The Demand, Selection, and Health Impacts of Household Energy in Pakistan

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Abstract

Globally, almost four million people die prematurely annually due to indoor air pollution (IAP), and millions are facing serious diseases. These adverse health impacts place a great burden on national health budgets, increase medical expenditures, and reduce the overall productivity of the economy. Worryingly, almost three billion people still depend upon solid fuels such as firewood, biomass, crop residues, animal dung, and coal, which are the major contributors to IAP. This thesis investigates the causal relationship between solid fuel consumption and both child mortality and life expectancy, the price and non-price determinants of solid fuel use (using Pakistan as a case study), and finally uses cost-benefit analysis (CBA) to evaluate alternative policies. Specifically, the thesis includes four empirical studies related to solid fuel use and IAP.

In the first study, panel data covering 101 countries over the period 2000-2012 were used to examine the causal impacts of solid fuel use on health outcomes. Utilizing an instrumental variables approach, it was concluded that solid fuel combustion *causes* increases in child mortality and decreases in male and female life expectancy.

The second study investigated the factors associated with the selection of solid and cleaner fuels by households. Using data from the Pakistan Social and Living Standards Measurement (PSLM) Survey 2013-14, the study identified that agricultural occupation, large family size, and having cattle, were associated with solid fuel consumption. In contrast, higher income, higher education, and living in an urban area were factors associated with cleaner fuel consumption. However, the study concluded that income growth alone will not be sufficient to ensure that

households switch to cleaner fuel use, particularly households in rural areas. Hence, the results challenge the practical aspects of countries moving along the Environmental Kuznets Curve, and suggest that in order to reduce IAP, direct policy intervention will be required.

The third study further explores household energy use by estimating the own and cross-price elasticities of household energy sources in Pakistan. For this, three PSLM data sets (2007-08, 2011-12, and 2013-14) were pooled and a Linear Approximate Almost Ideal Demand System model was estimated. The study found that cleaner fuels (natural gas, and liquefied petroleum gas (LPG)) were more price elastic than solid fuels, implying that lowering the prices of these cleaner fuels would lead many households to adopt them. In the final study, a CBA of several policy options for encouraging reductions in solid fuel use was undertaken. The study evaluated five major policy options: (1) natural gas; (2) LPG; (3) electric stoves; (4) biogas plants; and (5) improved cook stoves. The World Health Organization's guidelines for CBA were followed and it was found that encouraging LPG adoption has the highest benefit-cost ratio (BCR) of 3.68, while improved cook stoves had a BCR of 0.58. Encouraging natural gas adoption, electric stoves, and biogas plants have BCRs of 2.87, 2.22, and 1.39 respectively. The study concluded that, in order to mitigate the negative impacts of IAP, Pakistan should encourage cleaner energy sources in preference to adoption of alternative cooking appliances.

Note on Publications

Chapter 4 is published:

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Table of Contents

Chapter 1: Introduction

Air pollution is one of the largest challenges globally. It threatens the survival of human beings and puts the stability of the world in danger (Rockström et al., 2009). Pollution is directly associated with climate change, fossil fuel combustion, forest burning, inefficient cook stoves, and agricultural burns (Johnston et al., 2012). Consequently, it has become a cause for 85 percent of airborne particulate matter (PM) and almost all types of dangerous inhalable gases such as oxides of nitrogen, carbon, and sulphur (Landrigan et al., 2018). In the simplest way, pollution means anything solid or liquid present in the air. It generally includes smoke, soot, dust, fumes, and other inhalable gases that cause difficulties in breathing (Dockery, 2009), consequently adversely affecting human health and the environment.

In the early 20th century, respiratory infections were the main cause of death in the currently developed countries, but the death toll dramatically reduced mainly because of invention of the antibiotics and vaccination (Smith, Samet, Romieu, & Bruce, 2000). However, a reasonable reduction in mortality was observed before these medical interventions, perhaps due to the better nutrition and housing environment (Smith, et al., 2000). The potential contribution of exposure to indoor air pollution (IAP) to mortality, especially for children, has been acknowledged for only the last two decades. The World Health Organization (WHO) commenced a comparative risk assessment project in 2000, and estimated the burden of diseases due to IAP (Cohen et al., 2005). The findings of the project were published in Ezzati Lopez, Rodgers, & Murray, (2004), where it was concluded that IAP from the combustion of solid fuels such as firewood, animal dung, coal, charcoal, and crop residues[1] emits particulate matter (PM) and is associated with a range of health effects, from eye irritation to death. On the other hand, the use of clean fuels such as liquefied petroleum gas (LPG), piped natural gas, electricity, and biogas is negatively associated with IAP. Hence, these cleaner burning fuels have a number of health and environmental benefits (Goldemberg, Martinez-Gomez, Sagar, & Smith, 2018). However, the adoption of cleaner fuels is lacking in many countries, especially in low and middle-income countries, and this is mainly due to accessibility (Miele & Checkley, 2017).

Exposure to airborne PM has been consistently associated with adverse health impacts, and arguably, mortality due to IAP is one of the most important global problems (Cohen et al., 2005). There are two types of PM in the air: $PM_{2.5}$ and PM_{10}. The former type of particles are fine and have a diameter of no more than 2.5 micrometers, and the latter have a diameter of not more than 10 micrometers. Both types of PM are dangerous for health. However, $PM_{2.5}$ represents finer particulates that could be inhale relatively easier and hence results in larger adverse health impacts (Lu et al., 2015).

Solid fuel combustion is a fundamental source of fine $PM_{2.5}$ (Chafe et al., 2014) and exposure to it causes lung cancer, chronic obstructive pulmonary disease, stroke, ischemic heart disease, and premature death (Apte, Brauer, Cohen, Ezzati, & Pope, 2018). When solid fuels burn, they emit a combination of chemicals including cilia toxic, polycyclic aromatic hydrocarbons, nitrogen dioxide, formaldehyde, carbon monoxide, and other inhalable particulates. This ultimately damages the environment and people's health (Cooper, 1980; Torres-Duque, Maldonado, Pérez-Padilla, Ezzati, & Viegi, 2008). According to the Environmental

[1] These residues include stubble, leaves, bagasse, seed pods, cotton sticks, wheat straw, husks, roots, and corn stalks etc.

Protection Agency, in a household, the standard for carbon monoxide is 9 or 10 parts per million on average over 24 hours. However, in a household that consumes solid fuels for cooking and heating purposes, the average presence of carbon monoxide over 24 hours ranges between 2-50 parts per million and worryingly, it reaches 100-500 parts per million during cooking (National Ambient Air Quality Standards, 1997).

IAP is potentially hundreds of times more dangerous to health than outdoor air pollution (Smith & Mehta, 2003). According to recent estimates, globally, almost 4 million people die prematurely annually due to IAP[2] and millions more face serious diseases (Kim, Jahan, & Kabir, 2011). Pollution is predominantly accountable for more deaths than AIDS, tuberculosis, malaria, obesity, child and maternal malnutrition, alcohol, road accidents, or wars.

In many developing countries, solid fuels are often used for cooking and heating purposes. Thus, IAP is a greater problem in developing countries than in developed countries. It mostly affects women and children, because women usually cook food for their families, and children aged under five usually accompany their mothers (Edwards & Langpap, 2012). Children and infants do not have strong immune systems (Berman, 1991), so they are the most vulnerable to the health effects of IAP. Shockingly, babies born to women in households consuming solid fuels were noted to be 63 grams lighter than that of those women consuming cleaner energy sources such as gas and electricity in Guatemala (Boy, Bruce, & Delgado, 2002).

The household consumption of solid fuels not only badly affects the inhabitants' health, but also damages the environment. Because of woodcutting for

[2] http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

cooking and heating purposes, forests are depleting, especially in developing countries (Arnold, Köhlin, & Persson, 2006; Bhatt & Sachan, 2004). Nevertheless, forests are essential for environmental, health, social, and economic benefits and provide medicines, food, forest products, and social resources, as well as helping to reduce global warming. Forests influence climate through biological, chemical, and physical processes that affect hydrological balance and atmospheric composition (Bonan, 2008). Furthermore, deforestation causes an increase in downslope damages, flooding, on-site erosion, and a loss of agricultural productivity (Chomitz & Kumari, 1998).

The impact of IAP due to the consumption of solid fuel has primarily been analyzed with respect to environment damages, but it also has significant economic and health aspects such as premature deaths and diseases ultimately leading to an excessive burden on national budgets (Landrigan & Fuller, 2014). Due to mortality and morbidity, a country's productivity suffers, which adversely affects the gross domestic product of the country. With the financial loss, the welfare of those adversely affected by IAP and their families deteriorates (RenJie, BingHeng, & HaiDong, 2010).

Despite these substantial micro- and macro-level ill effects, the avoidance of IAP has not received the urgency it deserves at international level. Arguably, the most important reason for ignoring such an important issue is lack of awareness of the scope of the problem (Landrigan et al., 2018). In particular, there is a severe lack of empirical research at cross-country level investigating the relationship between health and household level solid fuel consumption.

Keeping in view this research gap, there is a great need to quantify the life loss cause by solid fuel consumption, so that countries can recognise the loss and respond appropriately to reduce it. In addition, to discourage solid fuel consumption, it may be necessary to understand what policy a government should adopt and whether there are better alternatives for households. Therefore, this thesis addresses four main research questions: (1) does solid fuel consumption at household level cause increases in mortality and decreases in life expectancy; (2) why do people choose solid and cleaner fuels; (3) how can price variations affect their fuel choices; and (4) what interventions are best to reduce IAP. Hence, this thesis contributes to the literature significantly and can provide an example for developing countries. It may help policy makers to form appropriate policy, as well as help national and international organizations who are trying to reduce IAP and its linked mortalities and morbidities.

Although an association between child mortality and solid fuel consumption has been found in the literature, the *causal* effect at cross-country level has not yet been adequately explored. Bloom, Zaidi, and Yeh (2005), and a recent report published in The Lancet by Landrigan et al. (2018), have recommended researchers to explore the causal relationship between IAP and ill health effects. Furthermore, over the last five decades, many policy analysts have developed compelling evidence about how IAP affects life expectancy; however, causal effects have not yet been sufficiently explored (Apte et al., 2018; Correia et al., 2013; Pope, Ezzati, & Dockery, 2009).

By taking into account the importance of the causal impact and research gap, Chapter 2 of this thesis explores the causal impact of solid fuel consumption on child mortality and life expectancy at cross-country level. In this chapter, 13 years of cross-country panel data from the year 2000 to 2012 are used, and it finds that an increase in solid fuel consumption at household level *causes* higher child and infant mortality and lower life expectancy. More specifically, a one percentage point increase in solid fuel consumption at household level leads to 1.30 per 1000 higher infant mortality and 2.44 per 1000 higher child mortality. Moreover, a one percentage point increase in solid fuel consumption at household level reduce female life expectancy at birth by 0.171 years and male life expectancy at birth by 0.132 years. If poor countries reach the level of upper middle income countries in solid fuel consumption, they can save 37.56 infants and 70.49 children per thousand. Similarly, 3.81 years could be added to male life expectancy and 4.94 years to female life expectancy. Hence, poor countries in particular are losing valuable lives because of higher household consumption of solid fuels.

Despite the adverse health and environmental impacts, the household consumption of solid fuels is very common in under-developed and developing countries. Astonishingly, the overall household consumption of solid fuels is expected to continue increasing until 2030 (Edwards & 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 (Landrigan et al., 2017). Especially in developing countries, the majority of households burn solid fuels in open places and use poorly functioning metal stoves, a three stone stove, or a U-shaped hole in a block of a clay. Consequently, due to poor ventilation a substantial amount of smoke emits and becomes a source of IAP (Bruce, Perez-Padilla, & Albalak, 2000). Exposure to IAP is not only a function of pollution but also various socio-economic factors.

According to the Environmental Kuznets Curve (EKC) theory, a country can grow out of environmental degradation as it develops, i.e. as its income grows (Kaika & Zervas, 2013). This concept has led many to assume that every country should focus on economic growth, and environmental issues would be ultimately eliminated by the process of economic growth (Kaika & Zervas, 2013). The inverted U-shaped EKC shows that at a particular point where countries achieve an adequate level of income per capita pollution will start reducing. The curve is similar to the original curve proposed by Kuznets (1955). Consequently, higher incomes reduce pollution and improve the quality of the environment. In support of the EKC, the "pollution-income relationship" paradigm states that *the best and the probably only way to achieve a decent environment is to become rich country* (Beckerman, 1992). However, the empirical support for the EKC theory in the literature is very mixed (Ali, Ashraf, Bashir, & Cui, 2017; Apergis & Ozturk, 2015; Stern, 2004).

Pakistan was selected as a particular case study for this thesis because it has diverse energy options including clean and dirty fuels, and is currently experiencing fast economic growth, which suggests a movement along the EKC. Perhaps, the increment in the per-capita income of the people will lead them to adopt cleaner fuels. Pakistan is located in South Asia and shares borders with Afghanistan, India, China, and Iran. It has an area of 796,096 km^2 and a population of 200 million (2018).[3] Pakistan has four provinces: the Punjab; Khyber Pakhtunkhwa; Sindh; and Balochistan; and two federally administrated territories: the Federally Administered Tribal Areas (FATA); and the Northern Areas. In addition, the territory of Azad Jammu and Kashmir (AJK) is under the administration of the Government of Pakistan. There is reasonable diversity to its socio-economic, environment, and climatic characteristics that differ significantly from region-to-region. The country has per capita gross domestic product (GDP) of USD 2000.

[3] http://worldpopulationreview.com/countries/pakistan-population/

Almost 64 percent of the population in Pakistan resides in rural areas and 24 percent of households are involved in agricultural related occupations. The urban population of Pakistan has easier access to cleaner fuels such as electricity and piped natural gas, while the rural population mostly relies on solid fuels such as crop residues, animal dung, and firewood. Like other middle-income countries, electricity, natural gas, LPG, firewood, crop residues, and animal dung, are the main cooking, heating, and lighting fuels in Pakistan.

Solid fuels, in the form of dry animal dung, agricultural waste or crop residues, and fuel wood contribute almost 36% of total energy supplies. In this way, solid fuel plays an important role in the primary energy mix demand of Pakistan. Pakistan’s large livestock and agricultural sector produces ample amounts of dry dung and agricultural waste in the form of roots, rice husks, bagasse, and corn stalks. These fuels are usually collected by the households and used outside the commercial economy as unprocessed fuel for cooking and heating purposes (Asif, 2009). On the other hand, renewable energy sources that use indigenous resources have the potential to provide clean energy services with zero or almost zero emissions of both air pollutants and greenhouse gases. In developed countries, most households have shifted from biomass to cleaner fuels due to modernization (Bruce et al., 2000).

Nevertheless, in developing countries households continue to consume solid fuels even when there are cleaner fuels available (Bruce et al., 2000). Various demographic, social, and economic factors are associated with the selection of household energy source. Similar to the EKC but at the household level, the energy ladder theory suggests that as the socio-economic status of a household increases, they tend to choose cleaner fuels for cooking and heating purposes (Hosier & Dowd, 1987; Leach, 1992). Cleaner fuels are more convenient and efficient, but also more costly than solid fuels. As the income of a household increases it tends to move upward on the energy ladder because of better purchasing power. The bottom step of the ladder is animal dung, and then second step is crop residues, and then firewood or coal, and then kerosene oil, and then LPG or piped natural gas, and then last upper step is electricity (Bruce et al., 2000).

However, many households do not jump from one fuel to another fuel instantly with an increase in their socio-economic status. Instead, they keep using some of the former energy source (Campbell, Vermeulen, Mangono, & Mabugu, 2003; Heltberg, 2004). This is referred to as energy stacking. In other words, households consume more than one fuel at a time and gradually shift from combinations predominantly based on solid fuels to combinations predominantly based on cleaner fuels. Surprisingly, to date no study has investigated the factors associated with the actual fuel *mix* choices of households, with the fuel mixes determined by the actual choices of households in the sample. Some studies have arbitrarily determined fuel use combinations *a priori* for analysis, but this may lead to biased estimates.

To avoid this important discrepancy, Chapter 3 of the thesis first grouped household fuel mix choices into categories using cluster analysis. This approach makes optimal use of the actual fuel mixes observed in the dataset, and avoids arbitrary decisions about which fuels make up a given fuel mix. This cluster analysis approach distinguishes this study from previous studies on fuel selection, where fuel selections have been either treated independently (Edwards & Langpap, 2012; Farsi, Filippini, & Pachauri, 2007; Nasir, Murtaza, & Colbeck, 2015; Osiolo, 2009; Ouedraogo, 2006; Pundo & Fraser, 2006) or where fuel mixes have been arbitrarily determined by the researchers (Lee 2013, Narasimha Rao & Reddy 2007, and Heltberg 2005). This approach is more appropriate for designing policy to encourage the use of cleaner fuels and discourage the use of dirty fuels, because it better reflects the actual fuel mix decisions of households.

The study finds that income, education, and urban area were significantly associated with cleaner fuel mix selection, while agricultural occupation, large family size, and having cattle were associated with dirty or solid fuel mix selection. Although income was the one of the most important factors associated with fuel selection in the extant literature, the analysis shows that Pakistan cannot grow out of solid fuel consumption relying only on increasing household incomes. Instead, access and availability of cleaner fuels will need to be addressed. Hence, this study contradicts the EKC, pollution-income relationship, and energy ladder theories.

After looking into the non-price factors associated with household energy selection in Chapter 3, Chapter 4 of the thesis looks at the impact of expenditures and price changes on fuel consumption at the household level. To estimate the price and income elasticities of each fuel, three PSLM data sets (2007-08, 2011-12, and 2013-14) were pooled. The datasets did not include market price information, so unit prices of the fuels were estimated by dividing total monthly expenditures on each energy source by total monthly quantity consumed by each household, and then the Linear Approximate Almost Ideal Demand System (LA-AIDS) model (Deaton & Muellbauer, 1980) was applied. Interestingly, the estimates obtained from this analysis substantially differ from those of an earlier study conducted by Burney & Akhtar (1990) in Pakistan. Astonishingly, they found a positive own price elasticity for firewood in urban areas and extremely low own price elasticities (close to zero) for other energy sources.[4] The results of Burney and Akhtar (1990) are clearly implausible and are also very different from other countries in the region. In contrast, the coefficients reported in Chapter 4 of this thesis are similar in sign to studies from other developing countries.

The analysis revealed that clean fuels such as piped natural gas and LPG are more price elastic than firewood, crop residues, and kerosene oil. Piped natural gas was the most price elastic energy source, and households residing in rural areas had more elastic demand than urban households for clean energy sources, perhaps because of the availability of cheaper solid fuel options in rural areas. On the other hand, cross price elasticities show that lowering the price of LPG could significantly reduce solid fuel consumption, especially in rural areas. In contrast, taxing solid fuels is not an appropriate policy option, because of poor market mechanisms. That is, many households do not buy animal dung and crop residues; therefore, it could be hard for the government to bring them into the tax net. Hence, if the government wants to reduce the consumption of solid fuels, it will be most effective to subsidise LPG.

Governments have limited budget to provide subsidies, and there are competing alternatives other than taxes and subsidies that could be used to address IAP. Therefore, Chapter 5 explores five clean fuel interventions[5] that can be considered for reducing the health and other ill impacts of IAP. To identify which clean fuel intervention is the best intervention to eliminate IAP, cost-benefit analysis is applied. In this chapter, five major interventions were considered: piped natural gas; LPG; electric stoves; biogas plants; and improved cook stoves. Earlier

[4] Natural gas, kerosene oil, and electricity.
[5] The term 'intervention' is used for consistency with World Health Organization guidelines (Hutton & Rehfuess, 2006).

studies have mostly only considered one intervention, while some studies included two or three interventions. Moreover, not a single study has considered the case of Pakistan, except as part of a larger region. This presents a problem, because cost-benefit ratios may differ from country to country due to differences in climate, infrastructure, and energy consumption behavior (Fullerton, Bruce, & Gordon, 2008).

Data from various domestic and international institutes' websites, research studies, and government institutes were used for the analysis. The World Health Organization's procedure of estimating the costs and benefits of household energy interventions was followed (Hutton & Rehfuess, 2006). All of the interventions had benefit-cost ratios greater than one except improved cook stoves. LPG had the highest benefit-cost ratio (3.68). Conversely, improved cook stoves had a benefit cost ratio of 0.58 meaning that the benefits from this intervention are less than the costs. The adoption of the improved cook stoves has been an unsuccessful intervention in many regions of the world (Hutton, Rehfuess, & Tediosi, 2007). Households adopting improved cook stoves do not stop consuming solid fuels and this could explain the low benefit-cost ratio. The estimates of this chapter support the findings of the Chapter 4, in that wider adoption of LPG is the best intervention to reduce IAP. Furthermore, net present value and internal rate of return also recommend the LPG as the best intervention.

This thesis highlights the harms caused by solid fuel consumption in terms of IAP, the factors associated with it, and ways to reduce solid fuel consumption. The overall contribution and summary of this research study is summarised in Chapter 6. The chapter also discusses the main policy implications and limitations of the thesis, and presents considerations for future research.

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Chapter 2: The causal impact of solid fuel use on mortality – A cross-country panel analysis[6]

2.1 Introduction

Today, pollution[7] 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 9 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, asthama, tuberculosis (TB), sinus problems, cardiovascular diseases, and cancer (Kim, Jahan, & Kabir, 2011; Lakshmi et al., 2012; Mishra, 2003b). The consumption of solid fuels remains higher in rural areas than urban areas (Irfan, Cameron, & 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 5 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).

[6] Note: The chapter is under review:
Irfan, M., Cameron, M. P., & Hassan, G. (under review). The causal impact of solid fuel use on mortality – A cross-country panel analysis. *Applied Economics.*

[7] Including all kind of pollution such as air pollution, noise pollution, light pollution, plastic pollution, and water pollution etc.

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 & Fuller, 2014). Pollution also damages the environment, and forests are depleting because of the excessive use of firewood as a cooking source (Arnold, et al., 2006). Worryingly, the overall consumption of solid fuel at household level is also expected to continue increasing until 2030 (Edwards & 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 & 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 (2003), Bloom et al. (2005), and Acharya Mishra, and Berg-Beckhoff (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 chapter 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 chapter is structured as follows. Section 2.2 discusses the relevant literature, Section 2.3 discusses the data and variables, and Section 2.4 presents the methodology. In Section 2.5 we discuss the results, and Section 2.6 concludes the chapter.

2.2 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, Mathee, Thomas, and Bruce (2009) found positive associations between ARI and solid fuel consumption among children under five years. Using panel data from India, Upadhyay, Singh, Kumar, and Singh (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 chapter 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).

2.3 Data and variables

Panel data has many advantages over time series and conventional cross-sectional data (Hsiao, Hammond, & 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),[8] and child and infant mortality rates data were obtained from the World Health Organization (WHO).[9] 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.[10] 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.[11] In the IV regression (described in the following section), we include the percentage of forested area, total production of

[8] https://data.worldbank.org/data-catalog/world-development-indicators
[9] http://www.who.int/gho/en/
[10] https://unstats.un.org/unsd/energy/edbase.htm
[11] We used an online calculator for this conversion (https://www.convertunits.com/from/tons/to/terajoule)

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.[12] 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.

[12] 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	299	10.09	505	1.82	599	0.32	619	7.69	2022
	(19.03)		(17.02)		(6.88)		(0.63)		(15.69)	
Infant mortality rate per thousand (0-27 days)	74.00	299	44.72	506	24.37	606	7.02	624	31.40	2035
	(21.28)		(22.44)		(18.96)		(5.51)		(28.56)	
Child mortality rate per thousand (1-59 months)	118.94	299	61.05	506	31.1	606	8.31	624	44.48	2035
	(40.86)		(36.07)		(29.46)		(6.49)		(46.64)	
Female primary school enrolment (gross)	75.96	299	89.84	506	84.20	606	91.72	624	86.69	2035
	(42.25)		(35.92)		(42.74)		(31.74)		(38.24)	
Male primary school enrolment (gross)	87.78	299	93.42	506	86.13	606	92.37	624	90.09	2035
	(42.91)		(93.42)		(43.86)		(32.03)		(38.64)	
Log of GDP per capita (USD)	5.95	297	7.03	500	8.31	601	10.02	617	8.16	2015
	(0.50)		(0.69)		(0.65)		(0.75)		(1.60)	

Total population (millions)	15.54	298	59.90	506	48.84	606	14.60	624	36.20	2034
	(15.60)		(186.43)		(190.62)		(24.51)		(141.63)	
Percentage of Urban population	26.99	298	41.24	506	59.77	606	75.70	624	55.24	2034
	(10.25)		(17.01)		(15.12)		(18.71)		(23.72)	
Percentage of Forest area of total area	21.86	299	29.92	506	38.27	606	28.33	624	30.73	2035
	(15.30)		(23.90)		(25.09)		(22.27)		(23.35)	
Log of LNG, LPG, and natural gas	4.55	73	7.24	301	9.49	428	9.45	499	8.68	1301
production (terajoule)	(4.57)		(7.15)		(5.64)		(5.50)		(6.07)	
Log of fuel oil and crude oil production	5.58	40	7.60	344	8.92	438	8.90	487	8.47	1297
(metric tons)	(2.04)		(2.10)		(2.36)		(1.87)		(2.23)	

Standard deviations are in ( )

2.4 Methodology

Our hypothesis is that increasing solid fuel consumption at household level causes indoor air pollution and 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) and 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:

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

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 the independent variables;

a_i is the unknown intercept for each country;

β_1 represents 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 household income, education level, access to the fuels, and other demographic variables that are also included in the regression model (Jan, Khan, & Hayat, 2012; Lee, 2013; Irfan, Cameron, & 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):

$$y_{it} = \beta_1 x_{it1} + \beta_2 x_{it2} + \beta_3 z_{it3} \ldots\ldots + \beta_k x_{itk} + a_i + u_{it}\,, \qquad t = 1,2,3,\ldots T \tag{2}$$

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 (i.e. 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 & 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 countries[13] are only 18,400, which is certainly too small to have an appreciable impact on country-level mortality (World Fire Statistics, 2017). Moreover, causalities due to wildfire or forest fire are reducing significantly due to better

[13] 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.

equipment for firefighting and advancements in weather forecasting (Doerr & 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 countries[14] were 8,386 (Hirschberg, Burgherr, Spiekerman, & Dones., 2004) and in the United States of America from 2003 to 2013 were 1,189 (Mason, Retzer, Hill, & Lincoln., 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.

[14] Afghanistan, Brazil, Egypt, Mexico, Philippines, Russia, and South Korea.

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:

$$y_{it} = \beta_1 x_{it1} + \beta_2 x_{it2} + \beta_3 z_{it3} + \beta_3 D_{it4} \; \ldots\ldots + \beta_k x_{itk} + a_i + u_{it}\,,$$

$$t = 1,2,3,\ldots T \qquad (3)$$

2.5 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 was the appropriate specification.[15] 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

[15] Results were: Prob>chi2 < 0.001 suggesting to apply fixed effect models.

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 & 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 (these results are presented in Table A3 in the Appendix).

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	0.534	-0.044	-0.051	-0.059
	(0.019)**	(0.038)**	(0.004)**	(0.004)**	(0.005)**
Female primary sch. enrolment	-0.324	-0.601	0.056	0.038	0.038
	(0.030)**	(0.061)**	(0.007)**	(0.007)**	(0.008)**
Male primary sch. enrolment	0.296	0.548	-0.053	-0.034	-0.034
	(0.029)**	(0.060)**	(0.007)**	(0.007)**	(0.007)**
Log of GDP per capita	-5.490	-7.771	0.115	0.261	0.179
	(0.474)**	(0.971)**	(0.116)	(0.113)*	(0.122)
Urban % of population	-0.560	-0.850	0.068	0.073	0.106
	(0.067)**	(0.137)**	(0.017)**	(0.016)**	(0.018)**
_cons	108.760	157.606	62.528	58.853	62.701

	(5.068)**	(10.375)**	(1.229)**	(1.203)**	(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, Gray, Mihaylova, & Clarke., 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 sch. enrolment	0.006 (0.029)
Male primary sch. enrolment	-0.011 (0.029)
Log of GDP per capita	-1.767 (0.370)***
Urban % 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 increase in infant mortality of 1.30 per thousand and a statistically significant increase 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.

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.

Table 4. Instrumental variable regression results

Models	Infant mortality rate	Child mortality rate	Both sex Life expectancy	Male life expectancy	Female life expectancy
Percent of solid fuel use	1.298	2.435	-0.102	-0.132	-0.171
	(0.092)**	(0.167)**	(0.018)**	(0.020)**	(0.021)**
Female primary sch. enrolment	-0.046	-0.078	0.031	-0.009	-0.005
	(0.037)	(0.067)	(0.007)**	(0.008)	(0.008)
Male primary sch. enrolment	0.037	0.062	-0.028	0.011	0.008
	(0.036)	(0.065)	(0.007)**	(0.008)	(0.008)
Log of GDP per capita	-4.510	-5.766	0.217	0.351	0.257
	(0.506)**	(0.914)**	(0.099)*	(0.109)**	(0.113)*
Urban % of population	0.042	0.111	0.019	0.037	0.050
	(0.084)	(0.151)	(0.016)	(0.018)*	(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

2.6 Conclusion

Almost half of the population in developing countries, and up to 90% 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 thousand [16] 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, [17] 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

[16] Coefficients of infant and child mortality from causal regressions (table 4) are multiplied by the reduced gap.
[17] https://esa.un.org/unpd/wpp/Download/Standard/Population/

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 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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2.7 Appendix

Table A1. Random effects regression of the percent of biomass fuel use on life expectancy at birth for both sexes combined

Models	**Both sex life expectancy at birth**
Percent of solid fuel use	-0.047
	(0.005)**
Female primary sch. enrolment	0.059
	(0.007)**
Male primary sch. enrolment	-0.056
	(0.007)**
Log of GDP per capita	0.522
	(0.113)**
Urban % of population	0.140
	(0.013)**
Constant	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)	<0.001	<0.001	<0.001	<0.001	<0.001
Joint significance of endogenous (Anderson-Rubin Wald test)	<0.001	<0.001	<0.001	<0.001	<0.001
Over Identification test for all instruments (Sargan statistic)	0.025	0.186	<0.001	<0.001	<0.001
Weak identification test (Cragg-Donald Wald statistic)	<0.001	<0.001	<0.001	<0.001	<0.001

Table A2a. Tests for Individual instruments

Test for	For All models		
	Instrument 1 (p-value)	Instrument 2 (p-value)	Instrument 3 (p-value)
Under Identification test (Anderson canon. corr. Lagrange multiplier statistic)	<0.001	<0.001	<0.100
Joint significance of endogenous (Anderson-Rubin Wald test)	<0.001	<0.001	<0.001
Over Identification test for all instruments (Sargan statistic)	<0.001	<0.001	<0.001
Weak identification test (Cragg-Donald Wald statistic)	<0.001	<0.001	<0.100

Instrument 1: Percentage of forest area, Instrument 2: Log of annual natural gas, LNG, LPG production.

Instrument 3: Log of annual crude and fuel oil production

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	1.214	-0.065	-0.107	-0.129
	(0.029)**	(0.053)**	(0.007)**	(0.008)**	(0.008)**
Female primary sch. enrolment	-0.078	-0.134	0.034	-0.007	-0.003
	(0.031)*	(0.056)*	(0.007)**	(0.008)	(0.008)
Male primary sch. enrolment	0.066	0.112	-0.031	0.010	0.005
	(0.030)*	(0.054)*	(0.007)**	(0.008)	(0.008)
Log of GDP per capita	-6.123	-8.677	0.306	0.409	0.356
	(0.385)**	(0.695)**	(0.090)**	(0.100)**	(0.103)**
Urban % of population	-0.234	-0.388	0.033	0.046	0.067
	(0.063)**	(0.114)**	(0.015)*	(0.016)**	(0.017)**
Constant	90.716	129.320	65.474	61.463	66.184
	(5.015)**	(9.060)**	(1.177)**	(1.310)**	(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 sch. enrolment	0.006 (0.029)
Male primary sch. enrolment	-0.011 (0.028)
Log of GDP per capita	-1.767 (0.370)***
Urban % 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

Chapter 3: Can income growth alone increase household consumption of cleaner fuels? Evidence from Pakistan[18]

3.1 Introduction

Solid fuel use in developing countries, and the resulting indoor air pollution, is a critical issue for health and development and is a major contributor to the global burden of disease (Huttunen, 2018). Globally three billion people depend upon solid fuels such as coal, charcoal, firewood, animal dung, and crop residues[19] for heating and cooking purposes (Landrigan *et al.,* 2017). Most of the indoor air pollution, and related adverse health outcomes, occurs in developing countries, and much less in developed countries. This makes it tempting to suggest that developing and middle-income countries could 'grow out of' their reliance on solid fuels for cooking and heating, and thus economic development could help solve the problem of indoor air pollution. The theoretical underpinning of this suggestion is based on the 'energy ladder model' (Hosier & Dowd, 1987) and the Environmental Kuznets Curve (Shafik & Bandyopadhyay, 1992).

The energy ladder model (described further in the following section) suggests that as household incomes rise, the household will reduce solid fuel use in favour of cleaner-burning fuel technologies such as natural gas. There is some empirical support for this contention. For instance, based on a study of Indian households, (Edwards & Langpap, 2012; Farsi, *et al.*, 2007; Nasir, *et al.*, 2015; Osiolo, 2009; Ouedraogo, 2006; Pundo & Fraser, 2006) conclude that "lack of

[18] Note: The chapter is under review:
Irfan, M., Cameron, M. P., & Hassan, G. (under review). Can income growth alone increase household consumption of cleaner fuels? Evidence from Pakistan. *World Development.*

[19] These residues include cotton sticks, bagasse, husks, wheat straw, roots, corn stalks, stubble, leaves and seed pods, etc.

sufficient income is one of the main factors that retard households from using cleaner fuels." Similarly, (Edwards & Langpap, 2012; Farsi et al., 2007; Nasir et al., 2015; Osiolo, 2009; Ouedraogo, 2006; Pundo & Fraser, 2006) find that "The only variable that has real impact on energy preference is household income" in Burkina Faso. Many other studies have argued that higher income is the main factor associated with reduction of solid fuel consumption at the household level (Edwards & Langpap, 2012; Farsi et al., 2007; Nasir et al., 2015; Osiolo, 2009; Ouedraogo, 2006; Pundo & Fraser, 2006)

The Environmental Kuznets Curve describes a hypothesised inverted U-shaped relationship between an environmental impact (e.g. indoor air pollution, or the health impacts of such) and income per capita. The implication is that as a country develops from a low level of income per capita, the environmental impact indicator at first becomes worse, but as the country further develops the relationship reverses and environmental impact begins to decline. While the micro-level evidence on the energy ladder model seems to support a negative relationship between indoor air pollution and household income, the overall evidence for the Environmental Kuznets Curve is very mixed (Ali, Ashraf, Bashir, & Cui., 2017; Apergis & Ozturk, 2015; Stern, 2004).

The objective of our study is firstly to identify the non-price factors associated with fuel selection in Pakistan. The novelty of our approach is that, unlike most previous studies, we recognize that households' choice to use any particular fuel is not independent of their choice to use other fuels. Thus, rather than looking at the factors associated with use of each fuel individually, we first group household fuel *mix* choices into categories using cluster analysis. This data-driven approach to defining household fuel mix selection more accurately reflects that the decision to use a particular fuel type is not made independent of the other fuels that households already use. While there have been many studies to date that have investigated the factors associated with solid fuel use in developing countries, most of these studies share an (often unstated) underlying assumption that fuel use choices are independent of each other.

Clearly, a household's choice to use one fuel is not made independently of their choice of whether or not to use other fuels. Given the reliance on this assumption, the extant literature lacks robustness. In contrast, our approach makes optimal use of the actual fuel mixes observed in the dataset, and avoids arbitrary decisions about which fuels make up a given fuel mix. This cluster analysis approach distinguishes our study from previous studies on fuel selection, where fuel selections are either treated independently (Edwards & Langpap, 2012; Farsi *et al.*, 2007; Nasir et al., 2015; Osiolo, 2009; Ouedraogo, 2006; Pundo & Fraser, 2006) or where fuel mixes are arbitrarily determined by the researchers (Lee, 2013; Narasimha Rao & Reddy, 2007; Heltberg 2005). Moreover, our treatment of fuel mix selection is more appropriate for designing policy to encourage the use of cleaner fuels and discourage the use of dirty fuels, because it better reflects actual fuel mix decisions of households, who likely do not make decisions about use of each fuel independently of their use of other fuels (World energy outlook, 2006)[20].

Second, we extent our analysis to consider the feasibility of increases in household income leading to meaningful changes in the adoption of cleaner burning fuels. Specifically, we use our empirical model results to identify income thresholds beyond which more than 50 percent of households would shift to cleaner fuel mixes. We identify these thresholds separately for rural and urban households. The

[20] https://www.iea.org/publications/freepublications/publication/cooking.pdf

remainder of the chapter is organized as follows. Section 3.2 provides additional background and discusses relevant literature, and in Section 3.3 we discuss the data and methodology. Section 3.4 presents the results of our analyses. Section 3.5 summarizes our findings and concludes and suggests some policy implications.

3.2 Background and literature review

The combustion of these solid fuels emits a multitude of complex chemicals including carbon monoxide, nitrogen dioxide, polycyclic aromatic hydrocarbons (PAH), formaldehyde, and other inhalable particulates, damaging people's health and the environment (Cooper, 1980; and Torres-Duque, et al., 2008). As a result of solid fuel use, almost 4 million people around the world die prematurely each year due to indoor air pollution[21], and millions more face serious diseases such as asthma, lung infections, eye infections, sinus problems, tuberculosis (TB), and cardiovascular diseases (Mishra, 2003; Kim, *et al.*, 2011; Kim *et al.*, 2011; Lakshmi *et al.*, 2012; Sehgal, Rizwan, & Krishnan., 2014). The number of annual deaths attributed to acute respiratory infections (ARI) among children under age five in Pakistan has been estimated at 51,760, with a further 18,980 annual deaths due to chronic obstructive pulmonary disease (Colbeck, Nasir, & Ali., 2010).[22]

The trade-offs associated with solid fuel as a source of energy not only occur for human health, but also for the environment. The forests of developing countries are progressively depleting due to the use of wood as a household cooking fuel (Arnold, et al., 2006; Bhatt & Sachan, 2004). Forests are necessary for economic, ecological, social, environmental, and health benefits, and provide food, medicines,

[21] http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health
[22] http://www.who.int/indoorair/publications/indoor_air_national_burden_estimate_revised.pdf?ua=1

forest products, and social resources, as well as helping to reduce climate change (Bonan, 2008).

Despite the adverse effects of biomass fuels on health and the environment, the use of solid fuels for cooking, lighting and heating purposes remains very common in developing and middle-income countries. Household fuel selection is associated with many socio-economic factors, of which household income is among the most important. The energy ladder model contends that households will switch from biomass to modern fuels, such as natural gas and electricity, as their income (or socio-economic status) rises (see Figure 1). The energy ladder model shows a three-stage fuel switching process. In the first stage, households use traditional solid fuel sources, such as agricultural waste, animal waste, and firewood. As their socio-economic status improves, households move upwards along the energy ladder, and use somewhat-cleaner fuels such as charcoal, kerosene, and coal. At the highest level of the energy ladder, households switch to using advanced 'clean' fuels like natural gas, LPG, biofuels, and electricity (Hosier & Dowd, 1987; Leach, 1992).

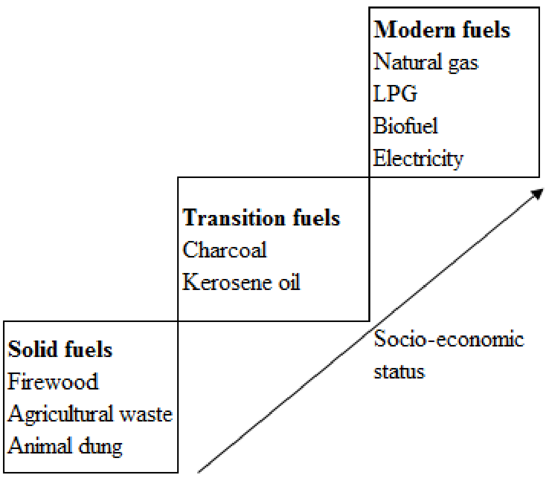

Figure: 1 Energy Ladder

However, for most households, energy switching does not occur on a series of simple discrete steps as suggested by the linear energy ladder model (Campbell et al., 2003) . Instead, the concurrent use of multiple fuels is common. Moreover, as household income increases, many households continue to use some amount of the fuels from the lower steps on the ladder. This is referred to as fuel stacking or energy stacking (see Figure 2). The energy transition shown in Figure 2 is a bi-directional process, as users can go up or down the ladder, while some continue to use traditional fuels alongside more advanced fuels. However, once households achieve the highest socio-economic status, most will only use modern fuels such as natural gas, LPG, biofuel, and electricity (Campbell et al., 2003; Heltberg, 2004; Pachauri & Jiang, 2008).

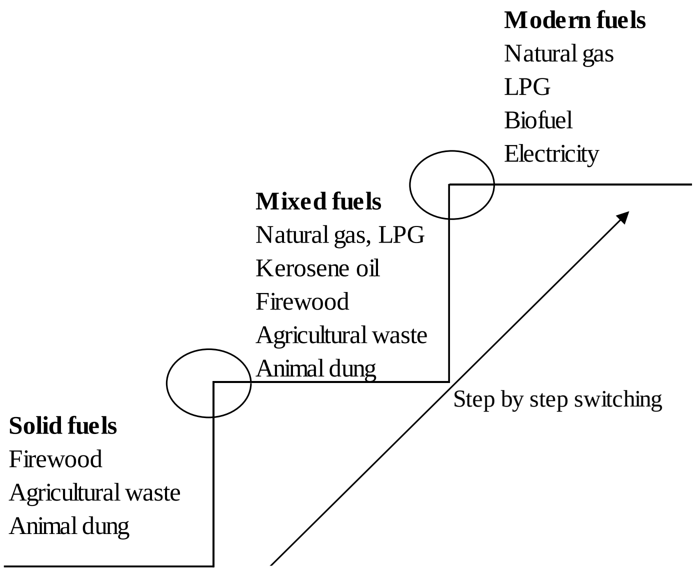

Figure 2: Energy Stacking

In Pakistan, like many other middle-income countries, evidence of fuel stacking is observable. Electricity, firewood, natural gas, crop residues, animal dung, and Liquefied Petroleum Gas (LPG) are the main fuels used for cooking and heating. In contrast, electricity is used for lighting. In rural areas, the consumption of solid fuels such as firewood, dry animal dung, and crop residues is higher than in urban areas. On the other hand, the consumption of clean energy sources such as natural gas is higher in urban areas than rural areas. Accessibility to fuels may be one of the main causes of consuming any specific fuel. In this chapter, we identify the factors associated with households' choice of fuel mix, contrasting fuel mixes that are heavily concentrated on solid fuels with those that include more modern fuels such as piped natural gas and LPG.

Many studies have investigated the determinants of households' fuel selection in developing countries. However, few of these studies investigate households' selection of *fuel mix*, and those that do use arbitrarily determined fuel mixes (that is, where the fuel mixes to be investigated are identified *a priori* by the researchers). Those research studies that investigate fuel use combinations at the household level have been limited to descriptive analyses of the fuel use combinations. Overall, the extant literature on the determinants of fuel selection mainly focuses on households' use of individual fuels, often their most commonly or extensively used fuel. These studies identify many socio-economic and demographic variables that are associated with the selection of household fuels including income, education, gender, household location (rural or urban), family size, land holding, and livestock holding.

Most studies have investigated the factors associated with household's fuel selection by only considering individual fuels, such as Farsi et al. (2007), who investigated the factors associated with fuel choice (firewood, kerosene, and LPG) for cooking in urban India. Based on the energy ladder as a theoretical framework, they applied an ordered probit model. They found that income and education were positively related to the use of LPG and that female-headed households were also more likely to adopt LPG. Similarly, Ouedraogo (2006) studied the determinants of fuel choice in Burkina Faso. A multinomial logit model was applied and they concluded that lower income was a significant constraint for the adoption of LPG, in comparison to firewood. In rural Kenya, Pundo and Fraser (2006) found that education of the wives of household heads played a vital role in fuel choice; as education of the wives increases the use of fuelwood decreases and the use of comparatively cleaner fuel like kerosene increases.

In Kenya, Osiolo (2009) examined fuel selection among firewood, charcoal, kerosene, LPG, and electricity. Total expenditure (a proxy of income) and education were positively associated with the adoption of kerosene, LPG, and electricity. On the other hand, they found that kerosene and LPG were less likely to be used in rural areas. Likewise, Jumbe and Angelsen (2011) applied a multinomial probit model on data from 404 households in 31 villages surrounding two forests in Malawi. They found that the distance to the firewood source, firewood species, and area of the firewood source were important determinants of selecting firewood as a fuel source. In Madhya Pradesh state in India, Sehjpal, Ramji, Soni, and Kumar (2014) collected data from 200 rural households and applied binary logit models to investigate households' selection between traditional and modern fuels. They found that if women got engaged in income generating activities, the chances of selecting cleaner fuels would increase. Moreover, other factors such as education, price of the fuels, and the availability of electricity connections were also important factors in fuel selection. Similarly, Rahut, Das, De Groote, and Behera (2014) applied a multinomial logit model on 2007 Bhutan Living Standard Survey data and found that female-headed households were more likely to adopt clean fuels such as LPG and electricity. In another study conducted in Bhutan, Rahut *et al.* (2014) found that higher education, higher income and female headed households were more likely to adopt cleaner fuels such as LPG and electricity.

Unlike the choice among individual fuels, fuel use combinations are rarely examined in the literature. Studies using fuel use combinations have generally not applied any statistical or econometric techniques to form the fuel mix combinations. For example, Heltberg (2005) made the fuel use combinations on his own (LPG only; wood only; LPG and wood; and LPG and charcoal) and using data from Guatemala he found that the prices of fuels play a vital role. Especially the price of solid fuels such as firewood significantly affects the quantity demanded. Furthermore, he found that households with higher education tend to consume cleaner fuels such as LPG and electricity. Similarly, Narasimha Rao and Reddy (2007) investigated the factors associated with fuel selection in India. They found that the education of the household head and household income played significant roles in the selection of cleaner fuels, such as biofuels and LPG.

Lee (2013) found that education and income are the key factors associated with fuel consumption in Uganda. They found that, as income and education increases the consumption of solid fuels decreases. Similarly, Jan, et al., (2012) explored the determinants of rural household energy choice in Pakistan by collecting data from 100 randomly selected households. They found that income was not the only factor associated with the cleaner fuel selection, the preference of the consumer and access to the alternative sources also played important role in fuel selection. In another study, Nasir, *et al.*, (2015) examined fuel choice in Pakistan and found that household location (urban or rural), availability of natural gas and electricity, and poverty were the main factors associated with fuel selection, while poverty was the main hindrance to the selection of clean fuels such as natural gas (piped gas) and LPG.

Some other studies have also used descriptive statistics to form fuel mixes, such as Brouwer and Falcão (2004) in Mozambique, Joon, Chandra, and Bhattacharya (2009) in India, Miah, Foysal, Koike, and Kobayashi (2011) in Bangladesh, and Peng, Hisham, and Pan (2010) in Hubei, China. Most of the findings are similar to those previously cited above, where households are more likely to use cleaner fuel mixes if they have higher income, more education, and better access to the cleaner fuels. Across most studies, income has consistently been an important factor associated with modern and cleaner fuel use, as predicted by the energy ladder model. However, to date no study has been specific about the levels of income that would induce households to select cleaner fuels or fuel mixes.

The extant literature suffers from some substantial shortcomings. Studies that use logistic models to investigate the odds of a household using individual fuels rely on the assumption that each household makes its decision about whether to use a given fuel or not independently of whether they are also using other fuels. A multinomial logit model exacerbates this problem, because it further assumes that the use of fuels are mutually exclusive. This may be appropriate in the context of determining the 'main' fuel used by households, but in so doing a great deal of the nuance of households' fuel mix choices is lost. Households rarely rely on a single fuel and, as demonstrated in this chapter, often use many fuels in addition to their 'main' fuel. Investigating the *fuel mix* choice of households is therefore preferable. However, extant studies that have looked at fuel mix selection have done so using fuel mixes that were arbitrarily determined by the researchers (for example, (Heltberg, 2005; Lee, 2013; Narasimha Rao & Reddy, 2007b), and therefore often suffer from the same problems of independence and mutual exclusion noted above.

To avoid these problems, in this chapter we adopt a data-driven approach to identifying the household fuel mixes actually represented within our sample. To achieve this, we use cluster analysis to determine the fuel mix selections of households. Cluster analysis allows us to identify mutually exclusive fuel mixes that households select, based on the observed mixes of fuels that households in our sample consume. To our knowledge, this is the first study to derive household fuel mixes and investigate the factors associated with them in this way.

3.3 Data and variables

3.3.1 Data

Data from the Pakistan Social and Living Standards Measurement Survey 2013-14 (PSLM) was used for this study. The Federal Bureau of Statistics (FBS) developed the data collection frame for the PSLM. Each city was divided into enumeration blocks consisting of 200-250 households. Each enumeration block was then classified into three strata based on household incomes, i.e. low, medium, and high. A two-stage stratified sample design was adopted to collect the data. Each primary sampling unit (PSU) from a stratum was selected through a probability proportional to size (PPS) method, and within each PSU 12 rural and 16 urban households were selected. Initially, 19,620 households from 1368 PSUs were selected. However, due to ongoing conflict in some areas 61 PSUs were dropped and finally 17,989 households were interviewed from 1307 PSUs. Thus, the data can be considered to be reasonably representative of households in both rural and urban areas in Pakistan.

Generally, households in Pakistan use natural gas, LPG, firewood, agricultural waste, animal dung, and kerosene oil at household level for cooking and heating purposes. The mean consumption of the fuels at household level in Pakistan and mean expenditures on these fuels are shown in Table 1. Households are spending the greatest proportion of their energy budget on firewood and the least proportion of their energy budget on kerosene oil.

Table 1. Mean consumption and expenditures of the household

Fuels	Acronyms	Mean consumption	Mean Expenditures (PKR)
Natural gas (MMBTU)	ng	0.68	197.88
LPG (Kg)	lpg	0.57	79.10
Firewood (Kg)	fw	53.62	362.46
Agricultural waste (Kg)	aw	36.98	141.87
Animal dung (Kg)	ad	31.79	105.72
Kerosene oil (Litre)	ko	0.07	9.15

Note: Authors' calculation and 1 USD = 100 PKR, 2014

3.3.2 Variables of the Models

Table 2 summarizes the key independent variables in the sample, with mean values weighted to account for the stratified nature of the sample. Urban households (36.4 percent of the weighted sample) have greater accessibility to natural gas, and would therefore be expected to be more likely to use that fuel source. Female-headed households (3.7 percent of the weighted sample) have been shown in the literature to be more likely to use cleaner fuels than male-headed households. Agricultural households (24.3 percent of the weighted sample included at least once household member with an agricultural occupation, and 7.1 percent of the weighted sample had cattle) can be expected to be more likely to use agricultural waste or animal dung as fuel sources. Annual expenditure is used as a proxy of income due to substantial missing income data and was linearized through taking its natural log. Annual expenditures cover expenditures on food, energy, housing, education, and hospitalization etc. The energy ladder suggests that households with higher income are expected to be more likely to use cleaner fuels.

Table 2. Description of the variables

Variables	Description	Mean
Urban	Urban =1; Rural =0	0.364
Age	Age of the household head in years	43.95
Gender	Household head gender, Male=1; Female=0	0.963
Household size	Number of family members in the household	6.345
Education	Number of schooling years of household head	4.964
Agri. Occupation	Any member of the household's occupation was agricultural in last year=1; otherwise=0	0.243
Cattle	Household has one or more cattle=1; otherwise=0	0.071
No. of rooms	Number of rooms in the household's dwelling	2.287
Elt. connection	Household has electricity connection=1; otherwise=0	0.915
Ln of Expenditures	Natural log of total yearly household expenditure	12.25

Note: Authors' calculation

Some other variables such as cooking habits, taste preferences, and other cultural factors could also affect household fuel selection. However, these are difficult to measure quantitatively and our data set did not had these variables. Secondly, the market price of the fuels was not available in the dataset, and therefore could not be included. However, as noted by Irfan, et al., (2018), there is little cross-sectional variation in fuel prices in Pakistan and thus, even if price data were available, it is unlikely that it would have been able to be included in our cross-sectional model.

3.3.3 Cluster Analysis

Before applying the fuel choice model, it is essential to create groups of households that use similar fuel mixes according to the actual fuel consumption of households in the sample. Cluster analysis is an appropriate technique for recognizing groups with similar attributes. We have a large dataset and therefore partitioning is the most suitable method to create the clusters. *K*-means cluster analysis aims at dividing the data into different segments in such a way that within cluster variation is minimized. The clustering/segmenting procedure starts by randomly allocating entities to a number of clusters; then the entities are reallocated to other clusters to decrease the variation within cluster, which is measured as the squared distance from each observation to the centre of the related cluster.

Initially, we normalized our fuel variables (natural gas [ng], liquefied petroleum gas [lpg], firewood [fw], agricultural waste [aw], animal dung [ad], and kerosene [ko]) to avoid scaling problems (Scott & Knott, 1974). The optimal number of clusters was determined by considering the Calinski/Harabasz pseudo-F (C-H F) values for different numbers of clusters (Caliński & Harabasz, 1974). The C-H F values were 3501 for eight clusters, 3536 for nine clusters, and 3328 for ten clusters, suggesting that nine clusters was the optimal solution. Each household was then allocated to one of the seven clusters. To achieve this, first each cluster's geometric centre (i.e., its centroid) was calculated, by calculating the mean values of the households contained in the clusters regarding given variables (ng, lpg, fw, aw, ad, and ko). Then the distances from each household to the newly located cluster centres were calculated and households were again allocated to a specific cluster on the basis of their least distance to other cluster centres. This process iterated until the sum of the squared Euclidean distances was minimised. We then merged the two clusters that had the smallest numbers of households (467 and 97 respectively) into their nearest neighbors, in order to avoid problems for the analysis related to having small cell sizes in the multinomial logit model. This was preferred to reducing the number of clusters directly in the cluster analyses, where smaller numbers of clusters still led to some clusters with only a small number of group members.

3.4 Methods

The Multinomial Logit Model (MLM) shows the behavior of consumers with a common consumption objective when they are faced with the choice between many mutually exclusive options. In our case, this is the choice between consuming different fuel mixes (represented by the fuel mix clusters determined using the method described previously). The MLM is based on the random utility model. Individuals make decisions by comparing the levels of utility associated with each possible alternative. In classical demand theory the problem of consumer choice is usually described as a problem of utility maximization under a limited budget, with a utility function characterizing the consumer's preferences for consuming varying amounts of each type of commodities.

The fuel mix selection model is based on the rule that a household selects the fuel mix that maximizes their utility. Let a household *p* from *n* total households in the sample select a fuel type *j* from *m* mutually exclusive fuel mixes (clusters). The utility function U_p of a fuel mix type X_j can be written as:

$$U_p = f(X_j) + e_{jp} \qquad (1)$$

where:

$j=1, 2, 3, \ldots\ldots\ldots, m$

$p = 1, 2, 3, \ldots\ldots\ldots, n$

and e_{jp} is the error term following an i.i.d extreme valued distribution. The CDF of each error term is given by $[F(e_{jp}) = \exp\{-e^{-ejp}\}]$.

Finally, we have:

$$\Pr[Cl = \mathrm{j}] = \frac{\exp^{\beta_j X_i'}}{1 + \sum_{j=0}^{m} \exp^{\beta_j X_i'}} \qquad (2)$$

where

$\Pr[Cl = j]$ is the probability of choosing fuel mix j, with one of the fuel mixes as a reference category.

j = number of fuel mixes (total seven) in the choice set.

$j = 0$ for the reference fuel mix.

X_i = explanatory variables.

β_j = vector of the estimated parameters (so that β_j shows the effect of X_j on the likelihood of choosing *jth* fuel mix).

The models were weighted to account for the stratified nature of the sample. The main limitation of the MLM is that it relies on the assumption of the independence of irrelevant alternatives (IIA), i.e. that the relative odds of the choices are independent of the number of alternatives. However, the absence of choice-specific variables in our dataset precludes the use of more flexible logit specifications such as mixed logit.

3.5 Results and discussion

3.5.1 Cluster Analysis Results

Figure 3 depicts the fuel use combinations in each fuel mix cluster, and Table 3 shows number of households in, and the fuel mix of each cluster. For the sake of simplicity, in Figure 3 we only show the fuels that make up more than one percent of the fuel use of households in each fuel mix cluster, and the name of each cluster does not reflect fuels that make up less than five percent of fuel use within that cluster. Cluster 2 (awadfw), Cluster 3 (fwadaw), and Cluster 7 (adfwaw) represent fuel mixes that are predominantly based on solid fuels (agricultural waste; firewood; and animal dung, respectively). We take these fuel mix clusters as the reference categories in the MLM models that follow. Cluster 4 (ngfw) is the fuel mix that has the greatest proportion of clean fuels, with 82 percent natural gas consumption. We considered Cluster 4 as a base category for our fourth MLM model. These different reference categories were taken to explore in detail the factors associated with choosing a predominantly solid fuel mix (Clusters 2, 3, and 7), as opposed to a fuel mix based on cleaner fuels (Cluster 4).

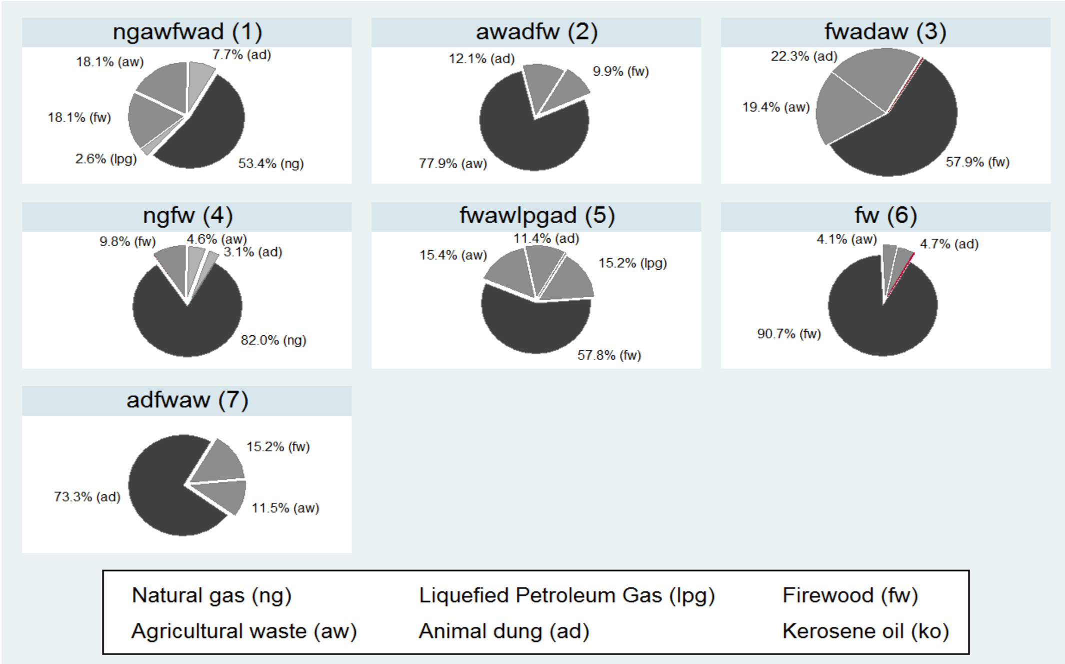

Figure 3: Fuel Cluster

Table 3. Description of the clusters

Cluster Number	Cluster Name	Number of Households	Description of the Cluster
1	ngawfwad	5881	Natural gas, agri. Waste, firewood, animal dung
2	awadfw	1626	Agri. Waste, animal dung, firewood
3	fwadaw	6037	Firewood, animal dung, agricultural waste
4	ngfw	1052	Natural gas, firewood, agri. waste, animal dung
5	fwawlpgad	494	Firewood, agri. waste, LPG, animal dung
6	fw	1872	Firewood, animal dung, agri. waste, kerosene oil
7	adfwaw	1027	Animal dung, firewood, agri. waste
Total		17989	

Note: Authors’ calculation from PSLM-2013-14

3.5.2 Multinomial Logit Model Results

We ran four multinomial logit models, using fuel mix clusters 2, 3, 4, and 7 as reference categories. The resulting model results (expressed as relative-risk ratios, or exponentiated coefficients) are shown in Table 4, with each column representing the results using a different fuel mix cluster as the reference category. The reference categories in first three models are fuel mixes that are predominantly solid fuels, while in the fourth model the reference category is a fuel mix that is predominantly natural gas (a cleaner fuel). Given the extensive nature of the results in Table 4, and the policy imperative to reduce use of solid fuels in favor of cleaner fuels, we concentrate our discussion here on variables that show a consistent association with a greater preference for cleaner fuels (as represented by fuel mix cluster 4), and a significantly lower preference for solid fuels (as represented by fuel mix clusters 2, 3, and 7).

The results show that households from urban areas are more likely to adopt the cleaner fuel cluster. In other words, urban households are more likely to adopt the cleaner fuel clusters (cluster 1 and 4) than any of the solid fuel clusters (awadfw, fwadaw, or adfwaw). This is likely due to the availability or accessibility of natural gas connections in the urban areas, and the lack of such connections in rural areas.[23] Interestingly, based on the size of coefficients this variable appears to be the most influential factor associated with the use of clean fuels. Our estimates suggest that the availability of cleaner fuels is a more influential factor for adopting clean energy sources than income and education growth. There are 13 to 20 times higher log odds of adopting the cleaner fuel mix (cluster 1) if households are residing in urban areas, where natural gas is available. Similarly, electricity connections (also more likely

[23] Our dataset does not contain any other availability variable. Therefore, we interpret urban area as a proxy for the availability of natural gas or cleaner fuels.

to be associated with urban households) are associated with a greater likelihood of choosing cleaner fuels clusters (cluster 1 and 4) than two of the solid fuel clusters (the exception being cluster 7, adfwaw) where the relative risk ratio is of the same sign but is statistically insignificant.

In contrast, agricultural households are much more likely to adopt solid fuel mixes. Based on the results for the agricultural occupation and cattle variables, agricultural households significantly less likely to adopt the cleaner fuel mix. Both variables are negatively associated with the choice of cluster 4 (ngfw), and positively associated with the solid fuel clusters (awadfw, fwadaw, or adfwaw). The free availability of agricultural waste and animal dung likely lead agricultural households to be more likely to make use of these fuel sources rather than cleaner fuels. Larger households are less likely to adopt the cleaner fuel mix. This may also relate to agricultural households and relative labour scarcity. The free availability of fuel collecting labor may make households more likely to adopt solid fuels rather than financially costly cleaner fuels.

In contrast, demographic factors associated with the household head had a weaker relationship with fuel mix choice. Age of the household head has a small effect on fuel mix choice, with older household heads more likely to choose cluster 2 (awadfw), and marginally more likely to choose cluster 3 (fwadaw) than the clean fuel cluster (ngfw), but cluster 7 (adfwaw) was not statistically significantly more likely to be selected than the clean fuel cluster. In contrast to much of the previous literature, female-headed households were mostly not significantly more likely to choose cleaner fuels than solid fuels.

Unlike other demographic factors, the education of the household head was a strong factor associated with the selection of cleaner fuel mix rather than the solid fuel mixes. This could be for a combination of two main reasons. First, education increases the opportunity cost of time spend collecting solid fuels such as firewood or agricultural waste. Second, greater education brings awareness about risks associated with indoor air pollution, so more educated households may be considering health benefits and thus avoid the use of solid fuels. Our estimates show that each year increase in schooling (education) is associated with 1.06 to 1.08 times higher log odds of adopting cleaner fuel mix (clusters 1 and 4).

Households with a greater number of rooms in the dwelling were more likely to adopt the cleaner fuel mix and less likely to use solid fuels. This likely demonstrates a wealth effect since a greater number of rooms is associated with a larger house and more wealth. Moreover, larger houses require more heating than smaller households, and so modern fuels will be more efficient in heating these larger spaces.

Finally, total expenditures were used as a proxy of income, and we found that this is significant and positively associated with choosing the cleaner fuel mix. Higher income households are more likely to be able to afford cleaner fuels such as natural gas and LPG, which are comparatively expensive, especially when compared with firewood and agricultural waste, which can often be collected at no financial cost to the household. These results support the phenomenon of fuel stacking, i.e. that as income increases, households tend to move towards the use of modern cleaner fuels.

Table 4. Multinomial Logit Model results

	Model 1 Base 2 (awadfw)	**Model 2 Base 3 (fwadaw)**	**Model 3 Base 7 (adfwaw)**	**Model 4 Base 4 (ngfw)**

ngawfwad (Cluster 1)				
Urban	19.07***	13.29***	20.39***	1.285
	(3.935)	(1.909)	(5.263)	(0.217)
Age	1.008**	1.013***	1.006*	1.001
	(0.002)	(0.002)	(0.002)	(0.003)
Male head	0.655	0.888	0.884	1.321
	(0.160)	(0.146)	(0.231)	(0.375)
Family size	0.806***	0.888***	0.834***	0.957*
	(0.015)	(0.013)	(0.015)	(0.017)
Education	1.081***	1.068***	1.085***	0.999
	(0.010)	(0.008)	(0.010)	(0.009)
Agri.	0.160***	0.293***	0.137***	0.932
Occupation	(0.020)	(0.0319)	(0.020)	(0.163)
Cattle	0.157***	0.379***	0.113***	1.452
	(0.025)	(0.053)	(0.019)	(0.477)
Rooms	1.077	1.076*	1.138**	0.905**
	(0.043)	(0.034)	(0.054)	(0.032)
Elt. Connection	1.596*	1.811**	0.613	0.565*
	(0.348)	(0.329)	(0.157)	(0.140)
Ln of	4.413***	3.073***	2.091***	0.174***
expenditures	(0.574)	(0.322)	(0.280)	(0.026)
awadfw (Cluster 2)				
Urban	Base category	0.697	1.069	0.0674***
		(0.132)	(0.313)	(0.016)
Age	Base category	1.004	0.998	0.992*
		(0.002)	(0.002)	(0.003)
Male head	Base category	1.355	1.349	2.016*

		(0.276)	(0.372)	(0.691)
Family size	Base category	1.101*** (0.016)	1.034 (0.018)	1.188*** (0.027)
Education	Base category	0.988 (0.007)	1.004 (0.010)	0.924*** (0.010)
Agri. Occupation	Base category	1.830*** (0.175)	0.852 (0.110)	5.819*** (1.137)
Cattle	Base category	2.406*** (0.291)	0.720* (0.111)	9.219*** (3.222)
Rooms	Base category	0.999 (0.035)	1.056 (0.050)	0.840*** (0.040)
Elt. Connection	Base category	1.135 (0.174)	0.384*** (0.086)	0.354*** (0.108)
Ln of expenditures	Base category	0.696*** (0.059)	0.474*** (0.058)	0.0395*** (0.007)
fwadaw (Cluster 3)				
Urban	1.435 (0.271)	Base category	1.534 (0.373)	0.0967*** (0.019)
Age	0.996 (0.002)	Base category	0.993* (0.002)	0.988*** (0.003)
Male head	0.738 (0.150)	Base category	0.995 (0.216)	1.488 (0.443)
Family size	0.908*** (0.013)	Base category	0.939*** (0.015)	1.079*** (0.022)
Education	1.012 (0.007)	Base category	1.016 (0.008)	0.936*** (0.009)

Agri. Occupation	0.546*** (0.0523)	Base category	0.466*** (0.050)	3.180*** (0.571)
Cattle	0.416*** (0.050)	Base category	0.299*** (0.040)	3.832*** (1.322)
Rooms	1.001 (0.035)	Base category	1.057 (0.044)	0.841*** (0.035)
Elt. Connection	0.881 (0.134)	Base category	0.338*** (0.066)	0.312*** (0.088)
Ln of expenditures	1.436*** (0.122)	Base category	0.680*** (0.075)	0.0567*** (0.009)
ngfw (Cluster 4)				
Urban	14.85*** (3.623)	10.35*** (2.054)	15.87*** (4.630)	Base category
Age	1.008* (0.003)	1.012*** (0.003)	1.005 (0.003)	Base category
Male head	0.496* (0.170)	0.672 (0.200)	0.669 (0.240)	Base category
Family size	0.842*** (0.019)	0.927*** (0.018)	0.871*** (0.020)	Base category
Education	1.082*** (0.012)	1.069*** (0.011)	1.086*** (0.012)	Base category
Agri. Occupation	0.172*** (0.033)	0.314*** (0.056)	0.146*** (0.028)	Base category
Cattle	0.108*** (0.037)	0.261*** (0.090)	0.0781*** (0.027)	Base category
Rooms	1.191*** (0.056)	1.189*** (0.050)	1.257*** (0.065)	Base category

Elt. Connection	2.824*** (0.865)	3.205*** (0.913)	1.085 (0.357)	Base category
Ln of expenditures	25.30*** (4.657)	17.62*** (2.968)	11.99*** (2.223)	Base category
fwawlpgad (Cluster 5)				
Urban	3.480*** (0.835)	2.425*** (0.442)	3.720*** (1.009)	0.234*** (0.059)
Age	1.001 (0.005)	1.006 (0.005)	0.999 (0.005)	0.994 (-0.005)
Male head	0.354** (0.119)	0.479* (0.144)	0.477* (0.173)	0.713 (0.250)
Family size	0.759*** (0.021)	0.836*** (0.021)	0.785*** (0.022)	0.902*** (0.027)
Education	1.090*** (0.013)	1.077*** (0.012)	1.094*** (0.013)	1.008 (0.012)
Agri. Occupation	0.388*** (0.0709)	0.710* (0.118)	0.331*** (0.063)	2.257*** (0.491)
Cattle	0.235*** (0.075)	0.565 (0.177)	0.169*** (0.055)	2.164 (0.918)
Rooms	1.295*** (0.059)	1.293*** (0.052)	1.367*** (0.074)	1.088 (0.049)
Elt. Connection	1.622 (0.722)	1.841 (0.814)	0.623 (0.294)	0.574 (0.302)
Ln of expenditures	15.10*** (2.466)	10.52*** (1.505)	7.155*** (1.180)	0.597* (0.120)
fw (Cluster 6)				
Urban	1.441	1.004	1.54	0.0970***

	(0.375)	(0.182)	(0.440)	(0.024)
Age	0.997 (0.002)	1.001 (0.002)	0.994 (0.003)	0.989** (0.003)
Male head	0.422*** (0.107)	0.572** (0.117)	0.569* (0.154)	0.851 (0.285)
Family size	0.972 (0.016)	1.071*** (0.015)	1.006 (0.018)	1.155*** (0.024)
Education	1.003 (0.011)	0.99 (0.009)	1.006 (0.011)	0.927*** (0.011)
Agri. Occupation	0.895 (0.110)	1.638*** (0.159)	0.763* (0.103)	5.209*** (1.009)
Cattle	0.463*** (0.074)	1.115 (0.159)	0.333*** (0.055)	4.272*** (1.501)
Rooms	1.076 (0.044)	1.074* (0.038)	1.136* (0.057)	0.903* (0.042)
Elt. Connection	0.337*** (0.066)	0.382*** (0.058)	0.129*** (0.029)	0.119*** (0.036)
Ln of expenditures	3.483*** (0.435)	2.426*** (0.261)	1.650*** (0.234)	0.138*** (0.025)
adfwaw (Cluster 7)				
Urban	0.935 (0.274)	0.652 (0.158)	Base category	0.0630*** (0.0184)
Age	1.003 (0.002)	1.007* (0.002)	Base category	0.995 (0.003)
Male head	0.741 (0.205)	1.005 (0.218)	Base category	1.495 (0.535)
Family size	0.967	1.065***	Base category	1.149***

	(0.017)	(0.017)		(0.026)
Education	0.997 (0.010)	0.984 (0.008)	Base category	0.921*** (0.010)
Agri. Occupation	1.173 (0.152)	2.147*** (0.234)	Base category	6.827*** (1.337)
Cattle	1.390* (0.215)	3.343*** (0.454)	Base category	12.81*** (4.522)
Rooms	0.947 (0.045)	0.946 (0.040)	Base category	0.795*** (0.041)
Elt. Connection	2.603*** (0.587)	2.955*** (0.576)	Base category	0.922 (0.303)
Ln of expenditures	2.111*** (0.263)	1.470*** (0.163)	Base category	0.0834*** (0.015)
N	17989	17989	17989	17989

Note: Note: Authors' calculation. Standard errors in parentheses, * p<0.05, ** p<0.01, *** p<0.001

The importance of income raises the question of whether countries such as Pakistan can simply grow out of using solid fuels. That is, as incomes rise through economic growth, how rapidly will households shift up the energy ladder and adopt cleaner fuels? To investigate this important question, we used the results from the MLM model in columns 1-3 of Table 4 to calculate the level of income. Where the probability of selecting the clean fuel mix (Cluster 4, ngfw) in preference to the other clusters was exactly equal to 50 percent. Holding other variables constant at their original values (and weighting to account for the stratified nature of the sample). That is, we calculated the income level where households would be more likely than not to switch to the clean fuel mix, using the following formula:

$$0.5 = \frac{1}{1 + \sum_{j=0}^{m} \exp^{\beta_j X_i'}} \qquad (3)$$

Table 5 shows this calculated level of income where the probability of selecting the clean fuel mix is exactly 50 percent. At incomes higher than this, the probability of choosing the clean fuel mix are greater than 50 percent and at incomes lower than this, the probability of selecting the clean fuel mix are less than 50 percent. It is evident from the table that the income level for choosing the clean fuel mix (ngfw) in preference to Cluster 3 (fwadaw) is higher as compared with the other clusters (awadfw and adfwaw). In cluster 3 (fwadaw), households are mostly consuming firewood, while in other two clusters they are mainly consuming agricultural waste and animal dung respectively. Firewood is a comparatively more expensive fuel than the other solid fuels, so as households' incomes increase they may shift from Clusters 2 and 7 first to Cluster 3, and then to the cleaner fuel mix at even higher incomes. This interpretation supports the energy ladder and energy stacking hypotheses. The table also shows that rural households would require much higher incomes than urban households to shift to the cleaner fuel mix. This reflects that only very high income rural households have access to piped natural gas, which forms the main energy source in the cleaner fuel mix cluster.

Given that the average income (monthly expenditures as proxy) in the weighted sample was 21,444 PKR (27,546 PKR in urban areas and 17,859 PKR in rural areas). This also demonstrates that, in the absence of a significant increase in the availability of piped gas connections, it is unlikely that Pakistan will grow out of solid fuel use, particularly in rural areas, without direct government policy intervention. Similarly, the availability of an electricity connection reduces the income level at which households are likely to switch to cleaner fuel mix use. In part, this is related to the rural/urban findings, since electricity connections are much less common in rural areas.

Table 5. Monthly income (PKR) threshold for choosing clean fuel mix

Base clusters	National level	Urban	Rural	Electricity connection Yes	Electricity connection No
Cluster 2	33297.8	12946.2	45324.2	30954.0	61249.9
Cluster 3	52778.8	22516.8	70652.3	48594.6	101788.8
Cluster 7	35431.6	9490.5	50625.1	33720.4	56291.9

Note: Authors' calculation and 1 USD = 100 PKR, 2014.

3.6 Conclusion and policy implications

Almost three billion people globally depend upon solid fuel consumption, despite the consequent serious health and environmental damage. In this chapter, we used nationally representative data from Pakistan to investigate the factors associated with the fuel mix selection of urban and rural households. Our study improves on the extant literature because most previous studies of fuel use have treated the choice to use a particular fuel as independent of the choice to use other fuels.

We found that the accessibility to piped natural gas is the most influential factor associated with the use of a clean fuel mix in Pakistan. Income and education were significant demographic factors associated with the use of cleaner fuels, supporting the hypothesis of energy stacking. We also demonstrated that income growth in Pakistan is unlikely to be conducive to households growing out of the use of solid fuels, particularly in rural areas.

This latter result suggests that, although there is some support for the energy ladder model and the Environmental Kuznets Curve, transitions to cleaner fuels for cooking and heating will require direct policy intervention by the government. If the government is concerned about indoor air pollution and wants to incentivise the use of cleaner fuel mixes by households, then expanding the availability of piped natural gas connections from main urban areas to include smaller urban areas and nearby villages is likely to encourage many, particularly non-agricultural households, to switch to cleaner fuels. Although our analysis excludes consideration of electricity due to data limitations, extending the electricity grid throughout the country, with particular focus on rural villages, may similarly allow these households to reduce their reliance on solid fuels (especially for lighting). While economic growth will raise incomes, it is unlikely to have a substantial impact on the use of solid fuels in rural areas without the increased accessibility of natural gas or cleaner fuels. Thus, policy change is critical in order to reduce the negative impacts of solid fuel use in Pakistan.

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Chapter 4: Household energy elasticities and policy implications for Pakistan[24]

4.1 Introduction

It is broadly recognized that energy is a key resource for economic growth and development (Sahir & Qureshi, 2007). Energy consumption in developing and middle-income economies (Middle East, Southeast Asia, South America, and Africa) will exceed that of developed countries (North America, Australia, New Zealand, Japan, and Western Europe) by 2020 (Pérez-Lombard, Ortiz, & Pout, 2008). Due to limited resources and increasing demand, especially from developing and middle-income countries, the price of energy sources has risen over time (Hadjipaschalis, Poullikkas, & Efthimiou, 2009). Consequently, the gap between the demand for and the supply of fuels is increasing, especially in developing and middle-income countries. The growing demand for energy and the reliance of countries on limited sources of energy mean that adequate energy provision will be one of the world's major problems in the next century (Khan & Ahmad, 2008).

Globally, three billion people depend upon solid fuels such as charcoal, coal, animal dung, firewood, and crop residues[25] for cooking and heating purposes (Landrigan et al., 2017). When burned, such solid biomass fuels emit a multitude of complex chemicals including carbon monoxide, nitrogen dioxide, formaldehyde, polycyclic aromatic hydrocarbons (PAH), cilia toxic, and other inhalable particulates, damaging the environment and people's health (Cooper, 1980; Torres-

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[25] These residues include cotton sticks, bagasse, husks, wheat straw, roots, corn stalks, stubble, leaves, seed pods, etc.

Duque, Maldonado, Pérez-Padilla, Ezzati, & Viegi, 2008). Solid fuels are generally burned in exposed fires or in three-stone stoves, leading to the emission of high levels of these noxious chemicals (Fatmi, Rahman, Kazi, Kadir, & Sathiakumar, 2010). Mostly as a result of solid fuel use, almost 4 million people around the world die prematurely each year due to indoor air pollution[26]. And millions more suffer from serious diseases such as asthma, lung infections, eye infections, sinus problems, tuberculosis (TB), cancer, and cardiovascular diseases (Mishra, 2003; Kim et al., 2011; Lakshmi et al., 2012; Sehgal, et al., 2014).

The consumption of solid fuels not only affects the population, but also damages the environment. The forests of developing countries are progressively depleting due to wood usage as a household cooking fuel (Arnold, et al., 2006; Bhatt & Sachan, 2004). Forests are necessary for economic, ecological, social, environmental, and health benefits, and provide food, medicines, forest products, and social resources, as well as helping to reduce global warming (Bonan, 2008). Despite the adverse effects of biomass fuel on health and the environment, the use of solid fuels for cooking, lighting and heating purposes remains very common in developing and middle-income countries.

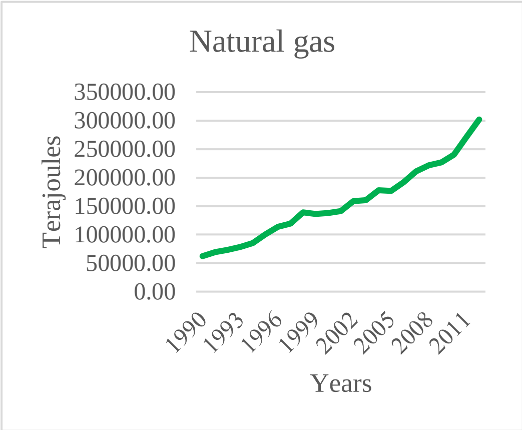
Like many other middle-income countries, electricity, firewood, natural gas, crop residues, animal dung, and Liquefied Petroleum Gas (LPG) are the main cooking and lighting fuels in Pakistan. Usually, electricity is used for lighting whereas other fuels are more commonly used for cooking and heating. In rural areas, the consumption of solid fuels such as firewood, dry animal dung, and crop residues is higher than in urban areas. On the other hand, the consumption of clean energy sources such as natural gas is higher in urban areas than in rural areas.

[26] http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

Pakistan has a population of 182 million and ranks as the sixth most populous country in the World (World Bank, 2013). The number of annual deaths attributed to acute respiratory infections (ARI) among children under age five years in Pakistan has been estimated to be 51,760, with a further 18,980 annual deaths due to chronic obstructive pulmonary disease (Colbeck, et al.,, 2010).[27] The total primary energy consumption of Pakistan was 2.54 Quadrillion British Thermal Unit (QBTU) in 2011 (U.S. Energy Information Administration (EIA)). The per capita energy consumption of Pakistan in 2013 was 475 kilograms of oil equivalent per year and Pakistan was ranked at 133rd globally.[28]

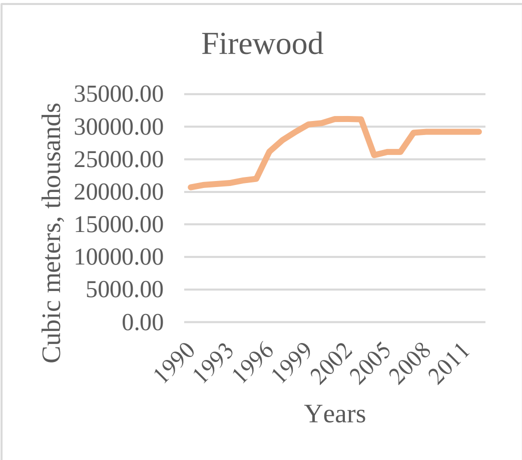
The six panels of Figure 1 show the overall energy consumption by Pakistani households of natural gas (Panel a), LPG (Panel b), fuelwood (Panel c), bagasse or agricultural waste (Panel d), animal dung[29] (Panel e), and kerosene (Panel f). The consumption of most fuels have an increasing trend, with the exceptions of LPG (which increased to a peak in 2006 then decreased) and kerosene oil (which exhibits a decreasing trend). The reduction in the consumption of LPG may be associated with the increase in the consumption of natural gas. The fluctuation in the in the consumption of the bagasse and crops residues may be because of various factors such as water availability, weather conditions, pests, and relative crops prices.

[27] See also: http://www.who.int/indoorair/publications/indoor_air_national_burden_estimate_revised.pdf?ua=1
[28] http://data.worldbank.org/indicator/EG.USE.PCAP.KG.OE
[29] Data are not available for animal dung after 2006.

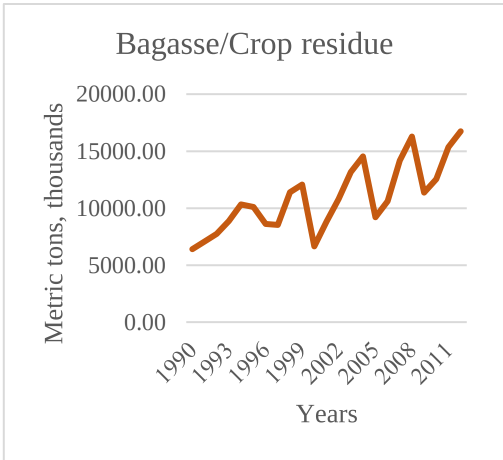


Panel (a) Natural gas consumption

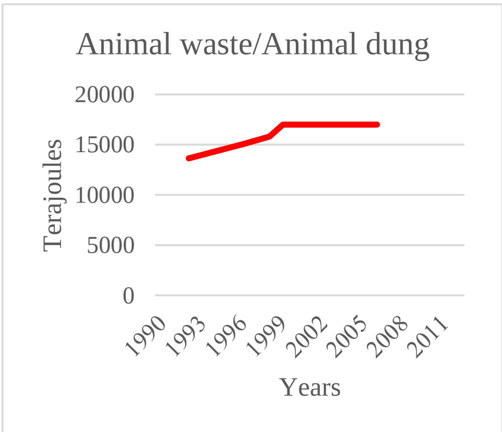
Panel (b) LPG consumption



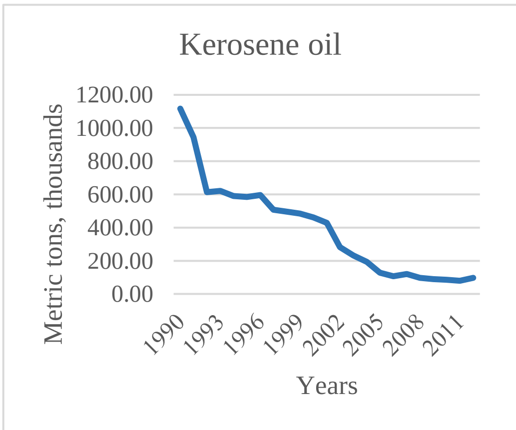
Panel (c) Firewood consumption



Panel (d) Crops residue consumption



Panel (e) Dry animal dung consumption



Panel (f) Kerosene oil consumption

Figure 4. Fuel consumption in Pakistan at household level

Source: UN Statistics Division Energy Statistics Database, 2015

Pakistan has sufficient energy resources to satisfy demand (Ali, Maitla, Murshid, & Iqbal, 2015). In recent years, the demand for energy has significantly increased, but due to inadequate policies this increase has not been catered for. Pakistan’s energy sector is poorly managed, there is extensive theft of gas and power, and service quality is low. Consequently, power shutdowns (blackouts or brownouts) are very common (Khan & Ahmad, 2008), which is not only impeding the development of the country, but also badly affecting quality of life (Javed et al., 2016).

Despite the importance of understanding patterns of energy demand in Pakistan, there is a lack of research that adequately addresses energy demand. The setting of optimal energy prices, levels of subsidies, and levels of taxation for solid and clean fuels continues to be problematic for the government. Prices, subsidies, and taxes play a vital role in household energy choices and consumption. In order to examine the impact of increases or decreases in the prices of energy sources at the household level, accurate estimates of the price and income elasticities of fuels are imperative. However, extant studies for Pakistan have mostly estimated only the demand elasticities of electricity, while the elasticities of other household fuels have been neglected. We have found only two prior studies that have estimated elasticities in Pakistan for household fuels other than electricity, those being Iqbal (1983) and Burney and Akhtar (1990). Unfortunately, both studies are now very dated, and their results are somewhat dubious (see Section 4.2 for further details). Similarly, few studies have estimated separate demand functions for rural and urban areas of developing countries, including Gundimeda and Köhlin (2008) for India and Arthur, Bond, and Willson (2012) for Mozambique.

The objective of this study is to estimate the uncompensated own price and fuel expenditure elasticities for household cooking and heating fuels in Pakistan. This study contributes to the literature by providing new estimates of these elasticities for Pakistan, disaggregated between rural and urban households. Moreover, we extend this analysis with simple simulations designed to suggest which of two clean fuels (LPG or piped natural gas) should be subsidised in order to encourage the greatest number of households to adopt these clean fuels. Answering this latter question is important for policy in many developing countries, where indoor air pollution (from burning solid fuels) is a significant and growing problem.

To undertake the analysis, we pool three national level micro survey data sets (Pakistan Social and Living Standard Measurement Survey (PSLM) for 2007-08, 2010-11, and 2013-14). The data are comprehensive and cover all the cooking and heating fuels used by households. We model energy demand as a multistage budgeting problem, and the allocation of fuel expenditures are analyzed using the Linear Approximate Almost Ideal Demand System (LA-AIDS) model. The LA-AIDS specification was proposed by Deaton and Muellbauer (1980), and is widely used to estimate price and expenditure elasticities when expenditure share data are available, but not unit prices. Although alternative models for the estimation of elasticities have been suggested that would allow for time varying elasticities (Barnett & Kanyama, 2013), Sherafatmand and Baghestany (2015) argue that the LA-AIDS model is preferable when the aim is to estimate linear parameters. Moreover, although our dataset includes several waves of the PSLM, households are not linked between waves, which does not lend itself to the efficient estimation of time-varying models.

Overall, we find that all fuel types except natural gas are price inelastic at the national level and for urban households. In rural areas, natural gas and LPG are more price elastic than in urban areas. Our policy simulations suggest that in order to reduce indoor air pollution, the Pakistan government should subsidise clean fuels rather than imposing taxes on solid fuels, and the preference should be for subsidising LPG rather than piped natural gas.

The remainder of the chapter is organized as follows. Section 4.2 discusses relevant literature, and in Section 4.3 we discuss the data and methodology. Section 4.4 presents the main results, Section 4.5 presents simple policy simulations, and Section 4.6 concludes.

4.2 Literature review

There is a limited literature on household demand for fuels used in cooking and heating in developing and middle-income countries (Ngui, Mutua, Osiolo, & Aligula, 2011). Studies such as Filippini and Pachauri (2004) in India, Atakhanova and Howie (2007) in Kazakhstan, Athukorala and Wilson (2010) in Sri Lanka, Shi et al., (2012) and Lin, Rizov, and Wong (2014) in China, have mainly estimated the demand for electricity only. Few studies are available for Pakistan, such as Jamil and Ahmad (2011), and Nasir, Tariq, and Arif (2008), but again they are also limited to demand for electricity.

In the Ogun state of Nigeria, Shittu, Idowu, Otunaiya, and Ismail (2004) estimated income elasticities for fuels by applying logit models for poor, average, and wealthy households. They found that wood had a negative income elasticity with values of -5.02, -4.94, and -4.31 for poor, average, and wealthy households respectively. Gundimeda and Köhlin (2008) calculated households’ price and expenditure elasticities in India by applying the LA-AIDS model, and found positive expenditure elasticities for low, medium, and high income groups in both rural and urban areas. The own price elasticities of electricity, kerosene, fuelwood, and LPG, were almost the same in both rural and urban areas. Fuelwood and LPG were almost unitary elastic for all groups.

Arthur, et al., (2012) investigated the price and income elasticities of domestic energy using the Mozambique National Household Survey on Living Conditions 2002/3. Surprisingly, fuelwood and charcoal were found to be more price inelastic (with values of -0.41 and -0.28 respectively) than electricity (-0.60) or candles (-0.88). On the other hand, candles, kerosene, and electricity were more sensitive to income changes than firewood and charcoal. Similarly, Akpalu, Dasmani, and Aglobitse (2011) found that the price elasticity of demand in Ghana was inelastic in the case of charcoal, firewood, and LPG, while kerosene was price elastic. Furthermore, they found that LPG was the most preferred fuel, followed by charcoal, firewood, and kerosene.

In Kenya, Ngui et al. (2011) estimated expenditure elasticities and own and cross price elasticities. The researchers found uncompensated price elasticities -0.28, -0.62, -0.67, -0.69, and -0.88 for LPG, fuelwood, charcoal, kerosene and electricity respectively. Surprisingly, kerosene oil was found to be expenditure elastic (1.06), implying that a proportionate increase in expenditure on kerosene oil would be higher than the proportionate increase in the total energy expenditures. They did not estimate elasticities for rural and urban areas separately. For Ethiopia, Guta (2012) calculated only expenditure elasticities and examined the fuel selection for rural residents. They separated fuels into two groups: (1) traditional (fuelwood, charcoal, leaves, and dung); and (2) modern (biogas and electricity). They found that the expenditure elasticity of the traditional fuel group was inelastic with a value of 0.72 in 2000 and 0.76 in 2004. The expenditure elasticity for the modern fuel group was higher, with values of 1.14 in 2000 and 1.15 in 2004.

There is severe lack of recent literature estimating the price and fuel expenditure elasticities of household cooking and heating fuels in Pakistan. A study conducted by Iqbal (1983) estimated the price and income elasticities of electricity, natural gas, coal, and kerosene. He merged natural gas, LPG, and electricity into one group and merged coal and kerosene into another. The study used time series data (1961-81) and OLS and GLS methods. Both fuel groups were found to be income elastic but price inelastic. However, the merging of different fuels together is potentially problematic. While LPG and natural gas could be merged because both are mostly used for cooking purposes, electricity has an entirely different usage from natural gas or LPG, being mostly used for lighting and to run electrical appliances. Therefore, households' response to changes in the price of electricity may be expected to be different to their response to changes in the prices of natural gas or LPG, leading to biased estimates of the elasticity for that group.

Burney and Akhtar (1990) used data from the Pakistan Household Income and Expenditure Survey 1984-85, and applied the Extended Linear Expenditure System to estimate the elasticities. They found that kerosene, natural gas, electricity and other fuels had positive expenditure elasticities, but not firewood. The own price elasticities were also extremely low – firewood had a positive price elasticity with a value of 0.01 for urban areas, whereas all other fuels were highly price inelastic with elasticities of -0.0018, -0.005, and -0.004 for kerosene, natural gas, and electricity respectively. These elasticities seem implausibly low, and this may be because this study used cross sectional data and likely had little variation in prices across the sample, particularly given that some fuel prices are set nationally.

Moreover, these elasticities are extremely low in comparison to those found in other developing countries, as can be seen in Table 1.

Most studies have used macro data, panel data, or time series data to investigate energy demand, while household-level micro data are rarely used (Sun & Ouyang, 2016). Variation in prices is necessary for the estimation of elasticities. Therefore, some researchers have pooled several cross-sections of data to estimate the elasticities. For instance, Bose and Shukla (1999) pooled data from 1985 to 1999 for India and applied unlagged and lagged models to calculate the price and income elasticities of electricity for commercial, residential, agricultural, large industry, and small and medium industries. Similarly in Spain, Labandeira, Labeaga, and Rodríguez (2006) merged three data sets - two cross sectional data sets from 1973-74 and 1980-81 and one cross sectional time series data set from 1985-1995 - to observe the variation in prices.

Table 1. Summary of literature.

Name	Country	Energy source/s	Methodology	Data	Findings	Rural /Urban classification
Burney and Akhtar (1990)	Pakistan	Electricity, natural gas, firewood, kerosene oil, other fuels	Extended Liner Expenditure System	National Household Income and Expenditure Survey 1984-85 (HIES)	Own price elasticities in urban areas: natural gas -0.08, firewood 0.01, kerosene -0.02 Own price elasticities in rural areas: natural gas missing, firewood -0.09, kerosene -0.09 Expenditures elasticities in urban areas: natural gas 1.03, firewood -0.21, kerosene 0.37 Expenditures elasticities in rural areas: natural gas missing, firewood 0.45, kerosene 0.40	Yes

Shittu et al. (2004)	Nigeria	Electricity, petrol, diesel, kerosene, firewood, domestic gas, and transport in commercial vehicles	Logit model	Primary data from 90 HH, 2002	Average income group level Income elasticities: domestic gas 0.08, wood -4.94, kerosene 0.08	No
Gundimeda and Köhlin (2008)	India	Electricity, LPG, fuelwood, kerosene	Linear Approximate Almost Ideal Demand System (LA-AIDS) model	Cross sectional data collected by National Sample Survey Organisation (NSSO 1999)	Medium expenditure group Own price elasticities in urban areas: LPG -1.01, fuelwood -1.02, kerosene -0.21 Own price elasticities in rural areas: LPG -0.98, fuelwood -1.03, kerosene -0.75 Income elasticities in urban areas: LPG 0.94, fuelwood 1.30, kerosene 0.97 Income elasticities in rural areas:	Yes

					LPG0.96, fuelwood 1.27, kerosene 0.84	
Akpalu et al. (2011)	Ghana	LPG, firewood, kerosene, charcoal	Regression analysis	Ghana Living Standards Survey 1998-1999	Own price elasticities: LPG -8.90, firewood -0.87, kerosene -1.29	No
Ngui et al. (2011)	Kenya	Electricity, LPG, fuel wood, kerosene, charcoal, MSP, AGO, lubricants	Linear Approximate Almost Ideal Demand System (LA-AIDS) model	Data from Kenya Institute for Public Policy Research and Analysis (KIPPRA) and Energy Regulatory	Own price elasticities: LPG -0.28, fuelwood -0.62, kerosene -0.69 Expenditure elasticities: LPG 0.87, fuelwood 0.93, kerosene 1.06	No

				Commission (ERC)		
Arthur, et al., (2012)	Mozambique	Electricity, firewood, kerosene, charcoal, candles	Regression analysis developed by Deaton	National Household Survey on Living Conditions 2002/3 Mozambique	Own price elasticities in urban areas: firewood -0.32, kerosene -0.73 Own price elasticities in rural areas: firewood -0.35, kerosene -0.75 Own price elasticities countrywide: firewood -0.41, kerosene -0.79 Income elasticities in urban areas: firewood 0.36, kerosene 0.76 Income elasticities in rural areas: firewood 0.39, kerosene 0.78 Income elasticities countrywide: firewood 0.45, kerosene 0.84	Yes
Sun and Ouyang (2016)	China	Electricity, Natural gas, transport energy	Linear Approximate Almost Ideal	China's Residential Energy	Own price elasticity: natural gas -0.77 Expenditure elasticity: natural gas 0.79	No

			Demand System (LA-AIDS) model	Consumption Survey 2013		

Table 1 summarises the key studies from developing and middle-income countries that are similar to our study. Almost all of the studies mentioned in the Table 1 show negative own price elasticities for all of the fuels, except for firewood in the Burney and Akhtar (1990) study in Pakistan (0.01). Some of the studies show implausibly large elasticities, such as Akpalu et al. (2011) for Ghana, who found that the own price elasticity for LPG was -8.90. and Shittu et al. (2004), who found the income elasticity for firewood was -4.94.

4.3 Data and methods

4.3.1 Data

Noting the problems with the Burney and Akhtar (1990) study outlined in the previous section, it is important to ensure that there is sufficient price variation in the dataset, particularly given that many fuel prices are set nationally in Pakistan. A single cross-section would not contain sufficient price variation, so instead we pooled cross-sections of data from the Pakistan Social and Living Standard Measurement Survey (PSLM) for the years 2007-08, 2010-11, and 2013-14. The data consist of a range of socio-economic and demographic variables, including fuel usage. The sampling frame for the PSLM involves a two-stage stratified design, with every district separated into enumeration blocks containing 200-250 households, and every enumeration block further classified into three categories of income, i.e. high, middle, and low. The data is reasonably representative of households in both rural and urban areas of Pakistan. While using this data as a panel for our analysis would be ideal (Labandeira et al., 2006), the PSLM data is a repeated cross-section rather than a traditional panel, i.e. it does not necessarily include the same households in each subsequent wave and households cannot be matched across waves of the survey. Therefore we simply pooled the three cross-sections of data. Initially, in total we have 49,842 households for analysis, of which 15,512 are from 2007-08, 16,341 are from 2010-11, and 17,989 are from 2013-14.

Market price data were not available for most fuels (except natural gas), so we divided total expenditures for each fuel by the quantity of that fuel to get the effective prices for each household. The price of natural gas is set by the Oil and Gas Regulatory Authority (OGRA). Although the wholesale price of LPG is also set by the OGRA, there is some variation in effective prices between households because different suppliers offer different consumer prices based on quantity demanded and geographical locations. Given the way that prices are estimated from household data, missing data is a problem (since there is neither expenditure nor quantity data for households that do not consume a particular fuel type). To deal with the expenditures function and the whole system of equations (see Methods below), prices must exist for all types of energy sources/fuels for all households. Therefore, we used the mean price of that specific fuel type within the same town/cluster as a proxy for missing values. Households (n = 1,921) that did not report expenditures for any fuel type were dropped from the data, leaving 47,921 households for our analysis. Because we have pooled the data across multiple years, we converted all prices to real prices for the 2007-08 year.

4.3.2 Methods

To evaluate the own price and fuel expenditure elasticities, we applied the Linear Approximate Almost Ideal Demand System (LA-AIDS) model (Deaton and Muellbauer, 1980). Our dataset does not have complete market price information, and the LA-AIDS model is widely used for this type of dataset (Arthur, et al., 2012; Labandeira et al. 2006; Ngui et al. 2011). Furthermore, the LA-AIDS model is comparatively easy to evaluate and interpret and fulfils the axioms of choice precisely. It can thus be interpreted in terms of economic models of consumer behaviour when estimated with aggregated or non-aggregated data. It is as flexible as other locally flexible functional forms, and it has the additional benefit of being harmonious with aggregation over consumers. This model is obtained from a detailed cost function and consequently matches a well-defined preference structure, which is also suitable for welfare investigation. In this model, homogeneity and symmetry restrictions depend only on the calculated parameters and are therefore easily tested and/or imposed. The model gives an arbitrary first-order approximation to any demand system. It aggregates perfectly across consumers without invoking parallel linear Engel curves. Furthermore, the demand function shows the relationship between quantity demanded and the price of the good on the assumption that other prices and the consumer's budget are held constant. Further details on the underlying assumptions and statistical properties of the LA-AIDS model are described in Deaton and Muellbauer (1980).

The LA-AIDS has a functional form that is consistent with known household budget data. Various researchers have applied this model to estimate fuel elasticities (Gundimeda & Köhlin, 2008; Ngui et al., 2011; Sun & Ouyang, 2016) and many other researchers have applied this model to estimate food demand systems (Agbola, 2003; Durham & Eales, 2010; Huang & David, 1993; Ortega, Holly Wang, & Eales, 2009; Taljaard, Alemu, & Schalkwyk, 2004).

The LA-AIDS models derives a budget share equation from the specification of a Price Independent Generalized Logarithmic (PIGLOG) cost function introduced by Deaton and Muellbauer (1980). It is defined as:

$$\ln c(u,p) = (1-u)\, ln\{a(p)\} + u\, ln\,\{b(p)\} \tag{1}$$

where u lies between 0 (subsistence) and 1 (bliss) so that *a(p)* and *b(p)* are the costs of subsistence and bliss respectively. The partial derivatives with respect to the prices of the cost function are the quantities demanded, i.e.

$$\ln c(u,p) = \alpha_0 + \sum_i \alpha_i \ln p_i + \frac{1}{2} \sum_i \sum_j \lambda_{ij} \ln p_i \ln p_j$$

$$+ \beta_0 u \prod_i p_i^{\beta_i} \qquad (2)$$

where $\ln c(u,p)$ is the cost function for utility u at price vector p, $\alpha_0, \alpha_i, \lambda_{ij}, \beta_0, and\ \beta_i$ are constants, and *i* and *j* are indexes representing fuel groups, in our case natural gas, LPG, firewood, agricultural waste, animal dung, and kerosene. By applying Shephard's lemma and substituting in the indirect utility function, we then obtain the expenditure share of the i^{th} group of fuels from Equation (2), $\frac{\partial c(u,p)}{\partial p_i} = q_i$ (Shephard, 1970; Diewert, 1971). By multiplying both sides by $p_i/c(u,p)$, we obtain:

$$\partial \ln \frac{c(u,p)}{lnp_i} = \frac{p_i q_i}{c(u,p)} = w_i \qquad (3)$$

where $w_i = \frac{p_i q_i}{x}$ is the budget share of good *i*. We can then obtain the budget share as a function of utility and price. For maximizing the utility total expenditures, *x*, is equal to *c(u,p)*, and we can obtain *u* as a function of *p* and *x*. Then we can also obtain the budget share as a function of *p* and *x*. The LA-AIDS demand equation in budget share form is:

$$w_i = \alpha_i + \sum_i \gamma_{ij} \ln(p_j) + \ \beta_i ln\left(\frac{x}{P^*}\right) \qquad (4)$$

The model uses the budget shares of each commodity group as dependent variables, and the natural logarithm of prices and real expenditure/income as independent variables. This model satisfies the desirable properties of the demand system, and p_j is the price of good j, x is total expenditure given by $x = \sum p_i q_i$, where q_i is the quantity demanded and p_i is the price for i^{th} group of fuels of the particular household. P^* is a Stone price index and is defined as follows:

$$\ln P^* = \alpha_0 + \sum_{I=1}^{n} \alpha_i \ln p_i + \frac{1}{2} \sum_{i}^{n} \sum_{j}^{n} \gamma_{ij} \ln p_i \ln p_j \qquad (5)$$

$$\gamma_{ij} = \frac{1}{2}(\gamma_{ij} * + \gamma_{ji} *) \qquad (6)$$

$$\ln P^* = \sum w_j \ln p_j \qquad (7)$$

where $a_i, \gamma_{ij}, and\ \beta_i$ are parameters to be estimated. To comply with the theoretical properties of consumer theory, the following restrictions on the demand function are imposed during estimation:

$$\textstyle\sum_i^n a_i^* = 1, \quad \sum_i^n \gamma_{ij} = 0, \quad \sum_i^n B_i = 0 \qquad \forall all\ i \qquad (8)$$

$$\textstyle\sum_i^n \gamma_{ij} = 0, \quad \forall\ j \qquad (9)$$

$$\gamma_{ij} = \gamma_{ji} \qquad (10)$$

Equation (8) is an adding up constraint, and ensures that the budget shares sum to unity. Equation (9) is a homogeneity restriction, and is based on the assumption that a proportional change in all prices and expenditures does not affect the quantities purchased. Equation (10) is a symmetry restriction and imposes consistency of consumer choice. Imposing the property of additivity of the expenditure function makes the variance and covariance matrix singular, and one of the equations needs to be omitted to estimate the LA-AIDS model. The uncompensated (Marshallian) own- and cross-price elasticity for good (*i*) with respect to good (*j*) is estimated as:

$$e_{ij} = -\delta_{ij} + \frac{\gamma_{ij-\beta_i}}{w_i} \qquad (11)$$

Where δ_{ij} is the Kronecker delta and equals one for own-price and zero for cross-price elasticities. The uncompensated price elasticity of demand represents changes in the quantity demanded as a result of changes in prices, capturing both substitution and income effects. Finally, the fuel expenditure elasticities are estimated by:

$$E_i = 1 + \frac{\beta_i}{w_i} \tag{12}$$

The seemingly unrelated regression estimation (SURE) method of Zellner (1962) is employed to estimate the system of equations (1 to 12). The SURE method allows restrictions inferred by economic theory to be imposed not only within an equation (such as the homogeneity restriction from Equation (9)), but also across different equations (such as the symmetry and adding up constraints in Equations (10) and (8) respectively). This improves efficiency, by estimating the model as a demand system. Moreover, a system of equations approach is more efficient than single equation models if the disturbance terms from different equations are correlated (Asatryan, 2004).

4.4 Results and discussion

Table 2 shows the mean household consumption of each fuel. The mean consumption of firewood in rural areas is higher than in urban areas, due to greater access and availability. The mean consumption of piped natural gas, LPG, and agricultural waste is slightly different between urban and rural areas. Interestingly, the mean expenditures on solid fuels (fuelwood, crop residues, and animal dung) are lower in rural areas can be seen in Table 3. There could be two reasons of this. First, it is easier (i.e. less costly) to access these fuels in rural areas, and second, sometimes landlords or farmers do not charge households in rural areas for crop residues or animal dung.

Table 2. Monthly fuel consumption

Energy sources	Urban		Rural		National	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Natural gas (MMBTU)	1.97	1.73	2.04	1.39	2.00	1.56
LPG (Kg)	5.56	3.29	5.59	3.38	5.57	3.34
Firewood (Kg)	107.29	72.58	110.56	88.83	108.94	81.23
Agricultural waste (Kg)	93.26	65.74	92.66	65.76	92.95	65.75
Animal dung (dry) (Kg)	98.93	66.94	96.37	65.47	97.63	66.21
Kerosene (L)	1.49	0.77	1.53	0.90	1.51	0.84

Notes: n = 49842; Urban n =24599; Rural n = 25243; source: authors' calculations from PSLM 2007-08, 2010-11, and 2013-14.

Table 3. Monthly fuel's expenditures PKR

Energy sources	**Urban**		**Rural**		**National**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Natural gas (MMBTU)	183.72	366.65	117.60	392.69	150.23	381.50
LPG (Kg)	47.84	236.90	76.69	301.16	62.45	271.74
Firewood (Kg)	364.39	705.03	339.19	491.57	351.62	606.51
Agricultural waste (Kg)	82.85	231.43	70.93	188.57	76.81	210.90
Animal dung (dry) (Kg)	67.44	203.10	54.11	140.27	60.69	174.26
Kerosene (L)	12.39	69.71	21.31	59.20	17.17	64.73

Notes: n = 49842; Urban n = 24599; Rural n = 25243; source: authors' calculations from PSLM 2007-08, 2010-11, and 2013-14; all values are in 2007 real PKR ($_{2007}$PKR 61 = USD 1).

Table 4 shows the uncompensated own price elasticities obtained from the LA-AIDS model for different cooking fuel types at the national level, and separately for urban and rural households. All differences in elasticities between rural and urban areas are statistically significant. Piped natural gas was the only fuel type found to be price elastic, and was so at the national level and in both urban and rural areas, implying that piped natural gas is relatively more price sensitive than all other fuels. The elasticity for piped natural gas in urban areas is far more price elastic the estimate of -0.087 by Burney and Akhtar (1990). Recall that Burney and Akhtar (1990) used a single cross-section of data, and their small elasticities may result from to a lack of variation in observed prices. LPG is price inelastic at the national level and in both urban and rural areas, but is relatively less price inelastic in urban areas than rural areas. Natural gas and LPG are both relatively more price sensitive in rural areas than urban areas, and this may be due to the availability of cheap alternative fuels in rural areas, such as crop residues and animal dung. LPG has been noted as price inelastic in many other studies, such as Athukorala and Wilson (2010), Guta (2012), and Ngui et al. (2011).

Firewood was found to be price inelastic at the national level and in both urban and rural areas, and in urban areas it was relatively less price inelastic than in rural areas. Our results contradict those of Burney and Akhtar (1990), as they found a positive price elasticity of firewood in urban areas (0.014), but as noted earlier those results are suspect. Many researchers such as Arnold et al. (2006), Ngui et al. (2011), Akpalu et al. (2011), and Arthur et al. (2012) have found that firewood is price inelastic. Our results show that crop residues is also price inelastic at the national level and in both urban and rural areas, and slightly more price elastic in rural areas than in urban areas.

We find that dry animal dung is price inelastic in both rural and urban areas, and slightly more inelastic in rural areas than in urban areas. Kerosene oil is the most price inelastic source among our selected household fuels at the national level, and in rural areas. However, in urban areas the price elasticity is higher than in rural areas, albeit still price inelastic, and slightly more price elastic than crop residues. Overall, our finding that kerosene oil is price inelastic is similar to the findings of Ngui et al. (2011), Akpalu et al. (2011) and Arthur et al. (2012).

Table 4. Own Price Elasticities

	National Level		Urban		Rural		z-test
Energy sources	**coef.**	**std.err**	**coef.**	**std.err**	**coef.**	**std.err**	**p-value**
Natural gas	-1.448***	-0.032	-1.390***	0.047	-1.613***	0.047	<0.001
LPG	-0.738***	0.021	-0.484***	0.031	-0.866***	0.033	<0.001
Firewood	-0.711***	0.018	-0.133***	0.047	-0.836***	0.015	<0.001
Crop residues	-0.733***	0.007	-0.628***	0.014	-0.761***	0.008	<0.001
Animal dung (dry)	-0.908***	0.005	-0.960***	0.009	-0.881***	0.007	<0.001
Kerosene oil	-0.595***	0.018	-0.647***	0.025	-0.508***	0.028	<0.001

Notes: *** p<0.01, ** p<0.05, * p<0.1, z-test results are based on the procedure in Clogg, Petkova, and Haritou (1995).

Table 5. Expenditures elasticities

	National Level		Urban		Rural		z-test
Energy sources	**coef.**	**std.err**	**coef.**	**std.err**	**coef.**	**std.err**	**p-value**
Natural gas	0.888***	0.006	0.814***	0.014	0.934***	0.006	<0.001
LPG	0.838***	0.006	0.728***	0.012	0.880***	0.006	<0.001
Firewood	0.840***	0.012	0.559***	0.025	0.905***	0.011	<0.001
Agricultural waste	0.883***	0.007	0.841***	0.013	0.882***	0.009	<0.001
Animal dung (dry)	0.914***	0.007	0.981***	0.013	0.900***	0.008	<0.001
Kerosene oil	0.906***	0.006	0.837***	0.011	0.938***	0.008	<0.001

Notes: *** p<0.01, ** p<0.05, * p<0.1, z-test results are based on the procedure in Clogg et al. (1995).

Table 5 presents the fuel expenditure elasticities of the households obtained from the LA-AIDS model at the national level, and separately for urban and rural areas. All fuel types have positive coefficients, greater than zero but less than one. This implies that as households' total fuel expenditures increase, the quantity demanded of each fuel would also rise but proportionately less than total fuel expenditures. These results are unremarkable since, as the quantity of fuels consumed rise, expenditure on fuels (as a group) can also be expected to rise. However, they provide confidence that the LA-AIDS model is producing sensible estimates. In most cases, the differences between rural and urban areas, in terms of fuel expenditure elasticity, are small but statistically significant. The largest differences are observed for firewood and LPG, where the fuel expenditure elasticities are greater in rural areas than in urban areas. For firewood, the findings are similar to Arthur et al. (2012) but in contrast to Burney and Akhtar (1990), who found a negative expenditure elasticity for firewood for urban households (-0.21).

The estimated fuel expenditure elasticity for dry animal dung is higher in urban areas than in rural areas. Many rural inhabitants have cattle and therefore they do not need to spend more on dung as their energy expenditures rise. The fuel expenditure elasticity of kerosene oil in rural areas is higher than in urban areas. Many urban households have piped gas connections, therefore they do not spend more on kerosene oil as their energy expenditures rise. Many other studies in developing countries also found fuel expenditures elasticity of less than one for kerosene oil such as Burney and Akhtar (1990), Arnold et al. (2006) Gundimeda and Köhlin (2008), and Arthur et al., (2012,) but in Kenya Ngui et al. (2011) found the fuel expenditure elasticity of kerosene oil to be slightly greater than one (1.06).

4.5 Simple policy simulation

The ill health effects associated with burning of solid fuels and kerosene are stated in many research studies (e.g. see Fatmi et al., 2010). The cutting of wood for cooking purposes also decreases forest resources and consequently, the depleting of the forest leads to the numerous environmental problems (Arnold, et atl., 2006; Bhatt & Sachan, 2004; Bonan, 2008). Therefore, it is important for governments to consider policies that encourage the use of cleaner fuels and disincentive the use of solid fuels.

For this purpose, we used the uncompensated own- and cross-price elasticities from the LA-AIDS model reported in the previous section to simulate what would happen if the Pakistan government were to subsidise clean fuels or impose taxes on solid fuels or kerosene. Specifically, we consider the impact of a 1% subsidy on each clean fuel (natural gas, LPG), and the impact of a 1% tax on each solid fuel (firewood, crop residues, dry animal dung) and kerosene. Each simulation (subsidy or tax) is evaluated independently, and for simplicity we only consider the first-order impacts of the change in prices on consumption of each fuel. The purpose of the simulation is to identify in a general sense whether subsidies of clean fuels, or taxes of solid fuels or kerosene, would be more effective in inducing households in Pakistan to substitute their fuel use towards clean fuels, and to identify which of the two subsidy options (natural gas or LPG) would likely be more cost-effective. The results of these simulations are shown in Table 6 (detailed tables of the cross-price elasticities from the LA-AIDS model are available in Appendix Tables A1 to A3).

If the government were to subsidise natural gas, such that consumer prices fell by 1 percent, the consumption of natural gas would increase by 1.390 percent in urban areas and by 1.613 percent in rural areas. Although the percentage increase in the consumption of natural gas in urban areas would be a bit lower than rural areas, the percentage reduction in solid fuel use would be higher in urban areas than in rural areas, as shown in the table. However, in the case of subsidising LPG (again such that consumer prices fell by 1 percent), consumption of LPG would increase by a greater percentage in rural areas than in urban areas, while as is the case for natural gas solid fuel reduction would be greater in percentage terms in urban areas.

Government has only limited influence in setting the prices of solid fuels, because solid fuels often do not have complete markets, although firewood is traded relatively more frequently that agricultural waste or animal dung. Therefore, taxing solid fuels can be a very challenging task. In any case if the government imposes a tax on firewood and consequently consumers face a 1 percent increase in the price of firewood, it would reduce the quantity demanded of firewood by 0.133 percent in urban areas and 0.836 percent in rural areas. Interestingly, taxing firewood would increase the quantity demanded of LPG comparatively more than natural gas, especially in urban areas.

Table 6. Effects of price changes on Quantity demand

Change in Price of Energy source	Area	Q.NG	Q.LPG	Q.FW	Q.AW	Q.AD	Q.KO
Natural gas 1 % ↓	Urban	1.390% ↑	0.645% ↓	0.332% ↓	0.109% ↓	0.121% ↓	0.299% ↓
	Rural	1.613% ↑	0.609% ↓	0.070% ↓	0.001% ↓	0.028% ↓	0.244% ↓
LPG 1 % ↓	Urban	0.458% ↓	0.484% ↑	0.514% ↓	0.094% ↓	0.172% ↓	0.116% ↑
	Rural	0.449% ↓	0.866% ↑	0.135% ↓	0.047% ↓	0.052% ↓	0.195% ↑
Firewood 1 % ↑	Urban	0.375% ↑	0.646% ↑	0.133% ↓	0.345% ↑	0.293% ↑	0.129% ↑
	Rural	0.076% ↑	0.110% ↑	0.836% ↓	0.050% ↑	0.067% ↑	0.022% ↑
Crop residues 1 % ↑	Urban	0.099% ↑	0.012% ↑	0.309% ↑	0.628% ↓	0.134% ↑	0.033% ↑
	Rural	0.049% ↑	0.092% ↑	0.123% ↑	0.761% ↓	0.087% ↑	0.019% ↑
Animal dung 1 % ↑	Urban	0.010% ↑	0.000% ↑	0.018% ↑	0.044% ↑	0.960% ↓	0.004% ↑
	Rural	0.071% ↑	0.083% ↑	0.141% ↑	0.080% ↑	0.881% ↓	0.019% ↑
Kerosene oil 1 % ↑	Urban	0.869% ↑	0.742% ↓	0.305% ↑	0.089% ↑	0.108% ↑	0.647% ↓
	Rural	0.854% ↑	1.126% ↓	0.066% ↑	0.013% ↑	0.022% ↑	0.508% ↓

Notes: Authors' calculations based on simulated effect of a 1 percent increase in price for solid fuels (firewood, crop residues, dry animal dung) and kerosene, or a 1 percent decrease in price for clean fuels (LPG, piped natural gas).

Although there is no proper market for other solid fuels (crop residues and animal dung), for comparative purposes we show in the table the effect of a tax that would increase their price by 1 percent. In both cases, the effect of the tax on the consumption of clean fuels (LPG and natural gas) is much smaller than either a tax on firewood, or subsidies on natural gas or LPG. Finally, our estimates show that taxing kerosene oil by 1 percent would increase the use of natural gas by more than 8 percent in rural and urban areas, and reduce kerosene consumption by 0.647 percent in urban areas and 0.508 percent in rural areas. Surprisingly, taxing kerosene would *reduce* the use of LPG in both rural and urban areas, which would offset gains in clean fuel use in terms of piped natural gas.

Table 7 compares the results for the two subsidies (piped natural gas and LPG) in terms of the reduction in solid fuel use and total cost. A subsidy that reduces the price of LPG by one percent would reduce solid fuel consumption by more than 50 percent more than a subsidy that reduces the price of piped natural gas by one percent. However, this reduction would come at a total cost that is just 39 percent higher (1,997 billion PKR vs. 1,434 billion PKR). Comparing the two subsidies, our policy simulation suggests that that subsidising LPG should be preferred over a subsidy of piped natural gas, since it more cost-effectively reduces solid fuel use.

Table 7. Impact of subsidy on solid fuel consumption

Fuels	**Area**	**No subsidy (millions of metric tons)**	**Natural gas subsidy Quantity decrease (thousands of metric tons)**	**LPG subsidy Quantity decrease (thousands of metric tons)**
Firewood	Urban	35.0	116.1 (0.33%)	179.8 (0.51%)
	Rural	36.0	25.2 (0.07%)	48.7 (0.14%)
Crop residues	Urban	30.4	33.1 (0.11%)	28.6 (0.09%)
	Rural	30.2	0.3 (0.001%)	14.2 (0.05%)
Animal dung	Urban	32.2	39.0 (0.12%)	55.5 (0.17%)
	Rural	31.4	8.8 (0.03%)	16.3 (0.05%)
Total annual cost	-	-	1,434 billion PKR (1.43 billion USD)	1,997 billion PKR (1.99 billion USD)

Notes: Authors' calculations of the simulated effect of subsidies that would reduce the price of natural gas or LPG by 1 percent; costs are measured in USD at the 2014 exchange rate, 100 PKR = 1 USD.

4.6 Conclusion and policy implications

This study applied the Linear Approximate Almost Ideal Demand System (LA-AIDS) model to estimate price and fuel expenditure elasticities in Pakistan. The complete energy demand model was estimated using Seemingly Unrelated Regression with adding up, homogeneity and symmetry restrictions. The own price elasticities suggest that all fuel types are price inelastic except for piped natural gas. For most fuel types (except animal dung and kerosene oil) demand was found to be more price elastic in rural areas than in urban areas, probably due to the ready availability of cheap or near-free substitutes (animal dung or crop residues) in rural areas. All fuels were expenditure inelastic and the differences between rural and urban areas in fuel expenditure elasticities were small but statistically significant.

We conducted simple policy simulations to suggest what would happen if the Pakistan government imposed taxes on solid fuels or provided subsidies on clean fuels. Subsidies would not only have practical advantages over taxes, being easier to implement, but would also have larger incentive effects. Comparing subsidising LPG with subsidising piped natural gas, subsidizing LPG should be preferred as it produces a more cost-effective reduction in solid fuel use. If the government were to subsidise only one clean fuel in order to reduce indoor air pollution, they should subsidise LPG instead of natural gas.

There are still a number of improvements that could be made to this approach. First, cross sectional sample survey data makes it difficult to calculate price elasticities, primarily due to the lack of variation in prices and the potential for unobserved variables such as idiosyncratic differences in fuel preferences between households to create bias in the results. We tried to avoid the former problem by pooling several cross-sectional data sets, but it would be better if panel data were available, since that would also deal with unobserved time-invariant differences between households. We could not follow a panel approach with our data, because the identity of households was not tracked between survey waves. Second, while we investigated price and fuel expenditure elasticities, and the potential impacts of changes in taxes and subsidies, there are a number of other factors that affect household fuel selection. Future research should investigate the non-price determinants of household fuel choices. Furthermore, while we have conducted a simple policy simulation of the effect of changes in taxes or subsidies, more detailed analysis could be conducted in the future to more fully evaluate the costs and benefits of changes in fuel use. Notwithstanding these limitations, our analysis contributes to a better understanding of the responses of households to changes in fuel prices, and the likely effect of policy options (in terms of taxes or subsidies).

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4.7 Appendix

Table A1. Own and cross price elasticities at the national level

Energy sources	Natural gas	LPG	Firewood	Agri. waste	Animal dung	Kerosene oil
Natural gas	**-1.448*****	0.573***	0.157***	0.027***	0.068***	0.248***
	(0.032)	(0.031)	(0.009)	(0.005)	(0.004)	(0.01)
LPG	0.402***	**-0.738*****	0.246***	0.059***	0.091***	-0.155***
	(0.019)	**(0.021)**	(0.009)	(0.005)	(0.004)	(0.006)
Firewood	0.131***	0.218***	**-0.711*****	0.113***	0.1***	0.042***
	(0.01)	(0.017)	**(0.018)**	(0.009)	(0.008)	(0.003)
Agri. waste	0.038***	0.05***	0.178***	**-0.733*****	0.098***	0.021***
	(0.008)	(0.012)	(0.011)	**(0.007)**	(0.005)	(0.003)
Animal dung	0.068***	0.088***	0.123***	0.085***	**-0.908*****	0.022***
	(0.007)	(0.01)	(0.011)	(0.005)	**(0.005)**	(0.002)
Kerosene oil	0.785***	-0.901***	0.139***	0.038***	0.057***	**-0.595*****
	(0.032)	(0.032)	(0.01)	(0.006)	(0.005)	**(0.018)**

Notes: *** p<0.01, ** p<0.05, * p<0.1; standard errors are given in the parentheses; own price elasticities are shown in bold along the diagonal, while all other values are cross-price elasticities for a change in the price of the row fuel.

Table A2. Own and cross price elasticities for urban households

Energy sources	Natural gas	LPG	Firewood	Agri. waste	Animal dung	Kerosene oil
Natural gas	**-1.39*****	0.645***	0.332***	0.109***	0.121***	0.299***
	(0.047)	(0.046)	(0.027)	(0.014)	(0.01)	(0.014)
LPG	0.458***	**-0.484*****	0.514***	0.094***	0.172***	-0.116***
	(0.026)	**(0.031)**	(0.023)	(0.01)	(0.008)	(0.008)
Firewood	0.375***	0.646***	**-0.133*****	0.345***	0.293***	0.129***
	(0.022)	(0.036)	**(0.047)**	(0.019)	(0.017)	(0.007)
Agri. waste	0.099***	0.012	0.309***	**-0.628*****	0.134***	0.033***
	(0.015)	(0.022)	(0.025)	**(0.014)**	(0.009)	(0.005)
Animal dung	0.010	0.000	0.018	0.044***	**-0.96*****	0.004
	(0.012)	(0.019)	(0.024)	(0.01)	**(0.009)**	(0.004)
Kerosene oil	0.869***	-0.742***	0.305***	0.089***	0.108***	**-0.647*****
	(0.043)	(0.042)	(0.022)	(0.012)	(0.008)	**(0.025)**

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.1$; standard errors are given in the parentheses; own price elasticities are shown in bold along the diagonal, while all other values are cross-price elasticities for a change in the price of the row fuel.

Table A3. Own and cross price elasticities for rural households

Energy sources	Natural gas	LPG	Firewood	Agri. waste	Animal dung	Kerosene oil
Natural gas	**-1.613*****	0.609***	0.07***	0.001	0.028***	0.244***
	(0.047)	(0.046)	(0.007)	(0.005)	(0.005)	(0.014)
LPG	0.449***	**-0.866*****	0.135***	0.047***	0.052***	-0.195***
	(0.03)	**(0.033)**	(0.008)	(0.005)	(0.005)	(0.009)
Firewood	0.076***	0.11***	**-0.836*****	0.05***	0.067***	0.022***
	(0.011)	(0.016)	**(0.015)**	(0.008)	(0.008)	(0.003)
Agri. waste	0.049***	0.092***	0.123***	**-0.761*****	0.087***	0.019***
	(0.01)	(0.014)	(0.012)	**(0.008)**	(0.007)	(0.003)
Animal dung	0.071***	0.083***	0.141***	0.08***	**-0.881*****	0.019***
	(0.009)	(0.013)	(0.011)	(0.007)	**(0.007)**	(0.003)
Kerosene oil	0.854***	-1.126***	0.066***	0.013**	0.022***	**-0.508*****
	(0.049)	(0.052)	(0.011)	(0.007)	(0.007)	**(0.028)**

Notes: *** p<0.01, ** p<0.05, * p<0.1; standard errors are given in the parentheses; own price elasticities are shown in bold along the diagonal, while all other values are cross-price elasticities for a change in the price of the row fuel.

Chapter 5: Interventions to mitigate indoor air pollution; a cost-benefit analysis[30]

5.1 Introduction

Currently, almost three billion people in low 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 for cooking and heating (Landrigan et al., 2017). When these solid fuels burn, they emit a multitude of complex chemicals including formaldehyde, nitrogen dioxide, carbon monoxide, cilia toxic, polycyclic aromatic hydrocarbons, and other inhalable particulates (Cooper, 1980; Torres-Duque et al., 2008). These pollutants lead to adverse effects on health and the environment (Edwards & Langpap, 2012). Alarmingly, the overall household consumption of solid fuels is expected to continue increasing until 2030 (Edwards & Langpap, 2012).

Biomass combustion causes indoor air pollution (IAP) and due to this almost four million people die prematurely each year[31], and millions face serious diseases such as lung infections, asthma, tuberculosis, sinus problems, cardiovascular disease, and cancer (Kim, et al., 2011; Lakshmi et al., 2012; Mishra, 2003). Furthermore, pollution is chiefly responsible for more deaths than AIDS, tuberculosis, obesity, malaria, child and maternal malnutrition, alcohol, road accidents, or war (Landrigan et al., 2017). However, causalities can be decreased by reducing solid fuel consumption by households (Irfan, Cameron, & Hassan, 2018b). Furthermore, various studies have found a positive association between

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[30] Note: The chapter is under review:
Irfan, M., Cameron, M. P., & Hassan, G. (under review). Interventions to mitigate indoor air pollution; a cost-benefit analysis. *Journal of South Asian Economics.*

[31] http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

IAP and the ill health effects and have suggested that cleaner fuels can save lives, and many health and environmental benefits can be gained (Barnes et al., 2004; Bruce, Perez-Padilla, & Albalak, 2000; Duflo, Greenstone, & Hanna, 2008; Ezzati, 2005; Fullerton, Bruce, & Gordon, 2008).

The consumption of solid fuels is higher in low and middle income countries than in developed countries, and often higher in rural areas than urban areas (Irfan, et al., 2018a). Hence the negative effects arising from IAP are not distributed evenly across the world population (Landrigan et al., 2017). Therefore, we selected Pakistan as a case study for our analysis of the costs and benefits of cleaner burning technology adoption. Pakistan can be a good example for developing countries because it has diverse household energy options, and currently a mix of clean and solid fuel household energy sources are in use by households (Irfan, et al., 2017). Generally in Pakistan, piped natural gas, LPG, firewood, crop residues, and animal dung are the main energy sources for cooking food, whereas electricity is rarely used for cooking (Irfan et al., 2017). Moreover, Pakistan has suitable microdata available for analysis, which are not available in all developing countries. The findings of this study may also provide some guidance for other low and middle-income countries, especially those in South Asia.

To address the issue of IAP, several interventions[32] were identified by the World Health Organization, which can be categorized into three types: (1) Interventions on the source of pollution; (2) Interventions on the living environment; and (3) Interventions to change user's behavior (Mehta & Shahpar, 2004; Quansah et al., 2015). In the first type of intervention, IAP can be reduced

[32] We adopt the term 'intervention' here, following World Health Organization (Hutton & Rehfuess, 2006), where "Hutton, G., & Rehfuess, E. (2006). Guidelines for conducting cost-benefit analysis of household energy and health interventions. Geneva: WHO" is the reference to the WHO report.

by switching from solid fuel to cleaner fuels. For instance, households may switch from coal, firewood, animal dung, or crop residues to electricity, liquefied petroleum gas (LPG), piped natural gas, or biogas. An example of the second type of intervention is improving ventilation of the cooking and living area. Examples of the third type of intervention include drying firewood before use, keeping young children away from smoke, and blowing out the fire immediately after cooking.

Despite the availability of potentially cost-effective interventions, these are yet to be adopted in many developing countries like Pakistan. Part of the reason for this may be a lack of understanding of the costs and benefits of these interventions in local conditions. We aim to contribute to the adoption of effective interventions to mitigate IAP, by demonstrating the net benefits of these interventions. Although Malla, Bruce, Bates, and Rehfuess (2011) and Hutton, Rehfuess, and Tediosi (2007) provide cost-benefit evaluations at the regional (multi-country) level, every country has different local behaviours in terms of energy consumption, as well as differences in infrastructure and climate, which can impact the costs and benefits of interventions (Fullerton et al., 2008). Thus, our study is undertaken for a single country to better consider the local conditions. This is one of the first studies to compare a range of possible IAP mitigating technologies at the country level. The study identifies the best and the least beneficial options to avert the ill effects of IAP. Five interventions were evaluated, including three examples of the first type of intervention (universal adoption of LPG; natural gas; or biogas), and two examples of the second type of intervention (universal adoption of electric stoves; or improved cook stoves (ICS)). Because of data unavailability, it is not possible to address third type of intervention.

Economic evaluation through cost-benefit analysis is a widely used analytical tool for comparing the benefits and costs of interventions (Hutton, et al., 2007). We follow the guidelines of the World Health Organization to estimate the benefit-cost ratio (BCR), net present value (NPV), and internal rate of return (IRR) of the five interventions, and find that universal adoption of LPG has the highest benefit-cost ratio of the five.

The remainder of the chapter is organized as follows. A literature review of related articles is provided in Section 5.2, and the data and methods are described in Section 5.3. We discuss the methods in Section 5.4, Costs in Section 5.5, Benefits in Section 5.6, Sensitivity analysis in Section 5.7, Results and discussion in Section 5.8 and after which Section 5.9 concludes.

5.2 Literature Review

There is very limited literature on cost-benefit analysis of household energy interventions. The existing literature does not evaluate all available choices a household can adopt to avoid IAP. However, Mehta and Shahpar (2004) examined the results of two major interventions (providing access to cleaner fuels and providing access to ICS) in six epidemiologic sub-regions.[33] They focused on two main health outcomes associated with IAP: (1) acute lower respiratory infections in young children under five years of age; and (2) chronic obstructive pulmonary disease in adults aged over twenty years. They estimated the cost using a costing template developed by WHO (2003), and found that these interventions could reduce the burden of diseases associated with IAP and save 500-600 international

[33] Africa Region, Region of the Americas, Eastern Mediterranean Region, European Region, South East Asian Region, Western Pacific Region(http://www.who.int/quantifying_ehimpacts/global/ebdcountgroup/en/).

dollars[34] per year per household. They concluded that providing access to cleaner fuels had a greater positive health effect than improving only ventilation through ICS, although there were also significant health benefits linked to ICS.

Hutton, et al., (2007) also applied cost-benefit analysis to evaluate two interventions: (1) access to the cleaner fuels; and (2) more efficient stoves, for same epidemiologic sub-regions as Mehta and Shahpar (2004). They followed the WHO's guidelines (2002-2005) for the estimation of economic cost and benefits. Costs included fuel costs, stove costs, program costs, and operational costs, while benefits included reduced health related expenditures, productivity gains, time savings, and environmental benefits. A sensitivity analysis was also carried out to explicitly estimate the uncertainty in the results. The BCR for LPG in urban areas ranged from 2.6 (for the South-East Asia Region) to 27.0 (for the Western Pacific Region) and for ICS it was negative for all but the Eastern Mediterranean Region-B, where the BCR was 136.1. Surprisingly, the BCR for LPG in urban areas was negative and for ICS in both urban and rural areas the BCR was negative for the Eastern Mediterranean Region-D (EMR-D, the region that includes Pakistan). This implies that the LPG and ICS interventions are not beneficial for the EMR-D region on average. In other words, in this region the net cost of the interventions is higher than the net benefits. On the other hand, Jeuland and Pattanayak (2012) carried out an extensive review of literature on cost-benefit analysis for ICS and found that the net benefit for households were mostly positive for ICS, however, sometimes they can be negative because of lower health benefits.

There are only a handful studies that have evaluated the costs and benefits of interventions at the country level, such as Abbas, Ali, Adil, Bashir, and Kamran

[34] International dollars ($I) have the same purchasing power as a US dollar (US$).

(2017) in Pakistan, Aunan et al. (2013) in China, Isihak, Akpan, and Adeleye (2012) in Nigeria, Malla, et al. (2011) in Kenya, Sudan, and Nepal, and García-Frapolli et al. (2010) in Mexico. Table 1 summarises the results. None of these studies have included more than three interventions. Consequently, some useful interventions such as natural piped gas and electric stoves remain unexplored. Our study fills this gap in the literature by providing analysis for five IAP mitigating technologies, including piped natural gas and electric stoves, which have thus far been largely ignored in the literature. However, both of these interventions are important alternatives for governments to consider.

Table 1. Summary of literature at country level

Study	**Country**	**Interventions**	**Results**
Abbas, et al., 2017	Pakistan	Biogas	BCR= 1.55 to 2.04 for $10m^3$
Rivoal and Haselip, 2017	Tanzania	LPG	BCR= 1.69 to 1.76, IRR=189% (over 10 years) BCR= 1.55 to 1.6, IRR=186% (over 5 years)
Aunan et al., 2013	China	ICS	BCR=3.3 to 14.7
Isihak, Akpan, and Adeleye, 2012	Nigeria	ICS LPG	ICS: BCR=2.57 LPG: BCR=2.70
Malla, et al., 2011	Kenya Sudan Nepal	Combination of ICS, smoke hoods, and LPG	Kenya: BCR=21.4, NPV=977 USD, IRR=429.3 Sudan: BCR=2.5, NPV=226.7 USD, IRR=61.8 Nepal: BCR=1.4, NPV=29.6 USD, IRR=19.0
García-Frapolli et al., 2010	Mexico	ICS	BCR= 9 to 11.4 (estimated for 7 years and 14 years)
Limmeechokchai and Chawana, 2007	Thailand	Biogas	BCR= 1.58 to 1.67 NPV= 852 to 5271 USD at 12%

Hutton, et al., 2007	For EMR-D Region only[35]	LPG ICS	BCR of LPG in Rural=2.2, Urban=Less than 1 BCR of ICS in Rural= Less than 1, Urban= Less than 1

[35] This region includes Afghanistan, Djibouti, Egypt, Iraq, Morocco, Pakistan, Somalia, Sudan, and Yemen, though they had estimated the BCRs for other regions.

5.3 Data

Various data sources were used for this study. The Pakistan Social Living Measurement Survey (PSLM, 2014) was used to estimate the total consumption of solid fuels, prices of the fuels, and households' dependence on clean and solid fuels. To collect information about the cost and benefits of the interventions, we also visited various websites of stakeholders such as the Rural Support Program Network (RSPN), Bio Energy Technology Application Pakistan (BETAPak), and Pakistan Council of Renewable Energy Technologies (PCRET). Mortality and morbidity data were obtained from the World Health Organization. The total population of children was from the United Nation's Population Division. Demographic variables such as region, age, and working age were obtained from Pakistan Bureau of Statistics. Per-capita income, total population, and average household size were from the World Bank. Electricity prices and natural gas connection charges were obtained from the Ministry of Water and Supply, and Sui Northern Gas Pipelines Limited (SNGPL), respectively. Finally, the number of days spent in bed because of illness, fuel collection time, time spent on economic activity, the operating cost of biogas plants, LPG, natural gas, electricity, the fixed costs of LPG, natural gas, and electric stoves and environmental related variables were constructed with the help of published research studies. Further details can be found in in Table A1 in the Appendix.

5.4 Methods

For monetizing the cost and benefits, this study follows the guidelines of the World Health Organization (Hutton & Rehfuess, 2006). All benefits and costs are presented on an annual basis in millions of Rupees (Pakistani currency) and US dollars for the year 2014, and benefit-cost ratios (BCRs) were calculated by dividing net annual average benefits by net annual average costs at the single household level. This analysis assumes 2015 as the first year of the intervention and forecasted an intervention period of 10 years through to the end of 2025. The choice of starting year of 2015 was because the household microdata that was used to construct various variables was from 2014. In addition to BCRs, we estimated the NPV and IRR. All the benefits and costs occurring after 2014 were discounted to 2014 values using discount rates of 3%, 5%, and 10%. The use of three different discount rates allows us to test the sensitivity of the results to the choice of discount rate. We assumed that there are two types of households: (1) those who are using clean fuels for cooking and heating purposes; and (2) others who are not. The costs and benefits were evaluated only for those households that depended on solid fuels at the start of the period.

As noted earlier, two main intervention types were chosen for this study: (1) changing from solid fuel use to cleaner fuels (biogas, LPG, natural gas, and electricity); and (2) adopting ICS or electric stoves. In first type of intervention, households can use the same type of stove for biogas, LPG, and piped natural gas, because it uses methane as a fuel source. However, electric stoves require electricity for functioning. They also do not emit harmful gases or create meaningful IAP. Although the consumption of electricity for cooking purpose is currently very rare in Pakistan (Irfan, et al., 2018a), we have included this in our analysis to evaluate whether it could be beneficial for Pakistan to adopt. Adopting an ICS reduces the use of solid fuels, and reduces IAP because of higher chimneys or better ventilation.

Initially, we estimated the costs for an individual household and then extrapolated the cost to the whole population who depended upon solid fuels in

2014. About 55% of Pakistani households do not use piped natural gas or LPG and most of them are from rural areas (PSLM, 2014).[36] Considering the total population in 2014 and taking an average of 6.7 members[37] per household, 15.22 million households out of 27.68 million households were depending on solid fuels and using traditional or inefficient stoves for cooking and heating. We estimated the benefits by assuming all those households who depend upon solid fuels (15.22 million households) adopted the cleaner fuels, electric stoves or ICS. Costs and benefits were carefully monetized as noted in the following subsections.

5.5 Costs

Operating and fixed costs of the biogas digester, LPG, piped natural gas, electric stoves, and ICS were estimated. The details are as below.

5.5.1 Biogas digesters

We sub-categorized total cost into fixed cost (installation cost, stove costs) and operating cost of biogas digesters. First, we estimated the cost of a biogas digester. There are different sizes of biogas plants available in Pakistan, ranging from 4 to 25 cubic meters. We took 10 m^3 size for the estimation because it is the median and most commonly installed size of biogas plant, as well as being sufficient to fulfil the energy demand for an average family (6-8 members) (Abbas, et al., 2017). We picked fixed dome digesters rather than floating drum and flexible bag plants because of their greater popularity, longevity, and production of gas. To install a fixed dome biogas plant, sufficient land is first required, preferably in the surrounding areas of the kitchen. The value of the land was not included in our cost estimation because: (1) households usually do not need to purchase the land for

[36] http://www.pbs.gov.pk
[37] https://data.worldbank.org/indicator/SP.POP.TOTL?locations=PK&view=chart

installing the biogas plant; and (2) after installation, the land can also be used for other purposes because biogas plants usually do not produce a foul odour.

It usually takes three to seven days to construct a biogas plant, and then another week to make it dry and ready for working. The cost of masonry, labour, materials (sand, bricks, cement, pipe, etc.), and pipes, is a fixed cost of around PKR 58,143 (USD 581) (Abbas, et al., 2017). Another fixed cost is purchasing a stove suitable for using biogas instead of simple burner. This costs around PKR 6000 (USD 60) and has an expected life of 10 years (Mehta & Shahpar, 2004) (we used the inflation adjusted price of PKR 12,547). A $10m^3$ biogas digester needs around 10kg of wet dung mixed with an equal amount of water to produce enough gas for an average family (Bhat, Chanakya, & Ravindranath, 2001). We did not include the expenditures on dung because usually biogas adopters have access to freely available animal dung (Irfan et al., 2018a). However, labour hours are also required to feed the plant and to collect the slurry (waste after using dung). We assume 45 minutes a day to do all these chores. Using the hedonic wage method (Department of the Environment, 2013), and the Pakistan minimum wage of PKR 500 per eight-hour day, this labour cost would be PKR 46.8.[38] Hence, the annual cost of labour a household bears is PKR 17,082 (USD 170).

The slurry can be used as an organic fertilizer for crops (Abbas et al., 2017; Gwavuya, Abele, Barfuss, Zeller, & Müller., 2012). It can save around PKR 600 monthly (Amjid, Bilal, Nazir, & Hussain., 2011). Thus, annually it saves PKR 7,200. We subtracted this amount from the operating cost and did not included it in the benefits section to avoid double counting. Likewise, the stove maintenance cost of PKR 374 (adjusted) per year per household (Soo, 2018) was added in the

[38] See https://paycheck.pk/main/salary/minimum-wages/minimum-wage-in-pakistan-2014

operating cost. Hence, in total, an annual fixed cost of installing a medium size biogas digester is PKR 58,143 (USD 1085), annual operating cost is PKR 10,256 (USD 102), and total annual cost is PKR 68,399 (USD 684).

5.5.2 Cost of LPG

The stove cost is the same as estimated in the previous section (PKR 12,547) because of the same usage. The average domestic LPG cylinder costs around PKR 5,628 (2007 price adjusted for 2014) with 10 years of life expectancy (Mehta & Shahpar, 2004). The average consumption of LPG and unit value price were taken from the Pakistan Social and Living Measurement Survey 2014. The monthly mean consumption of LPG is around 6.35kg and the average price of the LPG is PKR 138.5/kg, meaning an annual cost of PKR 10,553 (weighted consumption, PSLM-2014). The stove maintenance cost of PKR 374 per year per household was also included in the operating cost. In terms of fixed cost, we included the cost of stove and cylinder. So, a household that consumes LPG may face an annual total fixed cost around PKR 18,175 (USD 182) and operating cost around PKR 10,927 (USD 109) and, hence, in total 29,102 (USD 291).

5.5.3 Natural gas

Piped natural gas is the most widely used gas in urban areas of Pakistan for cooking and heating. On average, 1.8 Million Metric British Thermal Units (MMBTU) (weighted consumption, PSLM-2014) are consumed by each household monthly and the average price of piped natural gas for the year 2014 was PKR 442[39] and annual maintenance cost was PKR 374. In total, the operating cost for a household for each year is PKR 9,921. The same stove as for LPG or biogas can be used for

[39] https://www.indexmundi.com/commodities/?commodity=natural-gas&months=60&currency=pkr

piped natural gas. Total fixed cost includes the cost of stove, PKR 6000 (PKR 12,547 inflation adjusted) (Mehta & Shahpar, 2004), service and connection charges of PKR 6000[40], and PKR 8,844 charges for two days of labour gas fitters/plumber[41], and the cost of pipe. Hence, in total a household bears around PKR 37,312 (USD 373). That includes a total fixed cost of PKR 27,391 and operating costs of 9,921 for piped natural gas connection and consumption.

5.5.4 Cost of Electric stove

We took a medium size of modern electric stove, which uses around 1500 watts per hour.[42] A household usually cooks three times a day and spends 2-3 hours in the kitchen for cooking (Colbeck, et al., 2010). The price of per unit of electricity varies with the variation in total consumption, with higher consumption leading to higher price per unit. We took the average electricity price of PKR 10.50/kwh, which is charged to middle and lower middle class households (101-300 units).[43] We converted watts to kilowatts (1.5kw) and multiplied by the average cooking time to obtained kilowatts-hours (3.75kwh) and then we multiplied it by the per unit cost to obtain the operating cost of the electric stove, which is PKR 14372 per year. In addition, the maintenance cost of PKR 374 was included in the operating cost. The cost of a medium electric stove was around PKR 33,511 (adjusted from 2012 to 2014 price) (Jeuland & Pattanayak, 2012) and the life of an electric stove is usually around 10 years. Mainly the purpose of electricity connections for households is for lighting and cooling instead of cooking (almost 87 percent of households have electricity connections (PSLM-2014)). Therefore, we ignored the electricity

[40] https://www.sngpl.com.pk/web/page.jsp?pgids=861&pgname=PAGES_NAME&secs=ss7xa852op845&cats=ct456712337&artcl=artuyh709123465#conn
[41] https://www.salaryexpert.com/salary/job/plumber/pakistan
[42] http://energyusecalculator.com/electricity_stovetop.htm
[43] http://www.nepra.org.pk/Tariff/Ex-WAPDA%20DISCOS/Notifications/Schedule-I%2009-05-2012/LESCO%20Notification%20Schedule-I%2009-05-2012.pdf

connection cost in our analysis. Thus, a household bears PKR 33,511 (335 USD) as a total annual fixed cost and PKR 14,746 (147 USD) as a total annual operating cost. Hence, in total a household bears PKR 48,257 (USD 482.5) annually.

5.5.5 Cost of improved cook stoves

A household spends around PKR 3012 annually on solid fuel consumption (details are in the fuel savings section, below). An ICS can save up to 35 percent of fuel use (Vahlne & Ahlgren, 2014). Therefore, we took 65 percent of this fuel cost as the operating cost, that is PKR 1958, and added the rest of the 35 percent as fuel savings to avoid double counting. Similarly, each household spends an average of 0.3 to 4 hours for biomass collection in developing countries (Hutton et al., 2007). We took the average time 2.15 hours per day per household for biomass collection. However, adopters of ICS can save up to 8 minutes from biomass collection and 14 minutes from cooking food due to improved stove efficiency (Thakuri & Bikram, 2009). In this way using the minimum wage, a household bears PKR 42,375 (USD 423) as a labour cost annually. As a fixed cost the price of the ICS is PKR 1000 to 3000 (Jan et al., 2017) and has a life expectancy of three years (Hutton et al., 2007). We took the midpoint price PKR 2000 (USD 20) as a total fixed cost, and total operating cost is PKR 44,333, hence in total a household who adopts ICS bears PKR 46,333 (USD 463) annually.

5.6 Benefits

The list of benefits includes fuel saving, the cost averted due to illness associated with IAP, productivity gains, time saving, and environmental impacts. Some diseases that may increase due to IAP, such as mental stress or physiological pressure, are not included in the analysis because of non-availability of data.

Similarly, the environmental benefits at local and global level are not estimated because it was outside the scope of our study.

5.6.1 Fuel saving

The average consumption and prices of the biomass fuels such as firewood, agricultural residues, and animal dung were estimated from PSLM-2014 data. The average price of firewood is PKR 9/kg and average monthly consumption was 54kg per household. Similarly, crop residues and animal dung have the prices of PKR 5.31/kg and PKR 4/kg respectively. Average monthly consumption of crop residues and animal dung was 29.57kg and 27.54kg respectively per household. Hence, the annual expenditures a household saves was PKR 5832 for firewood, PKR 1884 for crop residues, and PKR 1322 for animal dung. The expenditures on animal dung and crop residues can vary significantly, because households may collect these two fuels themselves and therefore not pay. We took the average of major biomass fuels' expenditures, which is PKR 3012 (USD 30.12), because usually households use a mixture of these fuels. Thus, a household that adopts cleaner fuels such as LPG, piped natural gas, biogas, and electricity can save PKR 3012 annually. Households that adopt ICS keep consuming biomass. However, due to better efficiency they save 35 percent of the total biomass cost (Vahlne & Ahlgren, 2014), which is equal to PKR 1054 (10.5 USD).

5.6.2 Health impacts

5.6.2.1. Impact on Mortality and morbidity

We assume that universal adoption of any of the interventions would almost eliminate IAP-related mortality and morbidity. In developed countries, about one and half percent of infant and child mortality is associated with IAP (Irfan et al., 2018b). Therefore, we assumed 98.5% of mortality and morbidity can be averted by shifting from solid fuels to clean fuels. According to the Pakistan Strategic Country Environmental Assessment by the World Bank, IAP accounts for 28,000 deaths per year. Around 1,376,000 disability adjusted life years (DALYs) are lost each year due to IAP, of which 82% is from mortality and 18% from morbidity (Colbeck, et al., 2010).

To estimate the value of statistical life (VSL) various models have been used in past. For example Thaler and Rosen, (1976) used a hedonic (quality adjusted) wage model, Cameron et al. (2010) used contingent valuation methods, and Hutton et al. (2007) used a human capital approach. Recently, Viscusi and Masterman (2017) estimated the VSL for Pakistan by extrapolating from an international means and assuming an income elasticity of VSL equal to one. We converted the estimated VSL (0.248 million USD) into local currency (PKR 26 million) and used this for our calculations. Therefore, Pakistan can reap total benefits equal to PKR 717 billion (717 million USD) by averting mortality due to IAP, which is equal to 0.26 percent of total gross domestic product.

The second important health benefits arise from saving DALYs. Using 18 percent of the total (1,355,360) DALYs we came up with 243,964 DALYs due to morbidity. Using the human capital approach and considering average gross national income (GNI) in Pakistan for 2014, the earning of a year is PKR 509,000.[44] Hence, Pakistan can avert the loss of PKR 0.124 trillion (1.24 billion USD) annually through eliminating IAP.

5.6.2.2 Health care cost savings

We assume that the people of Pakistan who get ill due to respiratory illness were taking medicine and visiting doctors before their deaths. We make the simplifying

[44] https://data.worldbank.org/indicator/NY.GNP.PCAP.PP.CD?locations=PK

assumption that one DALY equates to one year of illness.[45] As mentioned above, in Pakistan the total lost years due to IAP was 1,355,360. Among these years we considered 86 percent (1,165,609 years) moderate cases, 12 percent (162,643 years) severe cases and 2 percent (27,107 years) very severe cases (Mehnaz et al., 1997; Stenberg et al., 2007). The average length of stay in hospital for patients depends upon the level of severity (Hutton et al., 2007). We assume moderate cases are not admitted to hospital, but visit hospital twice in each year, severe cases are admitted to hospital for 10 days, and very severe cases are admitted to hospital for 60 days in each year.

The cost of a day for a patient if they get admitted to hospital was PKR 1071. This includes medicine, radiology, labour, transport, patient's attendees, food, and hospital fee (Quah & Boon, 2003). The cost of visiting hospital (but not being admitted) was PKR 423, including the cost of medicine, transport, and hospital fee (Sagheer, et al., 2000). We used these costs after inflation adjustment (PKR 2418 per day for admissions and PKR 955 for visiting hospital). Moderate cases cost PKR 2.22 billion per year, whereas severe and very severe cases cost PKR 7.86 billion per year. So, in total the health care cost savings by eliminating IAP are PKR 10.09 billion (100.9 million USD).

5.6.3 Productivity gains

We used the human capital approach and took per capita GNI to estimate the illness-free value of productivity gains. We took the same years lost (1,355,360) due to IAP from the previous section, and made similar assumptions as in previous section. For example, out of total lost years, 86 percent are moderate cases who do not work

[45] This assumption probably understates the health care cost savings, as one DALY of IAP-related illness could be spread over multiple affected individuals.

for two days, 12 percent are severe cases who do not work for 10 days and 2 percent are very severe cases who do not work for 60 days in each year. In total this results in 5,584,641 wasted days. The total value of this lost productivity is equal to PKR 7.89 billion (78.9 million USD).

5.6.4 Time saving

We estimated the two types of net time savings in our analysis. First, we estimated the time saved if households do not need to collect biomass fuels, and second, time saved on cooking because of more efficient stoves. We used per capita GNI to monetize this total time saved (Hutton et al., 2007). The amount of time saved is different for different interventions. Therefore, we estimated the time saved separately. As stated earlier, an average household spends around 2.15 hours per day for biomass collection. In the case of biogas plants, a household will need to spend almost 45 minutes per day for feeding the biogas plant. By subtracting this time from biomass collection time a household that installs a biogas plant can save around 1.45 hours per day. Biogas also saves cooking time of around 42 minutes[46] per day because of efficient cooking source (Katuwal & Bohara, 2009). These 42 minutes can also be saved in case of LPG and natural gas interventions because of same stove attributes. Therefore, in total a household can save up to net 2 hours and 12 minutes in case of biogas adoption. Usually, households spend 25 percent of saved time on income generating activities and the rest of the time on other social activities (Katuwal & Bohara, 2009). Thus, a household spends 33 minutes of their saved time on income generating activities and the wage of a minute is around PKR 3 according to GNI. Hence, if a household adopts biogas it saves PKR 99 daily, equating to PKR 35,640 (356 USD) annually.

[46] Clean energy sources save utensils washing time, fire burning time, and have better efficiency.

Similarly, in case of LPG adoption a household saves around 42 minutes due to efficient cooking and 2:15 minutes by avoiding biomass collection. By taking 25 percent of time a household saves 44 minutes for income generating activities. In this way, time saving give that household PKR 132 daily and PKR 47,520 (479 USD) annually. Likewise, the time saved for natural gas and electric stove was calculated. total net saved time for natural gas and electric stove is 2:55 minutes and taking 25 percent of income generating time we come up with 44 minutes again hence the total benefits from the time saved are equal to PKR PKR 132 daily and PKR 47,520 (457 USD) annually. However, in case of ICS, wood collection time reduces by around 8 minutes because households require less biomass for cooking the same amount of food and cooking time saves around 14 minutes because of efficient cooking (Thakuri & Bikram, 2009). In total an ICS can save up to net 22 minutes per day and hence an annual income of PKR 5,940 (60 USD) per household.

Moreover, we assumed 35 percent of benefits for ICS (except time and fuel saving benefits as they estimated separately) therefore, we also assume 35 percent reduction in exposure of IAP (Bruce et al., 2004; Hutton et al., 2007). However, ventilation conditions widely vary among ICS and due to this; these estimates may be considered as a poor approximation (Hutton et al., 2007).

All these benefits and costs are given in table 2 and by following World Health Organizations' guidelines, the BCR was estimated by dividing total net benefits by total net costs (Hutton et al., 2006):

$$BCR = \frac{B}{C} = \frac{Total\ net\ intervention\ benefit}{Total\ net\ intervention\ cost} \tag{1}$$

Furthermore, NPV and IRR for all interventions were estimated, with discount rates for the NPV of 3%, 5% and 10% (Hutton et al., 2007; Malla et al., 2011).

5.7 Sensitivity analysis

Considerable uncertainty is anticipated in the results, because of lack of generalizable data and the number of necessary assumptions employed in the model. We performed sensitivity analysis to tackle this uncertainty. Specifically, we estimated the BCR and other measures for additional scenarios. In two optimistic scenarios, we increased total benefits (by 5 and 10 percent) from the base case benefits and reduced the total costs from the base case costs (by 5 and 10 percent). In two pessimistic scenarios, we reduced the total benefits (by 5 and 10 percent) from the base case and increased the costs (by 5 and 10 percent) compared to the base case costs (Isihak et al., 2012).

5.8 Results and discussion

Table 2 presents the BCRs of the five interventions. All have BCRs above one, except ICS, implying that all the IAP reducing interventions are beneficial except ICS. When households adopt ICS they do not stop consuming solid fuels, and this could be the main reason for a BCR of less than one for ICS. Our estimated BCR of ICS supports the World Health Organization's study (Hutton et al., 2007) conducted at the regional level, where they found the BCR of ICS was less than one in all the regions of the world except one (EMR-B). Households that adopt ICS continue to consume biomass; hence, the obtained benefits are less than other alternatives. This could be the main reason for the low BCR for ICS. On the other hand, our estimated BCR of ICS contradicts those of Aunan et al., (2013) Isihak, et al., (2012) and (García-Frapolli et al., 2010), all of whom found BCRs of greater than one.

Universal adoption of LPG has the highest BCR in our analysis. LPG has special requirement for connection, and consequently a low initial cost. This is the main reason for its high BCR. Surprisingly, our estimated BCR for LPG contradicts Hutton et al. (2007), but corroborates Rivoal and Haselip, (2017) Isihak, et al., (2012) and Malla, et al., (2011). Similarly, the BCR for Biogas digester was greater than one, and our estimates support the previous studies of Abbas, et al. (2017) and Limmeechokchai and Chawana (2007). Biogas plants had the least positive BCR, perhaps due the higher initial cost.

The second most beneficial alternative of solid fuel is piped natural gas, with a BCR of 2.89. Similarly, the BCR of electric stove adoption was found to be 2.23. To our knowledge no previously published study has carried out cost-benefit analysis for piped natural gas and electric stoves. Although electricity is the cleanest alternative, the energy infrastructure in Pakistan is poorly managed and there are frequent power blackouts, so households do not currently rely on electric stoves. Thus, for electric stoves to be a feasible solution to IAP, these supply problems will first need to be addressed. The estimated BCR does not account for the costs related to this infrastructure, and so the BCR of electric stoves is likely overestimated. Similarly, piped natural gas is currently only available in urban areas in Pakistan (Irfan et al., 2018a). To extend piped natural gas to rural households would require significant infrastructure investment, which is not included in our analysis, and thus the BCR for piped natural gas is likely to be substantially overestimated.

Table 2. Benefit-cost ratio of three interventions per household

Benefits	**Monetization of benefits in PKR**	**Cost**	**Monetization of costs in PKR**	BCR
Biogas				
Health Benefits	55,936	Operating cost	10,256	1.39
Productivity gain	519	Initial cost	58,143	
Time and Fuel savings	38,652			
Total	95,107	Total	68,399	
LPG				
Health Benefits	55,936	Operating cost	10,927	3.68
Productivity gain	519	Initial cost	18,175	
Time and Fuel savings	50,532			
Total	106,987	Total	29,102	
Natural gas				
Health Benefits	55,936	Operating cost	9,921	2.87
Productivity gain	519	Initial cost	27,391	
Time and Fuel savings	50,532			

Total	106,987	Total	37,312	
Electric Stove				
Health Benefits	55,936	Operating cost	14,746	2.22
Productivity gain	519	Initial cost	33,511	
Time and Fuel savings	50,532			
Total	106,987	Total	48,257	
ICS				
Health Benefits	19,578	Operating cost	44,333	0.58
Productivity gain	182	Initial cost	2,000	
Time and Fuel savings	6,994			
Total	26,753	Total	46,333	

Authors' calculations,

We estimated the NPV and IRR of each intervention, and the results are presented in Table 3, with NPV in Pakistani rupees evaluated at discount rates of 3%, 5%, and 10%. The results are consistent with the BCRs in Table 2. The NPV and IRR of biogas, natural gas, LPG, and electric stoves are positive, while these are negative for ICS at all levels of the discount rate. However, unlike the BCR analysis, the NPV and IRR suggest that the most beneficial intervention is adoption of electric stove, with Natural gas adoption as the second most beneficial intervention. However, these results do not account for the substantial infrastructure investment that would be required to extend piped natural gas to rural areas of Pakistan.

Table 3. NPV and IRR of alternative fuel options for a household

Interventions	**NPV (PKR)**			**IRR**
	3%	**5%**	**10%**	
Biogas	29,343	21,051	4,876	11.92%
LPG	62,058	53,223	35,990	33.06%
Natural gas	57,237	49,216	33,569	34.33%
Electric stove	92,275	80,354	57,097	42.75%
ICS	Negative	Negative	Negative	Negative

Authors' calculations (1 USD=100 PKR)

High uncertainty was anticipated due to many assumptions used in the analysis. Therefore, we undertook sensitivity analysis as noted above, and the results are shown in Table 4. In the pessimistic scenarios, we added five (or ten) percent to costs and deducted five (or ten) percent of the benefits. Similarly, in the optimistic scenarios we subtracted five (or ten) percent of the costs and added five (or ten) percent to the benefits. The results show that, even at the 10% pessimistic scenario, the BCRs of the interventions are above one, except for ICS.

Table 4. Benefit-Cost ratio for Optimistic and Pessimistic Scenario

Interventions	**Scenario**	
	Pessimistic	**Optimistic**
At 5 percent fluctuation		
Biogas	1.26	1.54
LPG	3.33	4.06
Natural gas	2.59	3.17
Electric stove	2.00	2.45
ICS	0.52	0.64
At 10 percent fluctuation		
Biogas	1.14	1.70
LPG	3.00	4.49
Natural gas	2.35	3.50
Electric stove	1.81	2.71
ICS	0.47	0.71

Authors' calculations.

5.9 Conclusion

Owing to IAP, almost four million people are dying prematurely annually and yet more than three billion people depend upon solid fuel consumption, even though it is the major contributor to IAP. Many local, international, government, and non-government organizations have intervened to control IAP by subsidising and investing in cleaner fuel adoption. However, previous cost-benefit studies have focused on LPG, biogas, and ICS, and few studies have considered the benefits and costs for a single country. We extended earlier analyses by including consideration of piped natural gas and electric stoves, alongside adoption of LPG, biogas, and ICS. We followed the guidelines of the World Health Organization (WHO) to conduct cost-benefit analysis in Pakistan.

It is challenging to rank the interventions because of different scales of the interventions, timing, and risk factors. However, based on our analysis, we conclude that LPG adoption is the most beneficial alternative. It has the highest BCR, and the third-highest NPV to piped natural gas and electric stove. However, electric stoves and piped natural gas would require significant infrastructure investment in Pakistan, which is not accounted for in our analysis. Nevertheless, other developing countries that do not face high infrastructure costs to adopt piped natural gas and electricity may find it to be a more cost-effective alternative.

We faced several challenges in monetizing the benefits and costs due to non-availability of credible data. Arguably, several of our assumptions were very close to the real life; however, we also accounted for uncertainty with sensitivity analysis. Even in the most pessimistic scenario, the BCRs of the alternative interventions (clean fuels) were greater than one, implying that the interventions are beneficial. Our findings can be used to guide governments and other stakeholders in choosing the most cost-effective intervention to reduce IAP.

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Appendix

Table A1. Data Sources

Variable	**Sources**
Prices of LPG, Firewood, Natural gas	PSLM-2013-14
Price of electricity	Ministry of Water and Supply
Total population	World Bank data
Average household size	World Bank data
Fixed cost of Biogas plant, Operating cost of Biogas plant, price of slurry	Bio Energy Technology Application Pakistan, published literature.
Minimum wage rate	Pay check Pakistan
Fixed cost of natural gas connection	Sui Northern Gas Pipelines limited (SNGPL)
Population of children	United Nation databank
Mortalities and morbidities (DALYS)	World Health Organization, published studies
Per capita income	World Bank data
Regional population, population of working age	Pakistan bureau of Statistics
Number of days spent in bed because of illness, fuel collection time, time spent on economic activity, Costs of health care, Operating cost of LPG, natural gas, electricity, and Fixed cost of LPG, natural gas, and electric stoves.	PSLM-2013-14 and published literature

Chapter 6: Conclusion

Globally, almost 4 million[47] people die prematurely annually due to IAP, and millions more face serious diseases (Kim, et al., 2011). The main cause of IAP is combustion of solid fuels such as crop residues, animal dung, firewood, coal, and charcoal for cooking and heating purposes. It is highly important to quantify the harms of IAP and identify suitable ways to reduce IAP. Therefore, this thesis addressed four main research questions: (1) does solid fuel consumption at household level cause increases in mortality and decreases in life expectancy; (2) why do people choose solid and clean energy sources; (3) how can price variations affect fuel choices; and (4) what interventions are best to reduce IAP.

Many studies have found a positive association between solid fuel consumption and adverse health impacts (Apte, Brauer, Cohen, Ezzati, & Pope, 2018; Cohen et al., 2005; Correia et al., 2013; Pope, Ezzati, & Dockery, 2009). However, despite various recommendations such as those of Bloom, et al., (2005) and Landrigan et al. (2018), the causal effect had not been explored. By taking into account the importance of the causal impact and research gap, this thesis explored the causal impact of solid fuel consumption on child mortality and life expectancy at cross-country level. In Chapter 2, it was found that an increase in household solid fuel consumption *causes* higher child and infant mortality and lower life expectancy. Eventually, reductions in solid fuel consumption can save millions of infants and children and can increase life expectancy.

With the causal relationship established between household solid fuel consumption and adverse health impacts, the next important step for any county

[47] http://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health

would be to explore the ways to reduce solid fuel consumption. Various theories such as the EKC theory, the energy ladder model, and the pollution-income relationship paradigm agree that to reduce pollution, income growth is sufficient. Likewise, other socio-economic and demographic variables can also discourage the solid fuel consumption. Therefore, an important question arises of what non-price factors are associated with the selection of solid and clean fuels, and this question was answered in Chapter 3 of the thesis. Pakistan was taken as a case study because of diverse energy options, and recent economic growth trends that might lead to reductions in household solid fuel use. It was found that agricultural occupation, large family size, and having cattle, are associated with solid fuel consumption. Higher income, higher education, and urban area were associated with clean fuel consumption. However, income growth or development alone will not be sufficient to switch households, particularly households in rural areas, to cleaner fuel use. Hence, the results in Chapter 3 challenge the practical aspects of countries moving along the EKC, and suggest that in order to reduce IAP, direct policy intervention will be required.

The estimates in Chapter 3 show that the most influential factor associated with the adoption of clean energy sources is urban location, rather than household income. This shows that even if Pakistan household incomes grow, the country cannot simply grow out of solid fuel consumption or IAP. Thus, to reduce the negative impacts of solid fuel use in Pakistan, policy change is required.

The significant and large coefficient of urban area shows that being in an urban area allows people to adopt cleaner fuels. People living in rural areas are less likely to adopt cleaner fuels because of a lack of accessibility to natural gas and electricity connections. Thus, rural residents are more inclined towards solid fuel consumption. Accessibility or availability of cleaner fuels was the most influential non-price factor. In addition, the estimates suggests that, if Pakistan want to address the issue of IAP and wants to discourage solid fuels, then expanding the accessibility of cleaner fuels from urban areas to smaller urban areas and nearby villages is likely to encourage many to switch to cleaner fuels. Though our analysis did not include electricity because of data limitations, extending the electricity grid throughout the country, with particular focus on rural villages, may also permit households to decrease their dependence on solid fuels, especially for lighting.

The thesis further explored the own and cross price sensitivities of the household energy sources in Chapter 4. It was found that cleaner fuels (natural gas, LPG) were more price elastic than solid fuels, implying that lowering the prices of cleaner fuels would lead households to adopt them. Moreover, subsidizing LPG would significantly reduce the consumption of solid fuels. On the other hand, it is quite challenging to tax solid fuels because of poor market structure. Many households, especially in rural areas, do not purchase solid fuels, especially animal dung and crop residues. In addition, sometime farmers offer free crop residues and animal dung to ready their fields for ploughing and to clean their premises. Therefore, adding a tax on solid fuels is quite infeasible.

Finally, in Chapter 5, five major interventions (natural gas, LPG, electric stoves, biogas plants, and improved cook stoves) were taken for cost-benefit analysis. Based on the estimated benefit-cost ratios, net present value and internal rate of return, it was found that LPG was the most beneficial alternative.

This thesis picked an important problem of household energy and indoor air pollution, investigated the expected health loss, figured out the non-price factors associated with energy selection, estimated price sensitivities, and conducted a cost-benefit analysis of several interventions. The results provide a coherent narrative of the problems and potential solutions for IAP facing a developing country like Pakistan.

6.1 Limitations

There are some limitations with the work presented in this this. First, medical test results could be helpful for the analysis to establish the casual impacts of solid fuel consumption on health. However, this method can take several years and a reasonable amount of funding; moreover, it is highly infeasible to conduct a randomized experiment where some households are kept on solid fuel consumption, when it is already known that there are ill effects of solid fuel consumption. Due to the limited time and funds, this thesis could not make use of experimental research, and suitable natural experiments could not be identified.

Second, supply side variables were not available in the data. It is important to also consider supply responses when determining the optimal subsidies or taxes. Future work should attempt to address this omission.

Third, for the measurement of elasticities, it is better to have a range of price and income fluctuations in the dataset. We pooled three cross-sectional datasets in order to provide reasonable variations in the prices and income. However, panel data at household level could give better and efficient estimates, since there are likely to be unobservable differences between households in their energy selections that were not able to be captured in the analyses in this thesis. The Pakistan Bureau of Statistics should collect data from the same households over time, perhaps as a rolling panel similar to that used by statistics agencies in developed countries for their income and expenditure surveys. This would help researchers to improve understanding of household decision-making, including but not limited to energy decisions.

Finally, in the cost-benefit analysis various assumptions were necessary because of non-availability of the data. Moreover, it is highly challenging to monetize the health impacts, and some health impacts are nearly impossible to measure, such as suffering through depression due to morbidity or physiological disorders. Therefore, not all of the costs and benefits of the interventions could be monetized, and some of the assumptions could be open to challenge.

6.2 Policy implications

The danger of IAP has been neglected by policymakers in the past. However, it is important to make this issue a top priority. The consumption of solid fuels is the main cause of IAP and has adverse effects on health, the environment, well-being, and the economy.

This thesis has a number of policy implications at the national and international level. First, IAP must be considered a great health hazard, and its reduction should be considered as part of the national planning process. It should not be treated as an isolated effect or a problem for households to deal with themselves. IAP has diverse ill effects that can damage the entire society. By reducing IAP, globally millions of lives, and especially the lives of infants and children, can be saved and life expectancy can be increased. Worryingly, women are at greater risk and losing more years of life due to solid fuel consumption than men are.

Recognizing the large benefits of clean energy and the huge ill impacts of solid fuels, this thesis explored the most appropriate way to disseminate cleaner energy, using Pakistan as a particular case study. The most important factors associated with households adopting cleaner fuels were the access and availability of cleaner energy sources. Therefore, governments should make efforts to increase the availability of clean energy sources such as piped natural gas, LPG, and biogas to households. Importantly, some energy options can be more useful in rural areas than urban areas. For example, biogas plants should only be encouraged in rural areas because of easy availability of dung as an input. In urban areas, people usually do not have livestock. So, they cannot easily get animal dung to feed the biogas digesters; they would have to buy the dung from rural areas, which can be expensive. Second, LPG is potentially a more useful energy source for rural areas; the results in this thesis show that LPG can reduce the consumption of solid fuels in rural areas. In addition, LPG is easy to install and does not require piped infrastructure like natural gas does.

It should also be noted that prices play a vital role in the adoption of clean energy sources. Solid fuels, mainly animal dung and crop residues, are very cheap and sometimes available freely. Cleaner energy sources have comparatively higher prices, particularly in rural areas. Therefore, attracting people towards cleaner fuels can be challenging for governments. To understand which energy source can easily be adopted, consideration of price elasticities is essential. This thesis revealed that piped natural gas was the most price sensitive energy option for Pakistani households. This implies that, if government wants to encourage households to adopt clean energy sources through influencing prices, natural gas could be the best option. On the other hand, the low price sensitivities of solid fuels such firewood, animal dung, and crop residues show that it will be hard for the government to cut down their consumption through price adjustments. Importantly, as stated above, solid fuels do not have proper market mechanisms; therefore, taxing solid fuels is difficult.

Furthermore, governments can introduce various clean energy interventions such as biogas, piped natural gas, LPG, and electric stoves to reduce IAP. The thesis identified that LPG should be the preferred intervention to reduce IAP based on cost-benefit analysis. Importantly, improved cook stoves is not a beneficial intervention in the case of Pakistan. The results for improved cook stoves are likely to be similar in other developing countries; however, countries should investigate within their own context.

Finally, Pakistan does not have any specific policy for household cooking and heating energy sources yet. This thesis may help the government in understanding the disadvantages of solid fuel consumption and in formulating adequate policy to deal with this crucial problem. This thesis urges policy makers to reduce the ill impacts of solid fuel consumption.

6.3 Future research

There are a number of improvements that could be made for future research, which this thesis could not cover. For example, there are various diseases such as tuberculosis, cardiovascular disease, asthma, lung cancer, and chronic obstructive pulmonary diseases that have positive associations with solid fuel consumption. However, a thorough investigation of causal impacts is missing. By following this thesis, future research could explore these causal impacts in more detail. Similarly, there could be various other factors, which can affect the selection of energy source, such as taste preferences, cooking habits, and other cultural norms. Future research could include these factors to better understand household energy preferences.

Moreover, taxation and subsidy simulation models could be developed to increase our understanding of household and supply-side responses to energy taxes and subsidies. Within these models, researchers should also estimate the effects on the well-being of households. Finally, some potential clean energy interventions were not studied in this thesis due to lack of data, such as box cookers, panel cookers, solar-funnel cookers, and parabolic cookers. The costs and benefits of these alternative interventions should be studied in future.

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6.3 Appendix

Co-Authorships forms

Co-authorships forms can be seen on the following pages.

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Chapter 2 "The causal impact of solid fuel use on mortality – a cross-country panel analysis" is a departmental working paper and under review at "Applied Economics" journal.

Nature of contribution by PhD candidate	Data downloading, data wrangling, data analysis, results interpretation, preparing the full draft, and addressing the supervisor's comments.
Extent of contribution by PhD candidate (%)	70 %

CO-AUTHORS

Name	Nature of Contribution
A.Prof. Michael Cameron	Guidance, critical feedback, and proof reading.
Dr Gazi Hassan	Helping in improvement of the chapter, providing critical feedback.

Certification by Co-Authors

The undersigned hereby certify that:

❖ the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
A.Prof. Michael Cameron	M Cameron	14-5-19
Dr Gazi Hassan	Gazi	16/5/19

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Chapter 3 "Can income growth alone increase household consumption of cleaner fuels? Evidence from Pakistan" is a departmental working paper and under review at "World Development" journal

Nature of contribution by PhD candidate	Data wrangling, data analysis, results interpretation, preparing the full draft, and addressing the supervisor's comments.
Extent of contribution by PhD candidate (%)	70 %

CO-AUTHORS

Name	Nature of Contribution
A.Prof. Michael Cameron	Guidance, critical feedback, and proof reading.
Dr Gazi Hassan	Helping in improvement of the chapter, providing critical feedback.

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The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

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Dr Gazi Hassan	[signature]	10/5/19

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Chapter 4 "Household energy elasticities and policy implications for Pakistan" is published at "Energy Policy journal"
For citation
Irfan, M., Cameron, M. P., & Hassan, G. (2018). Household energy elasticities and policy implications for Pakistan. Energy policy, 113, 633-642.

Nature of contribution by PhD candidate	Data wrangling, data analysis, results interpretation, preparing the full draft, and addressing the supervisor's comments.
Extent of contribution by PhD candidate (%)	70 %

CO-AUTHORS

Name	Nature of Contribution
A.Prof. Michael Cameron	Guidance, critical feedback, and proof reading, and helping in journal revisions
Dr Gazi Hassan	Helping in improvement of the chapter, providing critical feedback, and helping in journal revisions.

Certification by Co-Authors

The undersigned hereby certify that:

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Chapter 5 "Interventions to mitigate indoor air pollution; a cost-benefit analysis" is a departmental working paper and under review at "Journal of South Asian Development" journal.

Nature of contribution by PhD candidate	Data downloading, data wrangling, data analysis, results interpretation, preparing the full draft, and addressing the supervisor's comments.
Extent of contribution by PhD candidate (%)	70 %

CO-AUTHORS

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