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

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ABSTRACT

Biomass consumption causes indoor air pollution which impairs health and environment. In this paper, we examine the causal relationship between biomass fuel consumption and measures of life expectancy and infant and child mortality. Using 13 years of cross-country panel data which covers 105 countries over the period 2000-2012, we applied fixed effect model and instrumental variable regression. We find that solid fuel combustion causes increase in infant and child mortality and decreases in male and female life expectancy. A back-of-the envelope calculation suggests that, if the solid fuel consumption gap between low-income and lower-middle income countries were reduced by 50%, infant and child mortality in the low-income countries decrease by 16.5 and 29.8 per thousand respectively, and life expectancy would increase by 1.0 and 1.5 years for males and females respectively. Our findings suggest that governments, particularly of developing countries, should focus efforts to reduce solid fuel use.

Keywords: Solid Fuels; Indoor Air Pollution; Child Mortality; Life Expectancy; Causal Relationship
JEL Classifications: 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 (Landrigan et al., 2018). Globally in 2015, an estimated 9 million premature deaths and 14 million years lived with disability were attributed to pollution (Landrigan et al., 2018). Furthermore, millions are facing serious diseases such as lung infection, asthma, tuberculosis (TB), sinus problems, cardiovascular diseases, and cancer (Mishra, 2003b; Kim et al., 2011; Lakshmi et al., 2012). The consumption of solid fuels remains higher in rural areas than urban areas (Irfan et al., 2018) and higher in low-income and middle-income countries than in developed countries, and the deaths due to indoor air pollution are therefore highest in rural areas of lower and middle-income countries (Landrigan et al., 2018). Adverse health effects are concentrated among poor families (Duflo et al., 2008), and especially women and children, because women usually cook food for their families and children under age 5 usually accompany their mothers (Edwards and Langpap, 2012). Children and infants are particularly vulnerable because 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, increasing medical expenditures, and reducing the overall productivity of the economy (Landrigan and Fuller, 2014; Zhu et al., 2018). Pollution also damages the environment, and the excessive use of firewood as a cooking source depletes forests (Arnold et al., 2006; McNeill, 2006). Worryingly, the overall consumption of solid fuel by households is expected to continue increasing until 2030 (Edwards and Langpap, 2012). Currently, almost three billion people in low-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., 2018). 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 (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 (Duflo et al., 2008). 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 (e.g. Mishra, 2003a; Bloom et al., 2005 and Acharya et al., 2014), these studies have failed to establish *causal* effects, as they have been based only on cross-sectional or panel data. The main objective of this paper is to attempt 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 a better understanding about the adverse health effects of solid fuel consumption and form appropriate policies to reduce the consumption of solid fuels.

The remainder 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 methods that we employ. In Section 5 we discuss the results, then 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 Pandey et al. (1989), Bruce et al. (2000), Ezzati and Kammen (2002), Smith (2002), Larson and Rosen (2002), Dherani et al. (2008), Kim et al. (2011), and Oluwole et al. (2012). 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 5 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.

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 concluded that these gases were affecting children's health negatively. In other words, consumption of solid fuels (fuelwood, crop residues) were putting children's health at risk. Mishra (2003b) examined the effect of biomass combustion on children aged under 5 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, studies in Nepal Acharya et al. (2014) and in South Africa Barnes et al. (2009) have found positive associations between ARI and solid fuel consumption among children under 5 years. Using panel data from India, Upadhyay et al. (2015) similarly found a negative association between solid fuel consumption and children's health. 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 based on 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 were based on repeated cross-sections rather than panel data, and only considered the impact of kerosene consumption on health. This suggests that there may be enormous health benefits to the public provision of modern fuel consumption (Xue, 2018).

Children and infants are not the only vulnerable group that may be heavily impacted by indoor air pollution. 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 use clean cooking fuels.

In contrast to individual or household-level analyses, cross-country investigations of these relationships are much less common, including investigations of the relationship between life expectancy and solid fuel consumption. Pope et al. (2009) found a negative relationship between air pollution and life expectancy in the United States and in Canada, Stieb et al. (2015) found an inverse association between air pollution and life expectancy. Likewise, Chen et al. (2013) found that air pollution was significantly and negatively associated with life expectancy in Northern China. They used data from 1981 to 2000 for 90 cities and applied ordinary least squares and regression discontinuity approaches to explore the relationship between life expectancy and total suspended particulates. They concluded that a 100 $\mu g/m^3$ increase in total suspended particulates leads to a decline of 3 years in life expectancy at birth. However, they did not estimate the effects on life expectancy separately for males and females. If men and women face differential exposure to air pollution, then the impact on their life expectancies will differ. For example, traditional biomass combustion is a major cause of total suspended particulates and has a chronic impact on the life expectancy of women and children (Zahnd and Kimber, 2009). Women in developing countries are more at risk from IAP because of cooking responsibilities.

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. However, because of the cross-sectional nature of their study, it does not demonstrate the *causal* effect of solid fuel consumption on health. 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. We also estimate the causal effects on life expectancy separately by gender. Although our results do not differ qualitatively from those of the earlier studies, their robustness and the plausible attribution of causality makes them more suitable for policy applications, as suggested by Barnes et al. (2009) and Landrigan et al. (2018).

3. DATA AND VARIABLES

Most extant cross-country studies of the relationship between indoor air pollution and health outcomes have used cross-sectional data, whereas we employ panel data. Panel data has many advantages over time series and conventional cross-sectional data (Hsiao et al., 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 uncovering dynamic relationships, and generating more accurate predictions. Because of these advantages, panel data models have become increasingly popular among applied researchers (Hsiao et al., 2003).

Annual data on Gross Domestic Product (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 105 in our preferred Instrumental Variables (IV) specification due to lesser availability of gas production and forest cover data, which are our instruments (described below).

1 https://databank.worldbank.org/data/reports.aspx?source=World-Development-Indicators

2 http://www.who.int/gho/en/

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

The main independent variable, "percentage of solid fuel consumption", was constructed as the proportion of total energy consumption originating from household consumption 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 and total combined production of liquefied natural gas (LNG), liquefied petroleum gas (LPG), and natural gas (in terajoules) 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 overall, as well as separately for low-income, lower-middle income, upper-middle income, and high-income countries.[5] As anticipated, household consumption of solid fuel is higher in low-income 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 low-income and lower-middle income countries, as is the percentage of the population living in urban areas.

We faced some data limitations. For example, some other important variables were not included in the model, which may affect mortality and life expectancy such as access to clean drinking water, sanitation, calorie consumption, mother's health (for infant and child mortality), number of hospitals and doctors, other medical facilities, and technological advancement over time. We note that many of these variables are likely to be correlated with (log of) GDP per capita, which is included in the model along with country fixed effects and time dummies. This would create a problem of 'bad controls' (Angrist and Pischke, 2008), if these other variables were also included in the model. Moreover, country fixed effects will pick up country-specific time invariant differences, and general time trends and time-specific global shocks such as some improvements in technology will be captured by time fixed effects. In addition to avoiding bad controls, the more parsimonious specification also reduces problems of multi-collinearity and over-fitting.

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 begin with 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 four models with different dependent variables: (1)

4 We used an online calculator for this conversion (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								All Countries	n
	Low-income	n	Lower-middle	n	Upper-middle	n	Rich	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 population (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 population (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

Standard deviations are in parentheses.

infant mortality per thousand population; (2) child mortality per thousand population; (3) male life expectancy at birth; and (4) female life expectancy at birth. Explanatory variables included the proportion of energy derived from solid fuel consumption, male and female primary school enrolment (gross),[6] log of gross domestic product per capita, and the proportion of the population living in urban areas.

The general panel specification of our models is:

$$y_{it} = \beta_1 x_{it} + z_{it}\beta_2 + a_i + k_t + u_{it}, \; t = 1,2,3,\ldots\ldots\ldots.T \qquad (1)$$

Where:

y_{it} is the 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} represents a vector of other independent variables for country i in time period t;

z_{it} represents solid fuel consumption for country i in time period t;

a_i is a vector of country fixed effects;

k_t is a vector of time fixed effects;

β_1 and β_2 represent the coefficient for the independent variables; and

u_{it} is the idiosyncratic error term.

A particular issue for our reduced form specification is that solid fuel consumption may depend on various excluded and included variables such as taste preference, consumption habits, gender of the household head, household income, household size, education level, access to fuels, and other demographic variables (O'Neill and Chen, 2002; Mekonnen and Köhlin 2009; Jan et al., 2012; Lee, 2013; Irfan et al., 2021a). 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; and (2) annual production of natural gas (including LNG and LPG).

Both variables can be expected to affect the endogenous variable (solid fuel consumption), and are plausibly exogenous (i.e. have no direct effect on infant and child mortality or life expectancy). Households located near to forested areas are expected to consume more 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 fires across 31 countries[7] was only 18,400, which is certainly too small to have an appreciable impact on country-level mortality and life expectancy (World Fire Statistics, n.d.). Likewise, wildfires in Indonesia were associated with roughly 15,600 fetal, infant, and child mortalities were noted in 1997 (Jayachandran, 2009). However, deaths due to wildfire or forest fires have reduced significantly over time due to better equipment for firefighting and advancements in weather forecasting (Doerr and Santín, 2016).

Similarly, a country that has gas reserves is expected to consume less solid fuels because of the increased availability (and lower domestic price) of natural gas, LNG, and LPG. While production of gas is not expected to have an appreciable direct effect on

6 The number of children enrolled in primary schools, divided by the population of that age group and multiplied by 100. The variable is taken from WDI database.

7 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.

mortality or life expectancy. The adverse impact of fracking sites could be correlated with infants' health (mortality, low birth weight). However, the impact radius of fracking sites is only 1 km, and so the effect is expected to be minimal. For instance, informal estimates suggest only 29,000 of around 4 million birth occurs within 1 kilometer of active fracking sites in the United States (Currie et al., 2017). Furthermore, global data related to number of fatalities among those employed in gas extraction 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 in oil and gas related occupations in seven countries[8] was 8,386 (Hirschberg et al., 2004) and in the United States of America from 2003 to 2013 the corresponding number was 1,189 (Mason et al., 2015). Again, these numbers are too small to have an appreciable impact on country-level mortality. Moreover, gas extraction related mortality is more likely to affect adults than children.

While we are satisfied about the exogeneity of our instruments, we also accept the alternative view that they may not fully meet the exogeneity criteria. To check the robustness of our IV results, we also undertake the 'plausibly exogenous' bound estimation developed by (Conley et al., 2012). This method allows for statistical inference when a potential instrumental variable (IV) may be "close to," but not necessarily precisely, exogenous. Specifically, the Conley et al. (2012) method involves performing a sensitivity analysis of the coefficients when a small direct impact (referred to as γ) of the IVs on the dependent variable is allowed for. The (Conley et al., 2012) method allows two types of bounds testing for inference for IV: (1) the union of confidence interval (UCI) approach; or (2) the γ-local-to-zero (LTZ) approach. We used the Local-to-Zero (LTZ) approximation, as the UCI approach is not applicable when multiple instruments are used. The LTZ approach generates bounds of the coefficient of interest when the parameter γ is assumed to be drawn from $N(0, \delta^2)$ distribution, and the interpretation of the results of this sensitivity analysis is that if the IV-point estimates in the structural equation fall outside the bounds, then the results would be doubtful, but not otherwise. This sensitivity analysis is increasingly being employed when the exogeneity of IVs is doubtful, such as in Dang (2013), Roychowdhury (2017), and Tran et al. (2021).

Moreover, 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 also checked the correlation between the instruments and the log of GDP per capita. Table A1 in the appendix shows that one instrument (log of natural gas, LNG, and LPG) is significantly and positively associated with log of GDP per capita. We also ran the first stage regression without log of GDP per capita, and the results are presented in Table A2. The results are not sensitive to the exclusion of log of gas production or log GDP per capita. Furthermore, the suitability of the instruments was further tested for joint significance of endogenous (Anderson-Rubin Wald test, Stock-Wright LM S statistic) under-identification (Anderson canonical Correlation Lagrange multiplier statistics), over-identification (Sargan test), and weak identification (Cragg-Donald Wald F-statistic). The results of these tests are included in Table A3 in the appendix.

5. RESULTS AND DISCUSSION

We applied the Hausman test to identify whether random effects or fixed effects is the appropriate model specification. The test suggests that the fixed effect models are the appropriate specification. Hence, Table 2 presents the results of the fixed effects models. 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. Specifically, a one-percentage point higher proportion of household solid fuel use at the national level is associated with a 0.27 per thousand population higher infant mortality rate and a 0.53 per thousand population higher child mortality rate. A one-percentage point higher proportion of solid fuel use is also associated with 0.051 to 0.059 years lower life expectancy, with a slightly larger coefficient for women than men. These findings are consistent with the earlier results of Bloom et al. (2005), albeit our results utilise panel rather than cross-sectional data.

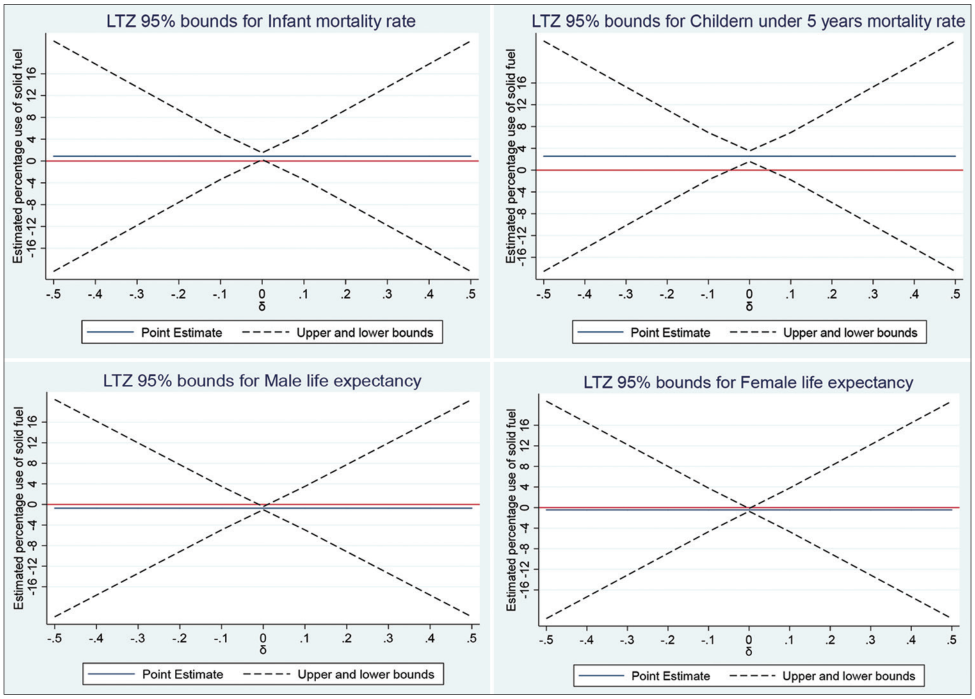
The coefficients on control variables are mostly as expected except male education. However, while female education has a negative association with both infant and child mortality, male education is positively associated with both variables. Our findings in this respect are the exact opposite to those of Bloom et al. (2005), who found that female education was positively and male education negatively associated with infant and child mortality (however, their coefficients were statistically insignificant whereas ours are significant). Similarly, we find that female education is positively associated with life expectancy, but male education is 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) has been previously found to be associated with lower solid fuel consumption (Pundo and Fraser, 2006; Acharya et al., 2014), which may explain our results. Moreover, mother's education play an important role in improving child's health (Chakrabarti, 2012). 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. Our IV regression analysis (see below) is run on a smaller sample of 105 countries for which we have data on the instrumental variables. We ran all fixed effect models with this smaller sample and the results are similar (Table A4 in the Appendix).

As previously noted, the proportion of household solid fuel use is likely to be endogenous. We applied the Anderson-Rubin Wald

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

Figure 1: γ-Local-to-zero (LTZ) approximation bounds tests for instruments validity



The estimates are generated by using STATA command plausexog by Clarke (2014)

Table 2: Fixed effect model results

	Infant mortality rate	Child mortality rate	Male life expectancy	Female life expectancy
Percent of solid fuel use	0.268*** (0.019)	0.534*** (0.038)	−0.051*** (0.004)	−0.059*** (0.005)
Female primary sch. Enrolment	−0.324*** (0.030)	−0.601*** (0.061)	0.038*** (0.007)	0.038*** (0.008)
Male primary sch. Enrolment	0.296*** (0.029)	0.548*** (0.060)	−0.034*** (0.007)	−0.034*** (0.007)
Log of GDP per capita	−5.490*** (0.474)	−7.771*** (0.971)	0.261** (0.113)	0.179 (0.122)
Urban % of population	−0.560*** (0.067)	−0.850*** (0.137)	0.073*** (0.016)	0.106*** (0.018)
_cons	108.760*** (5.068)	157.606*** (10.375)	58.853*** (1.203)	62.701*** (1.292)
Year fixed effects	Yes	Yes	Yes	Yes
R^2 (overall)	0.66	0.65	0.57	0.59
N	2,007	2,007	1,950	1,950
Number of countries	157	157	154	154

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

Country level clustered standard errors are in parentheses.

Table 3: First stage instrumental variable regression results for all models

Percentage of solid fuel consumption	Coefficients
Percentage of forest land of total land	0.707*** (0.113)
Log of Natural gas, LNG, LPG production	–0.441*** (0.090)
Female primary sch. Enrolment	–0.040 (0.029)
Male primary sch. Enrolment	0.033 (0.028)
Log of GDP per capita	–2.342*** (0.403)
Urban % of population	–0.610*** (0.065)
Year fixed effect	Yes
Number of countries	105
N	1289

*P<0.1; **p<0.05; ***p<0.01. Country level clustered standard errors are in parentheses

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. The first stage clearly satisfies the relevance restriction. As noted above, we also tested for under-identification, over-identification, and weak identification. The results of these tests are included in Table A3 in the appendix. The results of these tests confirm 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.

Finally, Table 4 presents the IV model (two-stage least squares) results. Although the sample size reduces from 157 and 154 to 105 (due to the unavailability of data on the instruments for some countries), the results support our hypothesis that solid fuel consumption causes increases in 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

Table 4: Instrumental variable regression results

Models	Infant mortality rate	Child mortality rate	Male life expectancy	Female life expectancy
Percent of solid fuel use	1.599*** (0.155)	2.892*** (0.272)	−0.0982*** (0.0279)	−0.144*** (0.0292)
Female primary sch. Enrolment	−0.132*** (0.0431)	−0.226*** (0.0757)	0.0120 (0.00774)	0.0180** (0.00811)
Male primary sch. enrolment	0.117*** (0.0417)	0.199*** (0.0732)	−0.00818 (0.00748)	−0.0141* (0.00785)
Log of GDP per capita	−2.742*** (0.706)	−2.831** (1.241)	0.363*** (0.127)	0.222* (0.133)
Urban % of population	0.152 (0.128)	0.249 (0.225)	0.0773*** (0.0231)	0.0945*** (0.0242)
Year fixed effects	Yes	Yes	Yes	Yes
R^2	0.502	0.461	0.757	0.739
N	1,289	1,289	1,289	1,289
Number of countries	105	105	105	105

*P<0.1; **P<0.05; ***P<0.01. Country level clustered standard errors are in parentheses.

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 increase in infant mortality of 1.599 per thousand population and a statistically significant increase in child mortality of 2.89 per thousand population. To get a sense of the size of these effects, the difference between the mean upper-middle income country and the mean low-income country in proportion of solid fuel use is 28.89% points in our sample. Ceteris paribus, this difference in solid fuel use would cause the infant mortality rate in low-income countries to be higher by 46.2 per thousand, and the child mortality rate in low-income countries to be higher by 83.5 per thousand, compared with upper-middle income countries.

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 0.098 years and female life expectancy at birth by 0.144 years. Again, considering the difference between the mean upper-middle income country and the mean low-income country, in low-income countries males are losing 2.8 years and females are losing 4.5 years of life expectancy at birth in low-income countries compared to upper-middle income countries. Other results are similar to the panel model in Table 2, except that male and female education becomes statistically insignificant in the model of male life expectancy, and urbanisation becomes insignificant in the models of infant and child mortality.

We further report the results of the sensitivity analysis, following Conley et al. (2012) in Figure 1 (the corresponding regression results are included in the appendix, Table A5). The LTZ approximation bounds do not encompass the zero line (with 95% confidence) only for very small values of δ, with somewhat greater confidence for mortality rates than for life expectancy. However, the bounds are relatively narrow, so that suggests that our results may be sensitive to violations of the exclusion restriction. As a whole, we interpret these results as showing the vulnerability of our results to violations of the exclusion restriction. As a result, further research should endeavor to identify alternative or additional instruments.

6. CONCLUSION

Almost half of the population in developing countries, and up to 90% of the 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, that not only affect child mortality directly but is also associated with water pollution, ocean pollution and climate change (Holdren, 1991). Our empirical results confirm this relationship using cross-country panel data. 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 are plausibly causal – increases in solid fuel use *cause* higher infant and child mortality and lower life expectancy. Nevertheless, our results are vulnerable to violations of the assumption of exogeneity of our instruments. We argue that they are exogenous, although there is no way to directly test this assertion, and further investigation of alternative instruments that perform better on the Conley et al. (2012) sensitivity analysis should be undertaken.

The effects that we identify are economically meaningful in terms of size. 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 and lower-middle income countries was reduced by 50% (10.31% points), infant and child mortality in the low-income countries would decrease by 16.5 and 29.8 per thousand population[9] respectively, and life expectancy at birth for males and females would increase by 1.01 and 1.5 years respectively. According to United Nations data,[10] low-income 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 deaths (combined) from reducing the solid fuel consumption gap between low-income countries and lower-middle income countries by half is approximately 2.85 million infant and child deaths averted per year.

Similarly, if the solid fuel consumption gap between lower-middle income countries and the upper-middle income countries was reduced by 50% (4.13% points), infant and child mortality in the lower-middle income countries would decrease by 6.61 and

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/

11.95 per thousand population 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 3.5 million infant and child deaths averted per year.

These back-of-the-envelope calculations suggest that there are significant potential mortality reductions and health gains available that can be obtained by reducing solid fuel consumption in low-income and middle-income countries. However, achieving these potential health gains will require direct policy intervention. As Irfan et al. (2021a) 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. In addition, various studies such as Hutton et al. (2007), Malla et al. (2011), Isihak et al. (2012), and Irfan et al. (2021b) have explored interventions to reduce the adverse impact of indoor air pollution in developing countries.

However, our results only demonstrate that there are substantial benefits in reducing solid fuel use (and even then, we have demonstrated only the benefits in terms of direct health gains and not those resulting from environmental quality improvements). Governments will need to weigh these potential benefits of reducing solid fuel consumption against the costs of doing so. The costs are especially salient for low-income 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 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: Association between log of GDP and instrumental variables

Log of GDP per capita	Coefficients
Percentage of forest land of total land	−0.003 (0.005)
Log of Natural gas, LNG, LPG production	0.012** (0.006)
Constant	7.920*** (0.223)
Year fixed effect	Yes
N	1,290
Number of countries	106

*P<0.1; **P<0.05; ***P<0.01. Country level clustered standard errors are in parentheses

Table A2: First stage instrumental variable regression results for all models without GDP

Percentage of solid fuel consumption	Coefficients
Percentage of forest land of total land	0.751*** (0.114)
Log of Natural gas, LNG, LPG production	−0.454*** (0.090)
Female primary sch. enrolment	−0.038 (0.029)
Male primary sch. enrolment	0.031 (0.028)
Urban % of population	−0.613*** (0.066)
Year fixed effects	Yes
N	1300
Number of countries	105

*P<0.1; **P<0.05; ***P<0.01. Country level clustered standard errors are in parentheses.

Table A3: Tests for instruments' validity

Statistical tests	Model 1 Infant mortality	Model 2 Child mortality	Model 3 Male Life expectancy	Model 4 Female Life expectancy
Under Identification test (Anderson canon. corr. LM statistics)	81.141***	81.141***	81.141***	81.141***
Over-identification test (Sargan statistics)	1.638	1.557	1.153	0.014
Weak identification test (Cragg-Donald Wald F statistic)	42.893	42.893	42.893	42.893

*P<0.1; **P<0.05; ***P<0.01. Cragg-Donald Wald F statistic is greater than 10% maximum relative bias (19.93) which means our instruments are not weak. Instrument 1: Percentage of forest area, Instrument 2: Log of annual natural gas, LNG, LPG production.

Table A4: Fixed effect models for 105 countries

Models	Infant mortality rate	Child mortality rate	Male life expectancy	Female life expectancy
Percent of solid fuel use	0.759*** (0.0329)	1.460*** (0.0586)	−0.135*** (0.00727)	−0.163*** (0.00770)
Female primary sch. enrolment	−0.195*** (0.0341)	−0.333*** (0.0608)	0.0103 (0.00753)	0.0176** (0.00798)
Male primary sch. enrolment	0.173*** (0.0331)	0.295*** (0.0591)	−0.00668 (0.00732)	−0.0138* (0.00776)
Log of GDP per capita	−4.945*** (0.475)	−6.588*** (0.848)	0.266** (0.105)	0.172 (0.111)
Urban % of population	−0.318*** (0.0781)	−0.554*** (0.139)	0.0548*** (0.0173)	0.0825*** (0.0183)
Constant	86.87*** (6.118)	123.3*** (10.92)	61.88*** (1.353)	66.48*** (1.434)
Year fixed effects	Yes	Yes	Yes	Yes
R^2	0.68	0.65	0.77	0.74
N	1,277	1,277	1,277	1,277
Number of countries	105	105	105	105

*P<0.1; **P<0.05; ***P<0.01. Country level clustered standard errors are in parentheses.

Table A5: Results of conley test for checking exclusion restriction

Variables	Infant mortality rate	Child mortality rate	Male life expectancy	Female life expectancy
Percent of solid fuel use	0.884*** (0.324)	2.560*** (0.492)	−0.716*** (0.154)	−0.444*** (0.139)
Female primary sch. enrolment	−0.769*** (0.108)	−0.909*** (0.167)	−0.0646 (0.0584)	0.0881** (0.0368)
Male primary sch. enrolment	0.689*** (0.105)	0.802*** (0.162)	0.0692 (0.0569)	−0.0706** (0.0356)
Log of GDP per capita	−6.876*** (0.893)	−7.044*** (1.294)	1.664*** (0.394)	2.339*** (0.335)
Urban % of population	−0.121*** (0.0340)	−0.0746 (0.0526)	−0.0126 (0.0185)	0.0141 (0.0157)
Constant	92.95*** (10.20)	95.60*** (15.64)	58.16*** (5.022)	54.14*** (4.209)
Year fixed effect	Yes	Yes	Yes	Yes
Observations	1290	1290	1290	1290

***P<0.01, **P<0.05, *P<0.1. Standard errors in parentheses.