenia, Sweden, Switzerland, Ukraine, USA and Vietnam.

⁷ Afghanistan, Brazil, Egypt, Mexico, Philippines, Russia and South Korea.

5. Results and Discussion

With the exception of the model for life expectancy for both genders combined, the Hausman test suggested that the fixed effect models is the appropriate specification.⁸ However, for simplicity, Table 2 presents the results of fixed effects models for all dependent variables (the random effects model for life expectancy at birth for both genders combined is included in Table A1 in the appendix).

In all models, the percentage of solid fuel consumption is statistically significant with the expected sign. Solid fuel consumption is significantly and positively associated with both infant and child mortality. These findings are consistent with the earlier results of Bloom *et al.* (2005), albeit our results use panel rather than cross-sectional data. A one-percentage point higher proportion of household solid fuel use at the national level is associated with a 0.27 per thousand higher infant mortality rate and a 0.53 per thousand higher child mortality rate.

Interestingly, female education has a negative association with child mortality, but male education is positively associated with both infant and child mortality. Our findings in this respect are completely the opposite to Bloom *et al.* (2005), as they found that female education was positively and male education negatively associated with infant and child mortality. Similarly, female education was positively and significantly associated with life expectancy, but surprisingly male education was negatively associated with life expectancy. Here again, our results are completely opposite to the findings of Bloom *et al.* (2005). Higher female education (but not male education) is associated with lower solid fuel consumption (Pundo and Fraser 2006, Acharya *et al.* 2014), which may explain these results. Alternatively, the endogeneity of solid fuel consumption may be causing these unexpected results.

As expected, per capita GDP and urbanization were both significantly negatively associated with infant and child mortality, and significantly positively associated with life expectancy. These findings are consistent with the earlier cross-sectional analysis of Bloom *et al.* (2005). Higher income countries generally provide people with better access to higher quality medical facilities and have more robust health systems, and people in urban areas typically have better access to medical care. We also ran all fixed effect models with the 101 countries that have complete data on the instruments. The sign of the coefficients are the same with these results presented in Table A3 in the appendix.

⁸ Results were $\text{Prob} > \chi^2 < 0.001$ suggesting to apply fixed effect models.

Table 2: Fixed Effect Model Results

	Infant Mortality Rate	Child Mortality Rate	Both Sex Life Expectancy	Male Life Expectancy	Female Life Expectancy
Percent of Solid Fuel Use	0.268 (0.019)**	0.534 (0.038)**	-0.044 (0.004)**	-0.051 (0.004)**	-0.059 (0.005)**
Female Primary School Enrolment	-0.324 (0.030)**	-0.601 (0.061)**	0.056 (0.007)**	0.038 (0.007)**	0.038 (0.008)**
Male Primary School Enrolment	0.296 (0.029)**	0.548 (0.060)**	-0.053 (0.007)**	-0.034 (0.007)**	-0.034 (0.007)**
Log of GDP Per Capita	-5.490 (0.474)**	-7.771 (0.971)**	0.115 (0.116)	0.261 (0.113)*	0.179 (0.122)
Urban Percent of Population	-0.560 (0.067)**	-0.850 (0.137)**	0.068 (0.017)**	0.073 (0.016)**	0.106 (0.018)**
cons	108.760 (5.068)**	157.606 (10.375)**	62.528 (1.229)**	58.853 (1.203)**	62.701 (1.292)**
R ²	0.59	0.49	0.66	0.69	0.66
N	2,007	2,007	1,950	1,950	1,950
Number of Countries	157	157	157	157	157

* p<0.1; ** p<0.05; *** p<0.01

Country level clustered standard errors are in parentheses.

As previously noted, the proportion of household solid fuel use is likely to be endogenous. We applied the Anderson-Rubin Wald and Stock-Wright Lagrange multiplier S-statistic test to confirm this in our models. Our first two exogenous variables (percentage of land that is forested and the log of natural gas, LNG, and LPG production) are statistically significant predictors of the endogenous variable (percentage of solid fuel consumption), as can be seen in Table 3, which presents the first-stage estimation from the IV regression, it satisfies the relevance restriction.

We also tested for under-identification (Anderson canonical Correlation Lagrange multiplier statistics), over-identification test (Sargan test), and weak identification (Cragg-Donald Wald F-statistic). The results of these tests are included in Table A2 in the appendix. We further ran these tests using individual instruments to check each instrument's suitability and validity in all five models, and these results are presented in Table A2a in the appendix. The results of these tests confirmed that that our instruments are strong and valid. Both the relevance and exclusion restrictions are therefore satisfied and our estimators are consistent (Alva *et al.* 2014, Behncke 2012). Moreover, the tests results support our instrumental variable approach and demonstrate the suitability of our chosen instruments.

**Table 3: First Stage Instrumental Variable Regression Results
for All Five Models**

Percentage of Solid Fuel Consumption	Coefficients
Percentage of Forest Land of Total Land	1.092 (0.102)***
Log of Natural Gas, LNG, LPG Production	-0.456 (0.084)***
Log of Fuel Oil and Crude Oil Production	-0.334 (0.259)
Female Primary School Enrolment	0.006 (0.029)
Male Primary School Enrolment	-0.011 (0.029)
Log of GDP Per Capita	-1.767 (0.370)***
Urban Percent of Population	-0.449 (0.059)***
N	1232
Number of Countries	101

* p<0.1; ** p<0.05; *** p<0.01

Country level clustered standard errors are in parentheses.

Finally, Table 4 presents the IV model (two stage least square) results. Although the sample size reduces from 157 countries to 101 countries (due to the unavailability of data on the instruments for some countries), the results support our hypothesis that solid fuel consumption causes increases child and infant mortality and decreases in life expectancy at birth. The coefficients in the IV regression are larger than in the fixed effect models (Table 2), which suggests that we may also be reducing the measurement error in the solid fuel consumption variable. Our results imply that a one-percentage point increase in the proportion of household solid fuel consumption leads to a statistically significant decrease in infant mortality of 1.30 per thousand and a statistically significant decrease in child mortality of 2.44 per thousand. To get a sense of the size of these effects, the difference between the mean upper-middle income country and the mean poor country in proportion of solid fuel use is 28.89 percentage points. *Ceteris paribus*, this difference causes the infant mortality rate in poor countries to be higher by 37.56 infants per thousand, and the child mortality rate in poor countries to be higher by 70.49 children per thousand, compared with upper-middle income countries.

Table 4: Instrumental Variable Regression Results

Models	Infant Mortality Rate	Child Mortality Rate	Both Sex Life Expectancy	Male Life Expectancy	Female Life Expectancy
Percent f Solid Fuel Use	1.298 (0.092)**	2.435 (0.167)**	-0.102 (0.018)**	-0.132 (0.020)**	-0.171 (0.021)**
Female Primary School Enrolment	-0.046 (0.037)	-0.078 (0.067)	0.031 (0.007)**	-0.009 (0.008)	-0.005 (0.008)
Male Primary School Enrolment	0.037 (0.036)	0.062 (0.065)	-0.028 (0.007)**	0.011 (0.008)	0.008 (0.008)
Log of GDP Per Capita	-4.510 (0.506)**	-5.766 (0.914)**	0.217 (0.099)*	0.351 (0.109)**	0.257 (0.113)*
Urban Percent of Population Enrolment	0.042 (0.084)	0.111 (0.151)	0.019 (0.016)	0.037 (0.018)*	0.050 (0.019)**
R ²	0.58	0.49	0.75	0.75	0.73
N	1,232	1,232	1,232	1,232	1,232
Number of Countries	101	101	101	101	101

* p<0.1; ** p<0.05; *** p<0.01

Country level clustered standard errors are in parentheses.

Solid fuel consumption also causes lower life expectancy at birth, with a one-percentage point increase in the proportion of household solid fuel consumption lowering male life expectancy at birth by 0.132 years and female life expectancy at birth by 0.171 years. Again considering the difference between the mean upper-middle income country and the mean poor country, in poor countries males are losing 3.81 years and females are losing 4.94 years of life expectancy at birth in poor countries compared to upper-middle income countries. Other results are similar to the panel model in Table 2, except that education becomes statistically insignificant in all models except for combined life expectancy at birth, and urbanization becomes statistically insignificant for child and infant mortality.

6. Discussion and Conclusions

Almost half of the population in developing countries, and up to 90 percent of rural population, depends upon solid fuels such as firewood, charcoal, coal, crop residues, and animal dung for cooking and heating purposes (Bloom *et al.* 2005). When these solid fuels burn they emit harmful gases and become a significant threat for the life of the people. Our causal empirical results confirm this relationship. We found that countries where the proportion of solid fuel use by households was higher had higher infant and child mortality and lower life expectancy at birth. Importantly, our IV regression results demonstrated that these effects were causal – that

increases in solid fuel use cause higher infant and child mortality and lower life expectancy. These results suggest a straightforward policy response. Child and infant mortality can be lowered, and life expectancy at birth increased, by reducing household use of solid fuels for cooking and heating.

How large could the health gains from reducing solid fuel consumption be? A simple back-of-the-envelope calculation provides an indication. If the solid fuel consumption gap between low income countries and lower-middle income reduced by 50 percent (which is 10.31 percentage points), infant and child mortality in the low income countries would decrease by 13.40 and 25.16 per thousand⁹ respectively, and life expectancy at birth for males and females would increase by 1.36 and 1.76 years respectively. According to United Nations data,¹⁰ poor countries had 103.397 million children aged under five years in 2015. Assuming one-sixtieth of those were infants (aged under one month), the reduction in child and infant mortality (combined) from reducing the solid fuel consumption gap between low-income countries and lower-middle income countries by half is approximately 2.58 million per year.

Similarly, if the solid fuel consumption gap between lower-middle income countries and the upper-middle income countries reduced by 50 percent (which is 4.13 percentage points), infant and child mortality in the lower-middle income countries would decrease by 5.37 and 10.07 per thousand respectively. Lower middle-income countries have 319.752 million children. Therefore, the reduction in child and infant mortality (combined) from reducing the solid fuel consumption gap between lower-middle income countries and upper-middle income countries by half is approximately 3.19 million per year.

These back-of-the-envelope calculations suggest that there are significant mortality reductions and health gains by reducing solid fuel consumption in poor and middle-income countries. However, achieving these potential health gains will require direct policy intervention. As Irfan et al. (2018) recently noted for Pakistan, income growth or development alone will not be sufficient to switch households, particularly households in rural areas, to cleaner fuel use.

Our results only demonstrate the benefits of reducing solid fuel use (and even then, only the benefits captured from direct health gains and not those resulting from environmental quality improvements). Governments will need to weigh the potential benefits of reducing solid fuel consumption against the costs of doing so. The costs are especially salient for poor and middle-income countries, where government budget constraints may be especially severe. There may also be a role for the international community in reducing mortality from indoor air

⁹ Coefficients of infant and child mortality from causal regressions (Table 4) are multiplied by the reduced gap.

¹⁰ <https://esa.un.org/unpd/wpp/Download/Standard/Population/>

pollution. Interventions in low-income countries that are demonstrated to have a high benefit-cost ratio, but where government budget constraints prevent investment, may need to be subsidized or provided by international donors. Given the substantial potential health gains, and the high and unequal health burden currently arising from indoor air pollution, urgent action is required.

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Appendix

Table A1: Random Effects Regression of the Percent of Biomass Fuel Use on Life Expectancy at Birth for Both Sexes Combined

Models	Both Sexes Life Expectancy at Birth
Percent of Solid Fuel Use	-0.047 (0.005)**
Female Primary School Enrolment	0.059 (0.007)**
Male Primary School Enrolment	-0.056 (0.007)**
Log of GDP Per Capita	0.522 (0.113)**
Urban Percent of Population	0.140 (0.013)**
_cons	55.714 (1.077)**
N	1,950
Number of Countries	154

* p<0.1; ** p<0.05; *** p<0.01

Country level clustered standard errors are in parentheses.

The random effects model was suggested by Breusch and Pagan Lagrange multiplier test.

Table A2: Tests for Instruments

Test for	p-values				
	Model 1 Infant Mortality	Model 2 Child Mortality	Model 3 Both Sex Life Expectancy	Model 4 Male Life Expectancy	Model 5 Female Life Expectancy
Under Identification Test (Anderson canon. corr. Lagrange multiplier statistic)	0.000	0.000	0.000	0.000	0.000
Joint Significance of Endogenous (Anderson-Rubin Wald Test)	0.000	0.000	0.000	0.000	0.000
Over Identification Test for All Instruments (Sargan Statistic)	0.025	0.186	0.000	0.000	0.000
Weak Identification Test (Cragg-Donald Wald Statistic)	0.000	0.000	0.000	0.000	0.000

Table A3: Fixed Effect Models for 101 Countries

Models	Infant Mortality Rate	Child Mortality Rate	Both Sex Life Expectancy	Male Life Expectancy	Female Life Expectancy
Percent of Solid Fuel Use	0.622 (0.029)**	1.214 (0.053)**	-0.065 (0.007)**	-0.107 (0.008)**	-0.129 (0.008)**
Female Primary School Enrolment	-0.078 (0.031)*	-0.134 (0.056)*	0.034 (0.007)**	-0.007 (0.008)	-0.003 (0.008)
Male Primary School Enrolment	0.066 (0.030)*	0.112 (0.054)*	-0.031 (0.007)**	0.010 (0.008)	0.005 (0.008)
Log of GDP Per Capita	-6.123 (0.385)**	-8.677 (0.695)**	0.306 (0.090)**	0.409 (0.100)**	0.356 (0.103)**
Urban Percent of Population	-0.234 (0.063)**	-0.388 (0.114)**	0.033 (0.015)*	0.046 (0.016)**	0.067 (0.017)**
Constant	90.716 (5.015)**	129.320 (9.060)**	65.474 (1.177)**	61.463 (1.310)**	66.184 (1.346)**
R ²	0.72	0.66	0.76	0.76	0.73
N	1,220	1,220	1,220	1,220	1,220
Number of Countries	101	101	101	101	101

* p<0.05; ** p<0.01

Country level clustered standard errors are in parentheses.

Table A4: Correlation between Log of GDP and Instrumental Variables

Log GDP Per Capita	Coefficients
Percentage of Forest Land of Total Land	-0.008 (0.017)
Log of Natural Gas, LNG, LPG Production	0.100 (0.014)**
Log of Fuel Oil and Crude Oil Production	0.028 (0.043)
Constant	7.760 (0.679)**
R ²	0.05
N	1,233
Number of Countries	102

* p<0.1; ** p<0.05; *** p<0.01

Country level clustered standard errors are in parentheses

Table A5: First Stage Instrumental Variable Regression Results for All Five Models Without GDP

Percentage of Solid Fuel Consumption	Coefficients
Percentage of Forest Land of Total Land	1.131 (0.102)***
Log of Natural gas, LNG, LPG production	-0.464 (0.084)***
Log of Fuel Oil and Crude Oil Production	-0.592 (0.254)**
Female Primary School Enrolment	0.006 (0.029)
Male Primary School Enrolment	-0.011 (0.028)
Log of GDP Per Capita	-1.767 (0.370)***
Urban Percent of Population	-0.444 (0.059)***
N	1242
Number of Countries	101

* p<0.1; ** p<0.05; *** p<0.01

Country level clustered standard errors are in parentheses