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THE ECONOMICS OF RURAL ENERGY USE IN DEVELOPING COUNTRIES

UJJAYANT **CHAKRAVORTY**
RIDHIMA **GUPTA**
MARTINO **PELLI**

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The economics of rural energy use in developing countries

Ujjayant Chakravorty[*], *Ridhima Gupta*[†]
Martino Pelli[‡]

Abstract/Résumé

Pollution from the use of fuels like fuelwood and crop residue is a huge environmental issue in developing countries. It leads to poor indoor air quality and adverse impacts on human health, mainly that of women and children who spend most of their time indoors. It also leads to deforestation in areas where fuelwood and charcoal use is high. This chapter describes the problem of fuel use for cooking in developing economies, and the challenges they pose for human health and the environment. The findings from many economic studies are analysed on different aspects of this issue, evaluations of government policies and the difficulties associated with the desired transition to cleaner, more efficient fuels such as natural gas and electricity.

La pollution due à l'utilisation de combustibles tels que le bois de chauffage et les résidus de récolte est un problème environnemental majeur dans les pays en développement. Elle entraîne une mauvaise qualité de l'air intérieur et a des effets néfastes sur la santé humaine, principalement celle des femmes et des enfants qui passent la plupart de leur temps à l'intérieur. Elle conduit également à la déforestation dans les zones où l'utilisation de bois de chauffage et de charbon de bois est élevée. Ce chapitre décrit le problème de l'utilisation de combustibles pour la cuisson dans les économies en développement, et les défis qu'ils posent pour la santé humaine et l'environnement. Les conclusions de nombreuses études économiques sont analysées sur différents aspects de cette question, les évaluations des politiques gouvernementales et les difficultés liées à la transition souhaitée vers des combustibles plus propres et plus efficaces tels que le gaz naturel et l'électricité.

Keywords/Mots-clés: Cooking fuels, air pollution, indoor air quality, fuelwood markets, clean energy / Combustibles de cuisson, pollution atmosphérique, qualité de l'air intérieur, marchés du bois de chauffage, énergie propre

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[*] Department of Economics, Department of Economics, Tufts University, Medford, MA, USA. Email: ujjayant.chakravorty@tufts.edu

[†] Faculty of Economics, South Asian University, India; Email: ridhima@sau.int

[‡] Department of Economics, Université de Sherbrooke, Sherbrooke, Quebec, Canada, CIREQ, CIRANO, and GREDI. Email: martino.pelli@usherbrooke.ca

1 Introduction

More than a billion people in the world, mainly in developing countries, do not have access to clean and reliable sources of energy, such as electricity and gas. Many of these people cook and keep themselves warm by using fuelwood, crop residue, dung cakes and other forms of biomass. This issue of access to clean sources of energy is important for several reasons. In areas with high population density, fuelwood collection has led to deforestation. Burning these fuels at home in stoves and open fires with low energy efficiency causes serious indoor air pollution, with significant adverse impacts on people exposed to it. This is especially true of women and children, who stay at home for longer hours and therefore face a higher exposure to particulate emissions. Stoves and open fires that burn wood and other solid fuels are less efficient in combustion, releasing proportionately larger volumes of harmful pollutants. These practices have implications not only for the immediate health of inhabitants and the environment, but also for greenhouse gas accumulation and global warming. Large volumes of fuelwood are transported to nearby urban areas, and adds to pollution and particulate emissions in nearby cities.

Although the general rise of per capita incomes has facilitated a transition to higher end fuels such as natural gas and electricity, progress has been slow, especially in economies with a significant population that is poor. Low income households find it difficult to afford modern fuels and subsidies offered by government programs have not been sufficient to facilitate adoption and continued use. Evidence suggests that households often revert back to using polluting but cheaper and easily available fuels such as fuelwood rather than continue to buy costly cleaner fuels. There has also been a major effort to electrify rural areas, but the use of electricity has been limited in rural areas. Many studies have found that the benefits from electrification at least in the short run, have been limited.

This chapter reviews the current state of knowledge on fuel use in developing countries. It describes the types of fuels used and the nature and severity of the pollution caused. It analyses the role played by government policies to promote a faster transition to cleaner fuels such as Liquefied Petroleum Gas (LPG) and electricity and the challenges posed. It reviews the state of current economic research on this problem.

The remainder of the chapter is organized as follows. Section 2 describes the current pattern of energy use for cooking fuels, which includes reviewing different fuel types and the current state of knowledge on their impacts. Section 3 focuses on policy efforts that try to push for the adoption of cleaner and more efficient fuels. Section 4 concludes the paper by highlighting gaps in knowledge and provides directions for future research.

2 Patterns of rural energy use

More than a billion people in the world, mainly in developing countries, do not have access to clean and reliable sources of energy, such as electricity and gas. Many of these people cook and keep themselves warm by using fuelwood, crop residue, dung cakes and other forms of biomass. This issue of access to clean sources of energy is important for several reasons. In areas with high population density, fuelwood collection has often led to deforestation. Burning these fuels at home in stoves and open fires with low energy efficiency causes serious indoor air pollution, with significant adverse impacts on people exposed to it. This is especially true of women and children, who stay at home for longer hours and therefore face a higher exposure to particulate emissions. Stoves and open fires that burn wood and other fuels are less efficient in combustion, releasing proportionately larger volumes of harmful pollutants.

Several different fuels are used to supply the needs of people living in rural areas. These include biogas, electricity – both on and off-grid (such as solar), kerosene and Liquefied Petroleum Gas (LPG). Governments have attempted to induce households to switch to cleaner fuels (e.g., from fuelwood to kerosene and LPG) and have promoted the use of more fuel efficient stoves. The main hurdles presented by modern fuels are related to the not insignificant investments needed from both end-users and utilities. For instance, in the case of LPG, end-users need a significant up-front investment: a new stove and a pressurized cylinder. Utilities need to provide a stable and reliable distribution system. The lack of good distribution ends up preventing even households who would otherwise be able to afford LPG from adopting it. An example of successful adoption of LPG for cooking is Latin America, and especially Brazil, where LPG has replaced solid fuels for cooking even in the most remote areas. The success of Brazil is due to the efficiency and reliability of its distribution and replacement system for LPG cylinders [UNDP, 2015]. It has been shown that the simple measure of stabilizing distribution, not linked to any specific push towards adoption, encourages many households to adopt LPG [Barnes et al., 1994]. Almost all rural households in Brazil use LPG for cooking. Other countries such as India, have been less successful.

A critical factor that determines the relative benefits and costs of providing energy to people living in rural areas is that they are usually widely dispersed. For instance, the population density in the province of Inner Mongolia in China is only 18 per sq km. For comparison, in big cities the density may be thousands of people per sq km. Most rural residents are poor and their per capita energy consumption is low [see Sievert and Steinbuks, 2020]. For these reasons, the cost of providing energy in rural areas is high, and the willingness to pay is low presenting a difficult challenge to policy makers who are looking for viable solutions. There is significant evidence that providing reliable energy to rural households can trigger economic growth in the long run [Lipscomb et al., 2013]. This process may also free up human energy which is currently spent collecting solid fuels. This is especially important given concerns about energy and environmental justice and the goal of reducing inequality between rich and poor in developing countries.

A sound rural energy strategy should be centered on the following goals: provide (a) liquid or gaseous fuels for cooking, and electricity for lighting and communication; (b) liquid fuels and electricity to mechanize agriculture (e.g., for irrigation, crop harvesting and other tasks); and finally (c) low cost electricity to attract industrial activity in rural areas, that also bring well-paying jobs to rural areas. These policies need to be adjusted to the specific circumstances that characterize rural populations around the globe. Ashworth and Neuendorffer [1982] suggest a five-step process for matching energy needs and available resources to decentralized energy systems in the rural areas of developing countries. Countries that have achieved some success in rural development over the last decades were successful in replacing solid fuels with kerosene and LPG [UNDP, 2015].

The consumption of rural energy can be expressed in terms of an energy ladder, where higher rungs correspond to more efficient and cleaner energy types, and lower rungs represent less efficient and dirtier sources of energy [see Hosier and Dowd, 1987, Leach, 1992, Bruce et al., 2000, Van der Kroon et al., 2013]. The bottom rung of this energy ladder for cooking consists of animal dung and crop residue. Households that move up this ladder use fuelwood, charcoal, kerosene, LPG and natural gas, and finally electricity. To meet lighting needs, the ladder starts with fire, then lamps powered by kerosene and other liquid fuels, gas lanterns and finally electric bulbs. For energy use in agriculture, again the ladder proceeds from human and animal energy to diesel fuel and electricity.

Of course the energy ladder is a dynamic concept and therefore has not stayed constant over time. Wood has been used since the beginning of human civilization, when forests were relatively abundant relative to human population [see Brander and Taylor, 1998]. Over time however, wood has become a scarce commodity, so that many poor people in recent times have had to switch to using dung, crop residue, shrub and grass, thereby moving down along the energy ladder. What is not well understood, is that because energy consumption is low in rural areas of developing countries, their fuel demands may also be modest. For example, it is estimated that the cooking needs of roughly 2 billion people not served by modern fuels can be met with only about 120 million tons of oil equivalent of LPG on an annual basis. This quantity of energy is equivalent to what is currently lost in flaring of gas from oil fields and refineries [UNDP, 2015].

Below is a discussion on issues related to access to cleaner and more efficient energy sources by fuel family. First the use of biomass is discussed and the efforts to make it cleaner and then proceed to liquid fuels such as kerosene and LPG. Finally, the difficulties relating to rural electrification in developing countries are analysed.

Use of Biomass in Cooking

Roughly 50% of the world population still relies on the household cooking fire for most of its energy needs. The household cooking fire takes biomass fuels (such as fuelwood, dung, or crop residue) and transforms them into energy. Baland et al. [2018] examine the co-movements between economic growth, household fuelwood collection and forest conditions in Nepal between 2003 and 2010. They find that fuelwood collection at the village level remain stable through the years because the impact of population growth has been offset by substantial reductions in per-household collection. Per capita fuelwood collection declines as the household increases in size. Households gradually substitute fuelwood with alternative energy sources, especially those for which livestock and farm based occupations decline in importance. The authors found that fuelwood is a normal good for all but the wealthiest households. It is quite possible that for much of the poor in the developing world, a widespread switch to cleaner cooking fuels will be possible only after these countries have experienced high economic growth and increased rural incomes significantly.

More evidence of the fact that fuelwood is a normal good is provided by Bošković et al. [2022]. Using Indian household survey data for 2005, the article finds that roughly a fifth of the fuelwood collected is consumed outside of rural areas, in nearby urban areas and towns. The article also finds that households located further away from the forest spend more time collecting fuelwood and distant households are more likely to sell more fuelwood and buy less. This is because reduced access to forests increases the fixed costs of collecting fuelwood and drives up local fuelwood prices. Therefore, households found it more profitable to collect more and sell the surplus fuelwood in nearby markets.

In countries with per capita incomes below $1,000, urban and rural households account for more than half of the total energy demand. Thus, cooking with solid fuels is energy intensive and accounts for very high exposure to air pollution in developing countries [Shupler et al., 2018]. For example, households are the most important source of ambient air pollution in India [Venkataraman et al., 2018] and the largest contributor to air pollution related mortality in China [Yun et al., 2020]. Unfortunately, decades of efforts to develop improved solid-fuel stoves have had only small impacts due to: *i)* technological limitations [Venkataraman et al., 2010, Sambandam et al., 2015]; and; *iii)* infrequent use of the stove even among adopters [Hanna et al., 2016, Sambandam et al., 2015, Venkataraman et al., 2010].

Hanna et al. [2016], one of the most cited studies on improved cook stoves adoption, randomly distributed subsidized improved biomass cook stoves in Orissa (India) in 2006 in order to study their impact on health and fuel use. The authors tracked households for up to 4 years after they received the improved stove. They find that initial take-up and usage of the new stoves is far from universal and fell substantially over time, especially because households failed to make the maintenance investments needed to ensure their smooth operation. The stoves were not successful in reducing exposure to harmful pollutants – due to both poor maintenance and inappropriate use of the stoves. As a result, the stoves failed to significantly improve health outcomes, both measured by researchers and when they are self-reported. Lastly, the treatment group spent a substantial amount of time in stove maintenance, while the stove did not affect fuel cost or the amount of time needed for cooking, which resulted in modest declines in their living standards without any concomitant reduction in greenhouse gas emissions.

Mobarak et al. [2012] study the demand for improved cook stoves in rural Bangladesh. They use a stated preference approach and find that women do not perceive indoor air pollution as a health hazard relative to other risks common in rural Bangladesh such as polluted water and spoilt food. Only a few women value reductions in indoor air pollution over their financial situation. This is an example where “invisible” threats, like air or water pollution, are underestimated compared to more compelling needs. Results similar to these are observed in other contexts as well, see for instance Kremer et al. [2011] for similar conclusions relating to water pollution in Kenya. Mobarak et al. [2012] find that the stated demand for nontraditional cook stove technologies is more price-elastic than demand for other non-essential goods and services, reflecting their low valuation. The revealed preference approach, based on an RCT on stove prices, reinforces the results from the stated preference approach. The authors' observed very low adoption rates at any price and high sensitivity of purchase decisions to price. Demand for improved cook stoves was very low at both market and highly subsidized prices. These findings lead the authors to conclude that for existing non-traditional cookstove technologies, any pricing strategy alone is unlikely to achieve high adoption rates. Other factors such as taste, beliefs and attitudes about food cooked with solid fuels may also be responsible for the low upkeep of liquid fuels in rural areas [see for instance, Gupta et al., 2019].

Compared to Asia and Latin America, most of Africa still relies on charcoal for cooking. Over 195 million people in sub-Saharan countries use charcoal as their primary cooking fuel and another 200 million as their secondary fuel [Rose et al., 2022]. The use of charcoal is increasing especially among the fast growing urban population in Africa. While charcoal stoves are more efficient, they use about 25% less fuel compared to traditional stoves [Bensch and Peters, 2013]; the burning of charcoal has severe adverse effects on human health. There is little economic analysis of the problem of charcoal use in developing countries, mainly because of the lack of good data on the topic.

Biogas is a clean-burning methane-rich fuel gas produced through anaerobic digestion (bacterial action in an airless tank) of the right biomass (usually cattle dung or other types of animal waste) and it is usually used for cooking. Biogas has several advantages: *i)* the waste produced by the biological reaction is a good and natural fertilizer; *ii)* biogas plants connected to latrines can provide invaluable sanitation services; *iii)* biogas can also be used to provide lighting services if used in mantle lamps.

Past experience with biogas has been mixed. China has been one of the earlier adopters and between 1973 and 1978 installed over seven million household-scale digesters. These units are quite difficult to manage and require constant quality control. The quality of these installations greatly improved over time and by 2013 over 43 million people were using biogas in China, with a production of roughly 1,000 tons of oil equivalent [Abdulmoseen et al., 2020]. India tried to go down the same road and by the end of 1998 had almost 2.8 million plants in operation, which increased to roughly 5 million by 2020 [Jaganmohan, 2022] Bhatia [1990] develops a case study for the promotion of biogas in India and finds that the main hurdle preventing the adoption by farmers is the unfavourable macroeconomic environment created by the government and inappropriate pricing policies by manufacturers.

One of the problems with household-scale biogas plants is that poor families do not have access to sufficient animal waste in order to operate them – they often do not own animals. Better-off families, owning a sufficient number of animals to produce the dung needed to run the biogas plant usually prefer buying fuel instead of investing time and resources collecting animal waste.

Liquid fuels such as LPG and Kerosene

While some countries have succeeded in inducing households to use LPG, others have not. The upfront costs of cylinders and the reliability of the distribution network have been the most critical factors. As mentioned above, in India the cost of a cylinder alone, without accounting for the burner and the piping, represents a major share of the monthly budget of most rural households.

Gupta and Pelli [2021] identified a causal relationship between access to electricity and the adoption of modern cooking fuels, such as LPG in rural India. Using an instrumental variables approach the authors find that electrification has no impact on the choice of a cooking fuel for richer households. However, poorer households, even if liquidity-constrained, will choose an electricity connection because it allows them to have good quality lighting and access to better sources of entertainment. They will then substitute away from other energy related expenses by avoiding using modern cooking fuels such as LPG, instead preferring to use freely available biomass. Hanna and Oliva [2015] have similar results. The paper studies the impact of a rise in rural household income on fuel consumption and the composition of fuel expenditures. The authors use data from an experiment conducted by Banerjee et al. [2011] in 2006 that transferred assets and money to rural households. The paper concludes that electricity use for lighting increased due to the change in economic status but households did not switch to cleaner cooking fuels. In fact, households switched to a worse but more readily available source i.e., cow dung.

Although affordability is an important factor explaining the low adoption of LPG, various other factors also contribute to its low consumption in rural India. The direct bank transfer feature of the cash-back LPG subsidy assumes smooth identification of beneficiaries and linkage to their bank accounts. Beneficiaries are identified based on their identity numbers (a 12-digit biometric based number) issued by the government to all residents, called an Aadhar card. Bank accounts are to be linked to these Aadhar numbers. But many beneficiaries are wrongly identified [Muralidharan et al., 2020], and for this reason they do not receive the money. Moreover, the subsidy amount varies every month depending on the global price of LPG. The text messages sent to registered customers to inform them about the successful transfer of money into their bank accounts are only in English and not in the local language, Hindi.

Afridi et al. [2021] conduct a randomized control trial in rural Madhya Pradesh in 2018-2019. The first treatment they introduced consists in informing households about the adverse effects of smoke from cooking with solid fuels and how to mitigate these effects. A second treatment added further information on the amount of subsidy that could be provided to the households for purchase of LPG and hence the residual amount of monthly expenditure on LPG to be incurred by the household. The paper finds an insignificant effect of the information campaign on annual LPG consumption. There was no decline in the use of solid fuels at the extensive margin but the intensity of usage fell, based on some measures such as the number of trips made to collect fuelwood. The monthly refill consumption increased slightly for households subject to the second treatment. These results cause the authors to conclude that LPG should be made more affordable for households in order to reduce air pollution from cooking. They propose two changes to the LPG subsidy program – make LPG cheaper to relax the budget constraint faced by poor individuals. Second, they propose to introduce upfront subsidies instead of cash back subsidies. However, since 2020 the government of India has abolished LPG subsidies for all households except those using LPG under the PMUY scheme. Afridi et al. [2021] conclude that even an understanding of the adverse health effects of cooking with solid fuels and a precise knowledge of the amount of LPG subsidy may not induce rural households to switch to cleaner fuels.

Grid electrification in rural areas

Electricity sits on the highest rung of the energy ladder and when possible, it is widely used in rural areas of the developing world. Electricity is mainly used for lighting, irrigation, communication and only seldom for cooking. As shown by a number of articles discussed below, if rural electrification is not accompanied by a full array of complementary policies, households are not able to take full advantage of it. When analyzing electrification both access and the quality of its supply come into play.

Globally, the coverage of rural electrification has improved significantly over the last few decades. Yet, these numbers hide large heterogeneities. While China has accomplished a 100% rate of electrification, India and Sub-Saharan Africa still lag far behind. Moreover, when looking at electrification rates, one has to be careful of the distinction between village and household electrification. For instance, the ambitious rural electrification program started in the early 2000s in India, called the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) or Rural Electricity Infrastructure and Household Electrification Scheme, has electrified over 80% of Indian villages, yet only less than 50% of households were actually connected to the network [Modi, 2005]. This problem may also be due to the low take-up by households even after their village is electrified.

In India, by 2018 over 90% of the population was considered connected to the power grid yet, average consumption per capita increased only from 272 kWh in 1990 to 804 kWh in 2014. In 2014, per capita consumption in China was 3,927 kWh, while in the US it was 12,994 kWh. Electricity prices are highly subsidized in India, especially for the agricultural sector [Ryan and Sudarshan, 2022], partly for this reason supply lags demand, leading to frequent outages and voltage fluctuations [Modi, 2005]. Estimates suggest that only 55% of the power supplied is billed and only 41% is paid for. Infrastructure theft has led to further declines in coverage [Balachandra, 2011]. However, there has been significant improvement in average consumption and production of electricity. The generation capacity expanded from 1,362 MW in 1947 to nearly 74,699 MW in 1991. Over the same period, per capita consumption increased from 15.55 to 252.7 kWh [Modi, 2005]. Total capacity exceeds 371 GW. India has also been among the first countries in Asia to adopt hydropower, with the first hydropower plants located in Darjeeling and Shivanasamudram, established in 1898 and 1902, respectively. Over the last century India has remained a dominant player in global hydroelectric power development, and is currently ranked fifth in the world in terms of hydropower generation installed capacity, with 50.07 GW, roughly 13.5% of the country's installed capacity [International Hydropower Association, 2020]. In 2004 India had 183 hydro power plants with a total capacity of 31,218 MW. Between 2005 and 2018, 49 new hydro power plants were commissioned with an additional 14,233 MW of capacity.

For various reasons, rural residents do not prefer electricity for meeting their cooking needs. It may have to do with the fact that in many countries, reliable supply is often not available, as well as the perception that food cooked on electric stoves does not have the same flavor when compared to cooking in open fires. A United Nations study suggests that its use will be crucial for lighting, communications, refrigeration, motor applications, agricultural productivity (e.g. mechanization and irrigation), and rural industrial activities [UNDP, 2015]. Many researchers have noted that electrification works best when a set of complementary conditions are in place, that ensure income growth in rural areas. These include social and infrastructure developments, such as water supply, health programs, primary and secondary education, and an efficient road network [UNDP, 2015, Lee et al., 2020a,b].

Universal access to electricity has been a priority for many low-income countries, prompted by the World Bank and the United Nations. Lee et al. [2020a] provide an excellent summary of the economic literature on the impact of electrification on household level developmental outcomes. Their main conclusion is that supplying poor households with access to electricity alone is not enough to improve economic and non-economic outcomes in a substantial manner. Results on the impact of electrification are mixed. While a prior literature documents that access to electricity is a driver of economic development [see for instance Lipscomb et al., 2013, Chakravorty et al., 2014, 2016], more recent studies find less significant impacts of electrification on developmental outcomes [Burlig and Preonas, 2022, Lee et al., 2020b]. Electrification is, like any other major infrastructure investment, very difficult to evaluate because of its endogeneity. As a consequence, each of these studies tries to find the optimal way to correct for this endeogeneity. While most of them are internally valid, their external validity is not always clear. Most of these studies have to be read within their specific context, accounting for the sub-population they deal with and, in the case of instrumental variable studies, being careful about the estimation of Local Average Treatment Effects (LATE). A major issue with economic studies of electricity is that they are inherently studying short-run effects and it is possible that the effects of grid connections occur slowly and only in the long run.

In developing countries it is difficult to analyze the long-term effects of electrification. At best data is available for up to 15-20 years. In order to investigate the long term effects of electrification one can also learn from the outcomes of connecting the grid in developed nations. Lewis and Severnini [2020] look at the short and long-run impacts of rural electrification in the US. Access to electricity in the rural US went from 10% to 100% between 1930 and 1960. The paper uses a difference-in-difference approach based on local access to electricity, where local access is measured by the distance to the closest power plant. This rather simple identification strategy is supported by three facts: i) records show that location decisions were based on costs and urban demand, ii) urban demand used up more than 90% of the production of these plants, and iii) no statistically meaningful difference is detectable in the rural population that was electrified first or at a later stage. In the short run electrification is not found to have an impact on income, but only on housing and farmland values. The authors estimate that the average farmer would have paid 24% of farm income in order to obtain an electricity connection. Electrification also had long lasting effects in the US. In 2000, counties that gained access to the grid earlier are on average 15% more populous relative to counties which gained access later but had similar characteristics before electrification. It is important to keep these long term impacts in mind when analyzing the impact of electrification in developing countries, where at best, some medium-run effects can be observed.

Electrification can lead to an increase in labor supply, especially for women [Dinkelman, 2011, Grogan and Sadanand, 2013, Grogan, 2018]; it can also increase household incomes [Khandker et al., 2012, Chakravorty et al., 2014, 2016, Van de Walle et al., 2017]. Fujii and Shonchoy [2020] finds that access to electricity results in the acquisition and use of television sets in rural Bangladesh with negative implications for fertility. Household electrification also implies a decrease in indoor air pollution and hence better respiratory health [Barron and Torero, 2017].

Burlig and Preonas [2022] use a regression discontinuity design to study the impact of electrification on several village-level development outcomes such as labor market participation or school enrolment rates in rural India. The discontinuity is based on the fact that the policy was aimed only at villages with a population larger than 300. They found statistically insignificant results of the impact of electrification on economic outcomes and therefore conclude that gains from electrification may be substantially smaller than previously thought. [Lee et al., 2020b] also reach a similar conclusion from employing a randomized controlled trial in rural Kenya. They randomly selected clusters of households and provided them with the opportunity to connect to the grid at a subsidized price. In order to estimate a demand curve for grid connections the authors randomly assign the connection price across treatments. One third of the households got a 29% subsidy, another third received a 57% subsidy and the final third got it for free. After 16 to 32 months of exposure to electrification, the average household did not benefit from it as measured from a wide range of outcomes such as total asset value, ownership of business or employment status. The authors conclude that on average, rural Kenyan households may be too poor to consume meaningful amounts of electricity, or to be able to afford the durable goods that take advantage of electricity (such as a fridge), but after a decade or two of sustained income growth they may be able to exploit the full benefits of electrification.

Banerjee et al. [2016] explore the use of induction stoves as an option for clean cooking in rural India. The authors provided induction stoves to 4,000 households in rural Himachal Pradesh, a state characterized by a high electrification rate. After a year, the authors surveyed 1,020 households, and found that for the majority of households, electricity largely replaced LPG. Yet, LPG was mostly used as a secondary and not primary cooking fuel. The program did not induce a similar shift from traditional mud stoves as the primary cooking fuel. Only 5% of the surveyed households switched to electricity as their main cooking fuel. Given these findings, the authors state that induction stoves have limited potential in bringing about a switch to cleaner cooking fuels.

Decentralized rural electrification

A major issue with centralized electrification is that laying out grid infrastructure is extremely costly. According to Greenstone and Weisbrod [2014], the electrification of a village located 15 kilometres away from the grid in India costs about 150 thousand dollars. Hence decentralized electrification (off-grid) may be especially cost effective in remote rural areas. Off-grid electrification can be effective in remote rural areas, because it eliminates the costs of transmission and distribution – especially to small and spatially dispersed consumers who mainly use electricity during peak-load hours. Kirubi et al. [2009] perform a case study in Kenya and show that community-based electric micro-grids enable the use of tools and equipment by small and micro enterprises generating significant improvements in productivity and in income levels up to 20-70%. Comello et al. [2017] analyse the reasons behind the lag in the development of mini-grids in India, that could compensate the inability of big distribution companies to fund central grid expansions. Investments in mini-grids are on hold because a potential expansion of the central grid would put them out of business. The large distribution companies, by regulatory order, would provide power at highly subsidized rates. The paper also finds, through a full life-cycle analysis, that mini-grids based on solar PV and storage are economically feasible in India.

Several technologies can supply off-grid electricity. They are: (a) Diesel-engine generator sets: These generators can either be operated directly by utilities or by private enterprises, and serve either a single user (e.g. a rural hospital) or a small local distribution network. This technology is often used to power rural hospitals, government offices and police stations in remote areas. It is widely used in Latin America. The Amazonia region in Brazil is electrified with diesel-engine generators: 900 generators with a total capacity of 391 MW [UNDP, 2015]. These generators usually have a capacity between 50 and 500 KW and the electricity they produce costs two to three times more than grid electricity, yet they are still cost effective for remote areas because of lower transmission and distribution costs [UNDP, 2015]. However, because these generators burn fossil fuel, they also contribute to air pollution and adverse health impacts. (b) Small-scale hydropower: This is a locally available resource that can be exploited to deliver electricity or mechanical power to rural areas. It usually comes in three different sizes: *i)* micro hydro (less than 100 KW); *ii)* mini hydro (100-1,000 KW); and *iii)* small hydro (1-30 MW). Small-scale hydro has been an important part of rural electrification in China since the 1950s. China developed and installed over half of the world small-scale hydro capacity – 31,200 MW, corresponding to roughly 1.5% of China's generation capacity. As of 2016, India reported a small-scale hydro capacity of

21,135 MW, roughly 6% of its installed capacity coming from 7,135 different sites [MNRE, a]. A major drawback of small-scale hydro power is that the power is almost exclusively obtained from run-of-river plants, i.e. plants that do not have reservoir capacity to store water. As a consequence, electricity production is subject to significant seasonal variation. (c) Photovoltaic: Off-grid solar power is becoming more and more popular over time. India started its program in 1992 and so far has installed over 6.5 million solar lamps, over 230,000 solar pumps (for irrigation), 650,000 solar street lamps, and 1.7 million solar home lighting systems, for a total of 212 MW of capacity [MNRE, b]. (d) Wind: There are two main ways to exploit wind in remote areas: *i)* household units (capacity of roughly 100 W) that can provide electricity in places where neither grid power nor mini-grid power (from diesel-engine generators or small-scale hydro) is cost-effective, (e) *ii)* community-scale wind-battery-diesel hybrid systems (capacity usually in the range of 5-100 KW). China implemented a successful program very early and by the end of 1995 already produced over 15.7 GWh of power with household units [Wu, 1995]. The program focused on regions with low population densities, like Inner Mongolia; (f) Small-scale biopower using producer gas: This technology is similar to the diesel-engine generators but offers two additional advantages. First, there is no need to import oil into the region, but one can use locally available biological waste as fuel. Second, this technology offers opportunities for increased rural income generation, ideally leading to rural industrialization through the organization and collection of biological waste.

3 Have Clean Energy Policies worked?

The use of traditional solid fuels for cooking (e.g. coal, fuelwood or dung) creates negative externalities at many levels. Lim et al. [2012] provide a global assessment of the burden of disease by risk factor and place indoor air pollution from the burning of solid fuels in second place for women (after high blood pressure) and in fourth place overall (after high blood pressure, tobacco smoking and alcohol use), responsible for 4.3% of global disabilityadjusted life years (DALY). Negative externalities also impact the environment and the resource base in the region where these fuels are collected and from where they are sourced, as shown by Masera et al. [2006] and Ghilardi et al. [2009]. The use of traditional fuels also has an important impact on the socio-economic status of households and individuals. See for instance, Duflo et al. [2008] and Kowsari and Zerriffi [2011] for surveys of the literature linking indoor air pollution to economic well-being. Last but not least, the use of solid fuels impacts the production of global pollutants and hence on climate, see Bond et al. [2004] and Jeuland and Pattanayak [2012].

Policy interventions may take place at different moments during the energy cycle. Usually, the energy cycle has three phases: harvesting, processing (combustion) and distribution. The main externalities occur during the two first phases: harvesting and combustion. While harvesting may have some environmental impact, the biggest threat to our well-being comes from the routine release of pollutants during the combustion process. Human energy production and use account for a significant share of anthropogenic impacts on the environment.

Harvesting of energy directly impacts the environment. The impacts are not as damaging as those coming from combustion, but they can still be significant. For instance, hydropower affects the environment through the construction of dams, which affects a variety of ecosystems [see for instance Duflo and Pande, 2007]. The use of dung may deprive the soil of needed nutrients. Fuelwood collection may lead to excessive deforestation which can in turn exacerbate fuelwood scarcity [see for instance, Bošković et al., 2022].

Most of the negative externalities generated by the energy cycle come from the second phase: combustion – or processing. Two fuel characteristics determine the level of health-damaging consequences of combustion. First, the physical form of the fuel is an important factor. Because of their solid form, it is usually difficult to pre-mix solid fuels with a sufficient amount of air in order to ensure complete combustion. The partial burning of fuels generates a wide array of health-damaging pollutants. If a stove manages to ensure full combustion of fuelwood or other biomass fuels, very little toxic products would be released. The full combustion of wood produces mainly carbon-dioxide and water. In practice, up to a fifth of the fuel carbon is released in the form of incomplete combustion products, many of which are important health-damaging pollutants like black carbon. Second, contaminants can vary from fuel to fuel. For instance, while charcoal is more energy efficient than wood, it is worse in terms of pollution because of its solid form and its pollution content. LPG and kerosene, despite containing sulfur and other pollutants, have low levels of emissions because it is relatively simple to pre-mix them with air and ensure almost full combustion. Their emissions of health-damaging pollutants are roughly an order of magnitude smaller than those from biomass [Smith et al., 2000].

What is important for policy is to measure how much pollution is released and when. Pollution from household stoves is usually released right at the time when many people are present, at meal time. Since women are mostly doing the cooking, they are most exposed, along with children. Although the total amount of health-damaging pollution released from stoves is not high relative to that from other fossil fuels, human exposure to a number of toxic pollutants is much larger than those created by outdoor pollution, and the health effects can be expected to be higher as well.

An additional problem of solid fuel stoves is that these stoves usually do not have a chimney and release a large share of emissions within the household. Yet, even when households do install a chimney in order to eliminate the smoke from their home, they still produce significant amounts of local outdoor pollution, which can result in much higher neighborhood pollution in dense villages and slums than in other settings [see for instance Shen et al., 2014, Ni et al., 2016].

Cooking energy is the largest component of rural energy use. Since the 1980s, governments in developing countries have created programs to induce the adoption of improved cooking stoves. The learning curve has been steep, with moderate success in the beginning and a larger response over time. The Chinese National Improved Stoves Program during 1982-99 has helped install 175 million improved stoves in rural areas of the country. These stoves were cheap (about 85 yuan, roughly $12) and the government contribution was small, about 4.2 yuan ($0.5). In about the same period, India installed about 30 million improved stoves (called chulhas) through the National Program on Improved Chulhas, providing a higher subsidy (Rs 200, i.e. $2.5) – about half the cost of the stove. However in India, only about half the stoves were still in use at the end of the program [UNDP, 2015].

Most stove programs focus on improving energy efficiency, which is important but only indirectly addresses the problem of reducing the exposure of households to indoor smoke. For example, replacing wood stoves with charcoal stoves increases energy efficiency because charcoal combusts better, but charcoal is also more polluting. Charcoal produces more carbon monoxide than wood, which is responsible for many deaths on an annual basis. Studies show that simply improving solid fuel burning stoves will not reduce pollution. Even the best stove, while decreasing indoor pollution, does not significantly reduce total emissions. Putting the health-damaging smoke outside the house does not significantly improve the situation, especially in densely populated slums and villages. LPG and kerosene also carry risks, the former can generate fires and explosions, while the latter can cause poisoning from bad storage. Yet, both risks are much lower than those induced by solid fuels. Barron and Torero [2017] has shown that a switch to electricity has a large impact on indoor air quality.

India is one of the largest countries in the world in terms of rural population lacking access to clean and efficient energy. Over the last decades it has engaged in several large rural electrification programs. Only a handful of villages had access to electricity when it achieved independence in 1947, but most of them are now connected to the grid, which is no mean task given about 600,000 villages in the country [Burlig and Preonas, 2022]. The number of electrified villages went from roughly 1,500 in 1947 to 576,554 in 2014 [Burlig and Preonas, 2022]. These programs started as early as 1950 and culminated in 2005 with the launch of the Rajiv Gandhi Grameen Vidyutikaraan Yojana (RGGVY) or Rural Electricity Infrastructure and Household Electrification Scheme, which merged all the existing programs. RGGVY covered all states except Andaman & Nicobar Islands, Chandigarh, Dadra & Nagar Haveli, Daman & Diu, Delhi, Goa, Lakshadweep, and Puducherry. The goal of this program was to fulfill the National Common Minimum Programme (NCMP) goal of universal electrification within five years through a program financed 90% by the Central government and 10% by the Rural Electrification Corporation (REC). The scheme covered all hamlets with a population larger than 100. A village was declared electrified if three conditions were fulfilled: *a*) basic infrastructure such as a distribution transformer and distribution lines are provided in the inhabited locality as well as the *dalit basti* hamlet where it exists (i.e. hamlet of backward castes); *b*) Electricity is provided to public places like schools, panchayat office, health centers, dispensaries, community centers, etc.; and *c*) The number of households electrified should be at least 10% of the total number of households in the village.

Another large governmental effort in India has been to push for the adoption of LPG in rural areas. Launched in 2013, the Direct Benefit Transfer of LPG (DBTL), or Pahal, provides subsidies for the purchase of LPG cylinders directly into recipients' bank accounts. The goal of this program is to increase the use of LPG and at the same time, eliminate misuse of program funds. In 2015, the government launched the program *Give It Up* to motivate households able to afford LPG at its market price to surrender their subsidies and transfer them to poorer households. Finally, in 2016, the *Pradhan Mantri Ujjwala Yojana* (PMUY, commonly known as Ujjwala) program was started, which aimed at providing LPG connections to 80 million poor households by 2019. All these programs must account for fuel stacking, that is happening everywhere and allows households to quickly switch back to solid fuels [Mukhopadhyay et al., 2012, Hollada et al., 2017, Troncoso and Soares da Silva, 2017]. Fuel stacking is a variation of the energy ladder idea. It predicts that, with rising incomes, households do not completely switch to a higher rung of the energy ladder, but rather rely on multiple fuels, using larger shares of superior fuels and smaller shares of inferior fuels. See for instance Masera et al. [2000], Heltberg [2004], and Masera et al. [2006].

Under the PMUY scheme, a woman in a rural, socio-economically disadvantaged household, obtaining an LPG account does not bear the significant upfront costs of an LPG connection which consists of a connection charge, the deposit for a cylinder and pressure regulator, and a rubber pipe. The security deposit and administrative charges for the creation of a new LPG account (amounting to roughly $25) are borne by the government. The woman also receives an interest-free loan of about $20 from one of the three state-owned Oil Marketing Companies (OMCs) to purchase the stove and the first cylinder. Initially, this loan was to be recovered by paying cash-back refill subsidy to the OMC instead of the customer until the principal was paid back in full. Since April 2018, the government has stopped withholding the transfer of the subsidy money to the bank account of the PMUY beneficiaries to encourage them to increase their LPG consumption. Since April 1 2020, the government has entitled PMUY beneficiaries who are eligible for financial support under another scheme to avail themselves of free LPG cylinder refills for a period of 3 months. The amount of the refills is credited in advance into the bank account of the PMUY beneficiaries. Some of the PMUY beneficiaries still did not use the advance credited into their account to purchase the cylinder refill within the scheme period and therefore the government extended the time-limit for using the advance by another three months. More recently, the subsidy covering the refill cost has been eliminated for all consumers except the beneficiaries of the PMUY scheme [see Ministry of Petroleum & Natural Gas, IANS, 2020]. Despite all these efforts, it has been a challenge to get rural households to refill their cylinders [see Johari, 2021, Pandey, 2021].

A critical issue that these programs pushing the introduction of LPG for cooking face is affordability. The subsidy on LPG refills amounts on average to about $2.7 for PMUY holders [see Johari, 2021]. In India, LPG is generally sold in metal cylinders marketed by state-owned oil companies at a price of roughly $12 for a 12.4 Kg capacity cylinder. If LPG is used as the exclusive cooking fuel, the average rural household consumes roughly a cylinder of gas a month [Dabadge et al., 2018] The current inflation adjusted all-India rural poverty line is $22 per capita per month, classifying individuals with monthly per capita income below this cutoff as poor. In December 2020, 37% of people in rural India had monthly expenditures below this cut-off and 70% of the individuals had monthly expenditures below $32 [Dhingra and Ghatak, 2021]. Therefore, refilling costs are substantial for the majority of people in rural India. Hence, it is not surprising that many PMUY beneficiaries still use solid fuels to cook [Gupta et al., 2019]. The lump-sum payment required for LPG connections is an additional impediment since most poor rural households who use lower quality fuels such as fuelwood are liquidity-constrained. This problem shows up in other developing countries as well [Lewis and Pattanayak, 2012, Rehfuess et al., 2014, Puzzolo et al., 2016, Gould and Urpelainen, 2018]. Even though LPG offers clear benefits in terms of ease of cooking and environmental benefits, the determinants of its adoption and use are not yet completely understood. Cheng and Urpelainen [2014] and Alkon et al. [2016] have studied the issue of LPG affordability, and Lewis and Pattanayak [2012], Bhojvaid et al. [2014], and Sehjpal et al. [2014] have focused on the characteristics of the household in order to understand the determinants of adoption.

4 Summary

Although progress has been made in transitioning poor people from using polluting solid fuels to cleaner liquids and gases which burn more effectively and produce less harmful pollutants, there are major challenges that need to be addressed. Many poor households can not afford the higher price of LPG, as the government experiments in India have shown. The unsubsidized cost of a cylinder of gas is still prohibitive for most households. There are other challenges as well. Creating and maintaining a robust distribution system in rural areas is expensive. The lack of access to natural gas can induce households to move back to using fuelwood and animal waste, which are more polluting and also have an adverse effect on the environment. However, Brazil has shown that it is possible to nudge people away from solid fuels to LPG even in the most remote areas. It is possible that the liquidity constraints facing households in regions such as South Asia pose larger constraints than in middle income economies like Brazil. If the demand for LPG is high, it is feasible to maintain an efficient distribution system in areas with low population density.

Studies have also found that fuelwood is a normal good for many rural households, and higher incomes induce more collection [e.g. Baland et al., 2018]. This trend does not bode well because as incomes rise households will collect more fuelwood, exacerbating the problems of deforestation, pollution and health. However, given the large impacts of this behavior on the accumulation of greenhouse gases, it may be optimal to provide subsidies to households to adopt natural gas for cooking. Many countries have proceeded to engage in costly electrification programs, but whether these efforts lead to a reduction in pollution and a shift in the use of polluting cooking fuels remains to be seen [Gupta and Pelli, 2021]. Further research needs to be done to study whether regions that have benefited from government clean energy programs have been able to reduce indoor air pollution from the use of solid fuels such as fuelwood and animal waste.

More studies are needed to determine the optimal subsidies that may be needed to induce low-income households to switch to cleaner fuels. Informational incentives may also play a role. One important future area of research may be to study how firms can supply clean energy in rural areas and yet achieve cost recovery, especially in the distribution of LPG and electricity to poor households. The role of small-scale hydro units, solar panels and wind turbines in reaching households living in remote locations is another important issue for further study.

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References

S.G. Abdulmoseen, N. Ali, I. Ahmad, M. Asif, R.-B. Guo, F.-L. Li, and M. Lu. Prospects of China's biogas: Fundamentals, Challenges and Considerations. *Energy Reports*, 6:2973–2987, 2020.

Farzana Afridi, Sisir Debnath, and Eswaran Somanathan. A breath of fresh air: Raising awareness for clean fuel adoption. *Journal of Development Economics*, 151:102674, 2021.

M. Alkon, S.P. Harish, and J. Urpelainen. Household Energy Access and Expenditure in Developing Countries: Evidence from India, 1987–2010. *Energy for Sustainable Development*, 35:25 – 34, 2016. ISSN 0973-0826. doi: https://doi.org/10.1016/j.esd.2016.08.003. URL http://www.sciencedirect.com/science/article/pii/S0973082616302204.

J.H. Ashworth and J.W. Neuendorffer. Escaping the Rural Energy Dilemma: A Process for Matching Technologies to Local Needs and Resources. *World Development*, 10(4):305–318, 1982.

P. Balachandra. Dynamics of Rural Energy Access in India: An Assessment. *Energy*, 36(9): 5556–5567, 2011.

Jean-Marie Baland, François Libois, and Dilip Mookherjee. Forest degradation and economic growth in nepal, 2003–2010. *Journal of the Association of Environmental and Resource Economists*, 5(2):401–439, 2018.

A Banerjee, E Duflo, R Chattopadhyay, and J Shapiro. Targeting the Hard-Core Poor, An Impact Assessment. Working paper, MIT, 2011.

M. Banerjee, R. Prasad, I.H. Rehman, and B. Gill. Induction Stoves as an Option for Clean Cooking in Rural India. *Energy Policy*, 88:159–167, 2016.

D.F. Barnes, K. Openshaw, K.R. Smith, and R. van der Plas. What Makes People Cook with

Improved Biomass Stoves? A Comparative International Review of Stove Programmes. Technical Paper 242, World Bank, Washington, D.C., 1994.

M. Barron and M. Torero. Household Electrification and Indoor Air Pollution. *Journal of Environmental Economics and Management*, 86:81–92, 2017.

G. Bensch and J. Peters. Alleviating Deforestation Pressures? Impacts of Improved Stove Dissemination on Charcoal Consumption in Urban Senegal. *Land Economics*, 89(4):676–698, 2013.

R. Bhatia. Diffusion of Renewable Energy Technologies in Developing Countries: A Case Study of Biogas Engines in India. *World Development*, 18(4):575–590, 1990.

V. Bhojvaid, M. Jeuland, A. Kar, J.J. Lewis, S.K. Pattanayak, N. Ramanathan, V. Ramanathan, and I.H. Rehman. How do People in Rural India Perceive Improved Stoves and Clean Fuel? Evidence from Uttar Pradesh and Uttarakhand. *International Journal of Environmental Research and Public Health*, 11(2):1341–1358, 2014.

T. Bond, C. Venkataraman, and O. Masera. Global Atmospheric Impacts of Residential Fuels. *Energy for Sustainable Development*, 8(3):20 – 32, 2004. ISSN 0973-0826. doi: https://doi.org/10.1016/S0973-0826(08)60464-0. URL http://www.sciencedirect.com/science/article/pii/S0973082608604640.

B. Bošković, U. Chakravorty, M. Pelli, and A. Risch. The Effect of Forest Access on the Market for Fuelwood in India. Technical report, CIREQ, 2022.

James A Brander and M Scott Taylor. The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use. *American Economic Review*, 88(1):119–138, March 1998. URL https://ideas.repec.org/a/aea/aecrev/v88y1998i1p119-38.html.

N. Bruce, R. Perez-Padilla, and R. Albalak. Indoor Air Pollution in Developing Countries: A Major Environmental and Public Health Challenge. *Bulletin of the World Health Organization*, 78:1078–1092, 2000.

F. Burlig and L. Preonas. Out of the Darkness and Into the Light? Development Effects of Rural Electrification. Working Paper 268, Energy Institute at Haas, 2022.

U. Chakravorty, M. Pelli, and B. Ural Marchand. Does the Quality of Electricity Matter? Evidence from Rural India. *Journal of Economic Behavior & Organization*, 107:228–247, 2014.

U. Chakravorty, K. Emerick, and M.-L. Ravago. Lighting up the Last Mile: The Benefits and Costs of Extending Electricity to the Rural Poor. Discussion paper, Resources for the Future, 2016.

C. Cheng and J. Urpelainen. Fuel Stacking in India: Changes in the Cooking and Lighting Mix, 1987–2010. *Energy*, 76:306 – 317, 2014. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2014.08.023. URL http://www.sciencedirect.com/science/article/pii/S0360544214009591.

S.D. Comello, S.J. Richelstein, A. Sahoo, and T.S. Schimdt. Enabling Mini-Grid Development in Rural India. *World Development*, 93:94–107, 2017.

Ashwini Dabadge, Ashok Sreenivas, and Ann Josey. What has the pradhan mantri ujjwala yojana achieved so far. *Economic & Political Weekly*, 53(20):69–75, 2018.

Swati Dhingra and Maitreesh Ghatak. How has covid-19 affected india's economy? https://www.economicsobservatory.com/how-has-covid-19-affected-indias-economy, 2021. Accessed: 2022-04-9.

Taryn Dinkelman. The Effects of Rural Electrification on Employment: New Evidence from South Africa. *American Economic Review*, 101(7):3078–3108, December 2011. URL http://ideas.repec.org/a/aea/aecrev/v101y2011i7p3078-3108.html.

E. Duflo and R. Pande. Dams. *The Quarterly Journal of Economics*, 122(2):601–646, 2007.

E. Duflo, M. Greenstone, and R. Hanna. Indoor Air Pollution, Health and Economic Well-Being. *S.A.P.I.EN.S. [Online]*, 1(1), 2008.

T. Fujii and A.S. Shonchoy. Fertility and rural electrification in Bangladesh. *Journal of Development Economics*, 143:102430, 2020.

A. Ghilardi, G. Guerrero, and O. Masera. A GIS-Based Methodology for Highlighting Fuelwood Supply/Demand Imbalances at the Local Level: A Case Study for Central Mexico. *Biomass and Bioenergy*, 33(6):957 – 972, 2009. ISSN 0961-9534. doi: https://doi.org/10.1016/j.biombioe.2009.02.005. URL http://www.sciencedirect.com/science/article/pii/S0961953409000415.

C.F. Gould and J. Urpelainen. LPG as a Clean Cooking Fuel: Adoption, Use, and Impact in Rural India. *Energy Policy*, 122:395–408, 2018.

M. Greenstone and A. Weisbrod. Energy, Growth and Development. *International Growth Center Evidence Paper*, 2014.

L. Grogan. Time Use Impacts of Rural Electrification: Longitudinal Evidence from Guatemala. *Journal of Development Economics*, 135:304–317, 2018.

L. Grogan and A. Sadanand. Rural Electrification and Employment in Poor Countries: Evidence from Nicaragua. *World Development*, 43:252–265, 2013.

Aashish Gupta, Sangita Vyas, Payal Hathi, Nazar Khalid, Nikhil Srivastav, Dean Spears, and Diane Coffey. Persistence of Solid Fuel Use Despite Increases in LPG Ownership: New Survey Evidence from Rural North India. Technical report, 2019.

R. Gupta and M. Pelli. Electrification and Cooking Fuel Choice in Rural India. *World Development*, 146:105539, 2021.

R. Hanna and P. Oliva. Moving Up the Energy Ladder: The Effect of an Increase in Economic Well-Being on the Fuel Consumption Choices of the Poor in India. *American Economic Review*, 105(5):242–46, 2015.

R. Hanna, E. Duflo, and M. Greenstone. Up in Smoke: The Influence of Household Behavior on the Long-Run Impact of Improved Cooking Stoves. *American Economic Journal: Economic Policy*, 8(1):80–114, 2016.

Rasmus Heltberg. Fuel switching: evidence from eight developing countries. *Energy economics*, 26(5):869–887, 2004.

J. Hollada, K.N. Williams, C.H. Miele, S.A. Danz, D. aand Harvey, and W. Checkley. Perceptions of Improved Biomass and Liquefied Petroleum Gas Stoves in Puno, Peru: Implications for Promoting Sustained and Exclusive Adoption of Clean Cooking Technologies. *International Journal of Environmental Research and Public Health*, 14(2):182, 2017.

R.H. Hosier and J. Dowd. Household Fuel Choice in Zimbabwe. *Resources and Energy*, 9: 347–361, 1987.

IANS. Govt eliminates cooking gas subsidy as Covid-19 turns oil market favourable, 2020. URL https://www.business-standard.com/article/economy-policy/govt-eliminates-cooking-gas-subsidy-as-covid-19-turns-oil-market-favourable-120090101003_1.html. Accessed: 2022-04-9.

International Hydropower Association. 2020 Hydropower Status Report: Sector trends and insights. Report, 2020.

Madhumitha Jaganmohan. Number of biogas plants across India as of March 2021, by state,

2022. URL https://www.statista.com/statistics/941298/india-number-of-biogas-plants-by-state/. Accessed: 2022-04-9.

M.A. Jeuland and S.K. Pattanayak. Benefits and Costs of Improved Cookstoves: Assessing the Implications of Variability in Health, Forest and Climate Impacts. *Plos One*, 7(2): 1–15, 02 2012. doi: 10.1371/journal.pone.0030338. URL https://doi.org/10.1371/journal.pone.0030338.

Aarefa Johari. India′s poor were struggling to refill LPG cylinders. Now with record price hike, many have given up, 2021. URL https://scroll.in/article/988886/india-s-poor-were-struggling-to-refill-lpg-cylinders-now-with-record-price-hike-many-have-given-up. Accessed: 2022-04-9.

S.R. Khandker, D.F. Barnes, and H.A. Samad. The Welfare Impacts of Rural Electrification in Bangladesh. *The Energy Journal*, 33(1), 2012.

C. Kirubi, A. Jacobson, D. Kammen, and A. Mills. Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya. *World Development*, 37(7): 1208–1221, 2009.

R. Kowsari and H. Zerriffi. Three Dimensional Energy Profile: A Conceptual Framework for Assessing Household Energy Use. *Energy Policy*, 39(12):7505 – 7517, 2011. ISSN 0301-4215. doi: https://doi.org/10.1016/j.enpol.2011.06.030. URL http://www.sciencedirect.com/science/article/pii/S0301421511004861. Clean Cooking Fuels and Technologies in Developing Economies.

M. Kremer, J. Leino, E. Miguel, and A. Peterson Zwane. Spring Cleaning: Rural Water Impacts, Valuation, and Property Rights Institutions. *The Quarterly Journal of Economics*, 126(1):145–205, 2011. URL https://ideas.repec.org/a/oup/qjecon/v126y2011i1p145-205.html.

G. Leach. The Energy Transition. *Energy Policy*, 20(2):116–123, 1992.

K. Lee, E. Miguel, and C. Wolfram. Does Household Electrification Supercharge Economic Development? *Journal of Economic Perspectives*, 34(1):122–44, February 2020a. doi: 10.1257/jep.34.1.122. URL http://www.aeaweb.org/articles?id=10.1257/jep.34.1.122.

K. Lee, E. Miguel, and C. Wolfram. Experimental Evidence on the Economics of Rural Electrification. *Journal of Political Economy*, 128(4):1523–1565, 2020b.

J. Lewis and E. Severnini. Short- and Long-Run Impacts of Rural Electrification: Evidence from the Historical Rollout of the U.S. Power Grid. *Journal of Development Economics*, 143:102412, 2020. ISSN 0304-3878. doi: https://doi.org/10.1016/j.jdeveco.2019.102412. URL http://www.sciencedirect.com/science/article/pii/S0304387819304547.

J.J. Lewis and S.K. Pattanayak. Who Adopts Improved Fuels and Cookstoves? A Systematic Review. *Environmental Health Perspectives*, 120(5):637, 2012.

S.S. Lim, T. Vos, A.D. Flaxman, and al. A Comparative Risk Assessment of Burden of Disease and Injury Attributable to 67 Risk Factors and Risk Factor Clusters in 21 Regions, 1990 – 2010: A Systematic Analysis for the Global Burden of Disease Study 2010. *The Lancet*, 380(9859):2224 – 2260, 2012. ISSN 0140-6736. doi: https://doi.org/10.1016/S0140-6736(12)61766-8. URL http://www.sciencedirect.com/science/article/pii/S0140673612617668.

Molly Lipscomb, A Mushfiq Mobarak, and Tania Barham. Development effects of electrification: Evidence from the topographic placement of hydropower plants in brazil. *American Economic Journal: Applied Economics*, 5(2):200–231, 2013.

O. Masera, A. Ghilardi, R. Drigo, and M.A. Trossero. WISDOM: A GIS-Based Supply Demand Mapping Tool for Woodfuel Management. *Biomass and Bioenergy*, 30(7):618 – 637, 2006. ISSN 0961-9534. doi: https://doi.org/10.1016/j.biombioe.2006.01.006. URL http://www.sciencedirect.com/science/article/pii/S0961953406000262.

O.R. Masera, B.D. Saatkamp, and D.M. Kammen. From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. *World Development*, 28(12):2083 – 2103, 2000. ISSN 0305-750X. doi: https://doi.org/10.1016/S0305-750X(00)00076-0. URL http://www.sciencedirect.com/science/article/pii/S0305750X00000760.

Ministry of Petroleum & Natural Gas. URL http://www.pmujjwalayojana.com. Accessed: 2022-04-9.

MNRE. Small Hydro Energy, a. URL https://mnre.gov.in/small-hydro/current-status. Accessed: 2022-04-9.

MNRE. Solar Energy, b. URL https://mnre.gov.in/solar/solar-offgrid. Accessed: 2022-04-9.

Ahmed Mushfiq Mobarak, Puneet Dwivedi, Robert Bailis, Lynn Hildemann, and Grant Miller. Low demand for nontraditional cookstove technologies. *Proceedings of the National Academy of Sciences*, 109(27):10815–10820, 2012.

V. Modi. Improving Electricity Services in Rural India. Working Paper 30, Center on Globalization and Sustainable Development. The Earth Institute at Columbia University., 2005.

R. Mukhopadhyay, S. Sambandam, A. Pillarisetti, D. Jack, K. Mukhopadhyay, K. Balakrishnan, M. Vaswani, M.N. Bates, P.L. Kinney, N. Arora, and K.R. Smith. Cooking Practices, Air Quality, and the Acceptability of Advanced Cookstoves in Haryana, India: An Exploratory Study to Inform Large-Scale Interventions. *Global Health Action*, 5(1):19016, 2012. doi: 10.3402/gha.v5i0.19016. URL https://doi.org/10.3402/gha.v5i0.19016. PMID: 28140858.

Karthik Muralidharan, Paul Niehaus, and Sandip Sukhtankar. Identity verification standards in welfare programs: Experimental evidence from india. Technical report, National Bureau of Economic Research, 2020.

K. Ni, E. Carter, J.J. Schauer, M. Ezzati, Y. Zhang, H. Niu, A.L. Lai, M. Shan, Y. Wang, X. Yang, and J. Baumgartner. Seasonal Variation in Outdoor, Indoor, and Personal Air Pollution Exposures of Women Using Wood Stoves in the Tibetan Plateau: Baseline Assessment for an Energy Intervention Study. *Environment International*, 94:449–457, 2016. ISSN 0160-4120. doi: https://doi.org/10.1016/j.envint.2016.05.029. URL https://www.sciencedirect.com/science/article/pii/S0160412016302136.

Kundan Pandey. Govt admits refilling LPG cylinders under Ujjwala a challenge, plans a new scheme, 2021. URL https://www.downtoearth.org.in/news/energy/govt-admits-refilling-lpg-cylinders-under-ujjwala-a-challenge-plans-a-new-scheme-63835. Accessed: 2022-04-9.

E. Puzzolo, D. Pope, D. Stanistreet, E.A. Rehfuess, and N.G. Bruce. Clean Fuels for Resource-Poor Settings: A Systematic Review of Barriers and Enablers to Adoption and Sustained Use. *Environmental Research*, 146:218 – 234, 2016. ISSN 0013-9351. doi: https://doi.org/10.1016/j.envres.2016.01.002. URL http://www.sciencedirect.com/science/article/pii/S0013935116300020.

E.A. Rehfuess, E. Puzzolo, D. Stanistreet, D. Pope, and N.G. Bruce. Enablers and Barriers to Large-Scale Uptake of Improved Solid Fuel Stoves: A Systematic Review. *Environmental Health Perspectives*, 122(2):120, 2014.

J. Rose, G. Bensch, A. Munyehirwe, and J. Peters. The Forgotten Coal: Charcoal Demand in Sub-Saharan Africa. *World Development*, 25:100401, 2022.

N. Ryan and A. Sudarshan. Rationing the Commons. *Journal of Political Economy*, 130(1), 2022.

Sankar Sambandam, Kalpana Balakrishnan, Santu Ghosh, Arulselvan Sadasivam, Satish Madhav, Rengaraj Ramasamy, Maitreya Samanta, Krishnendu Mukhopadhyay, Hafeez Rehman, and Veerabhadran Ramanathan. Can currently available advanced combustion biomass cook-stoves provide health relevant exposure reductions? results from initial assessment of select commercial models in india. *EcoHealth*, 12(1):25–41, 2015.

R. Sehjpal, A. Ramji, A. Soni, and A. Kumar. Going Beyond Incomes: Dimensions of Cooking Energy Transitions in Rural India. *Energy*, 68:470 – 477, 2014. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2014.01.071. URL http://www.sciencedirect.com/science/article/pii/S0360544214000930.

Guofeng Shen, Yanyan Zhang, Siye Wei, Yuanchen Chen, Chunli Yang, Pengchuan Lin, Han Xie, Miao Xue, Xilong Wang, and Shu Tao. Indoor/Outdoor Pollution Level and Personal Inhalation Exposure of Polycyclic Aromatic Hydrocarbons through Biomass Fuelled Cooking. *Air Quality, Atmosphere & Health*, 7:449–458, 2014.

Matthew Shupler, William Godwin, Joseph Frostad, Paul Gustafson, Raphael E Arku, and Michael Brauer. Global estimation of exposure to fine particulate matter (pm2. 5) from household air pollution. *Environment International*, 120:354–363, 2018.

M. Sievert and J. Steinbuks. Willingness to Pay for Electricity Access in Extreme Poverty: Evidence from Sub-Saharan Africa. *World Development*, 128:104859, 2020.

K.R. Smith, R. Uma, V.V.N. Kishore, K. Lata, V. Joshi, J. Zhang, R.A. Rasmussen, and M.A.K. Khalil. Greenhouse Gases from Small-Scale Combustion Devices in Developing Countries, Phase IIa: Household Stoves in India. Research and Development EPA/600/R-00/052, U.S. Environmental Protection Agency, 2000.

K. Troncoso and A. Soares da Silva. LPG Fuel Subsidies in Latin America and the Use of Solid Fuels to Cook. *Energy Policy*, 107:188 – 196, 2017. ISSN 0301-4215. doi: https:

//doi.org/10.1016/j.enpol.2017.04.046. URL http://www.sciencedirect.com/science/article/pii/S0301421517302719.

UNDP. *World Energy Assessment: Energy and the Challenge of Sustainability*. 2015.

Dominique Van de Walle, Martin Ravallion, Vibhuti Mendiratta, and Gayatri Koolwal. Long-term gains from electrification in rural india. *The World Bank Economic Review*, 31(2): 385–411, 2017.

B. Van der Kroon, R. Brouwer, and P.J.H. van Beukering. The Energy Ladder: Theoretical Myth or Empirical Truth? Results from a Meta-Analysis. *Renewable and Sustainable Energy Reviews*, 20:504–513, 2013.

Chandra Venkataraman, Ambuj D Sagar, Gazala Habib, Nick Lam, and Kirk R Smith. The indian national initiative for advanced biomass cookstoves: the benefits of clean combustion. *Energy for sustainable development*, 14(2):63–72, 2010.

Chandra Venkataraman, Michael Brauer, Kushal Tibrewal, Pankaj Sadavarte, Qiao Ma, Aaron Cohen, Sreelekha Chaliyakunnel, Joseph Frostad, Zbigniew Klimont, Randall V Martin, et al. Source influence on emission pathways and ambient pm 2.5 pollution over india (2015–2050). *Atmospheric Chemistry and Physics*, 18(11):8017–8039, 2018.

L. Wu. Inner Mongolia: One of the Pioneers of Chinese Wind Power Development. In *Proceedings of the Beijing International Conference on Wind Energy*, 1995.

Xiao Yun, Guofeng Shen, Huizhong Shen, Wenjun Meng, Yilin Chen, Haoran Xu, Yuang Ren, Qirui Zhong, Wei Du, Jianmin Ma, et al. Residential solid fuel emissions contribute significantly to air pollution and associated health impacts in china. *Science Advances*, 6 (44):eaba7621, 2020.