Returns to Grid Electricity on Firewood and Kerosene: Mechanism

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Abstract

Household dependence on firewood is ubiquitous in developing countries, undermining the carbon services that forests provide. In addition, kerosene is widely used for lighting that emits black carbon. This study examines the effect of grid electricity on firewood consumption and kerosene by using an instrumental variable (IV) estimation strategy, and it evaluates the underlying mechanisms. I use three waves of large sample household surveys from Bhutan and other administrative data to complement the main results. The results show that grid electricity reduces firewood consumption by approximately 0.83 – 2.09 cubic meters per month and electrified households are approximately 61 – 71% less likely to use kerosene as lighting fuel. Households respond to electricity provision by adopting basic electrical appliances and electricity for lighting. The results also suggest that the effect of electricity on firewood consumption is driven by road accessibility and that the reduction in firewood consumption is larger for richer households. However, I do not find such evidence for kerosene. Furthermore, one electrified household saves emissions of approximately 5.9 tCO2 of carbon dioxide and 5.2 tCO2e of black carbon annually from displaced firewood consumption. Similarly, kerosene displaced due to electricity is associated with approximately 2.45 tCO2e black carbon annually..

Key words: electricity, firewood, household technology, kerosene, electrical appliances

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1 Introduction

Climate discussions are centered on identifying policy measures to reduce the emissions of greenhouse gases (GHGs) and reverse the increase in GHGs, especially carbon dioxide, in the atmosphere. This policy debate is changing the conventional role of the forest, from resources for consumption (e.g., commercial logging, fuel for household energy, and recreational services), into that of a carbon sink. Deforestation has been estimated to contribute approximately 6 to 17% of the total global carbon emissions (Werf et al., 2009). However, developing countries depend on firewood for household energy, undermining the carbon services that forests can provide. For instance, Hosonuma et al. (2012) states that firewood and charcoal production are responsible for approximately 31% of global forest degradation. In addition, kerosene is also a primary lighting fuel in developing countries that emits detrimental climate substances called black carbon.

A number of studies have linked forest degradation to the unsustainable and inefficient harvesting of firewood in developing countries (Baland et al., 2010; Heltberg et al., 2000; Specht et al., 2015), and Baland et al. (2018) report that firewood harvesting is the primary reason for forest degradation in Nepal. Approximately 2.7 billion people, especially in developing countries, depend on solid fuels for cooking and heating (IEA, 2015), and forests are among the primary sources of such fuels. Heltberg et al. (2000) indicates that 59% of households in India report collecting firewood from common forests, suggesting that forests are the major source of firewood. Similarly, Kissinger et al. (2012) states that in Africa, firewood and charcoal production are the primary causes of forest degradation. Furthermore, Chettri et al. (2002) relates that the health of forests near human settlements in Northern India is poor due to firewood and timber extraction. Therefore, firewood extraction is one of the drivers of forest degradation in developing countries. Similarly, in our study area, UNDP (2012) reports that Bhutan has the highest per capita firewood consumption in the region, with 1.3 tons consumed annually.

To benefit from forests in terms of carbon services, households must reduce their dependence on firewood. One option to reduce household dependence on firewood or biomass is to increase accessibility to alternative sources of energy, such as electricity. Studies by Dendup and Arimura (2019) and Dinkelman (2011) report that the use of firewood for cooking is negatively associated with electricity provision. Similarly, Meeks et al. (2019) and Somanathan and Bluffstone (2015) show that biogas users consume less firewood than nonusers, and Brooks et al. (2016) reports a reduction in firewood consumption by adopting clean cookstoves (mostly liquified petroleum gas (LPG) users) in Northern India, suggesting that households respond positively to new forms of cooking fuels. Conversely, electricity has the potential to directly influence household technology by enabling households to use basic electrical appliances for home production, which could reduce dependence on firewood. However, in the economic literature, studies of the benefits of electrification have concentrated on how grid electricity enhances private welfare, whereas the benefits in terms of firewood conservation are largely unclear, with the exception of the study by Litzow et al. (2019). The available studies suggest that access to electricity improves (female) labor outcomes (Dinkelman, 2011; Grogan and Sadanand, 2013; He, 2019), increases household consumption (or expenditure) (Khandker et al., 2013; Van de Walle et al., 2017; Thomas et al., 2020), increases housing prices and human development indices (Lipscomb et al., 2013), decreases indoor air pollution (Barron and Torero, 2017), has positive returns for education (Barron and Torero, 2014; Kumar and Rauniyar, 2018; Lipscomb et al., 2013; Thomas et al., 2020) and increases manufacturing output (Rud, 2012), while electricity shortages reduce firm revenue (Allcott et al., 2016). On the other hand, recent evidence from field experiment in Kenya show little or no impact on the number of household outcomes (Lee et al., 2020).

The primary objective of this study is to examine the effect of household electrification on firewood consumption and kerosene by exploiting the variation in household electrification status. I use three waves of nationally representative household surveys conducted in Bhutan in 2007, 2012 and 2017 and other administrative data. The second objective is to examine the mechanism of the relationship between electricity and firewood consumption. An understanding of the underlying mechanism would allow governments to prescribe meaningful complementary policies. Rural electrification could stimulate economic development and enhance household welfare, whereas complementary policies, such as access to the market, financial services and information, may be necessary for households to take full advantage of the potential of electricity. Evidence from India on the impact of rural electrification also suggests the need for such complementary policies: Burlig and Preonas (2016) reports no significant effect of rural electrification on employment (and number of development indicators), while Fetter and Usmani (2020) finds evidence of a transition from agriculture to nonagriculture employment after electrification but only in areas that experience a boom in agricultural commodities. Furthermore, Aklin et al. (2018) also emphasizes the significance of complementary interventions in household technology adoption in developing countries.

However, examining the effect of grid electricity is challenging because it is confounded by both household and community characteristics. Who receives electricity depends on factors such as the cost of building the (electrification) infrastructure, the political importance of the community, and proximity to power stations. When a community is electrified, whether a household connects to electricity is also an endogenous decision. In this study, to account for the nonrandom assignment of electricity provision, I use an IV strategy, using land gradient and proximity to power plants as instruments. The locations of power plants can also be driven by potentially endogenous individual, household and community characteristics that could affect household outcomes. To address this concern, first, I show that, conditional on controlling for potentially endogenous individual-, household- and community-level characteristics, the location of power plants is driven by factors not correlated with the factors that affect electricity provision. Second, based on anecdotal evidence and conversations with electricity utilities in Bhutan, the location of the power plant is largely affected by exogenous geological and engineering parameters, such as seismic fault lines, river velocity and ground stability. Third, one of the key identification assumptions is not a question of whether households are electrified or not but whether the communities closer to power plants and those in the lower gradient are connected to the grid first. My data show that households in the lower gradient and those closer to power plants obtain connections compared to those in the higher gradient and those located farther away from hydropower plants or mini hydels.

This study contributes to the literature on the effect of grid electricity on firewood conservation and the understanding of the mechanism in poor rural villages of developing country settings. However, this study differs from Litzow et al. (2019) in three ways. First, this study uses recent survey data obtained in 2017, resulting in a larger sample size. Second, this study uses an IV strategy (not propensity score matching as in Litzow et al. (2019)). Third, this study examines the underlying mechanism and provides new evidence of the effect of rural electrification on the adoption of basic electrical appliances by poor rural households. The overall results show that compared to nonelectrified households, electrified households consume less firewood by approximately 0.83 – 2.09 cubic meters per month. Similarly, electrified households are approximately 61 – 71% less likely to use kerosene as lighting fuel and 86 – 90% more likely to use electricity for lighting. I also examine the resilience of IV results under mild deviation from exclusion restriction and exogeneity. Applying Conley et al. (2012) to examine the resilience of IV results under the mild deviation from exclusion restriction, the results show that under reasonable deviation from exclusion restriction, the effect of electricity on firewood and kerosene are negative and comparable with the main results. Next, following Nevo and Rosen (2012), I estimate the bounds for the IV results using a weaker form of instrument exogeneity (i.e., correlation between the error term and IV is of the same direction as the correlation between an endogenous variable and the error term). The results show that under small deviations from exogeneity, point estimates for firewood and kerosene are negative, and bounds include the point estimates of the effect of electricity on firewood and kerosene. Compared to unelectrified households, electrified households are 59 – 67%, 65 – 69 and 54 – 58% more likely to adopt rice cookers, curry cookers and water boilers, respectively, suggesting that the underlying mechanism behind the reduction in firewood consumption is operating through a change in household technology.

This paper is arranged as follows. Section 2 discusses the rural electrification program in Bhutan, and section 3 describes the data and summary statistics. Section 4 discusses the effect of electricity on firewood consumption. Section 5 discusses the impact of rural electrification on climate mainly through displaced firewood and kerosene consumption. Section 6 concludes the study.

2 Background

2.1 Bhutan Context and Hydropower Developments

The Bhutanese people are one of the highest firewood consumers in the region. According to (UNDP, 2012), per capita firewood consumption is 1.3 tons annually. Similarly, a small sample study by Wangchuk et al. (2014) in Bhutan also suggests that the average firewood consumption per household is approximately 54 cubic meters annually, which is much higher than the per capita household consumption of 9 kg per day (or 16 cubic meters annually)[1] reported by Brooks et al. (2016) in Northern India, suggesting that Bhutanese households are among the greatest firewood consumers. Furthermore, problems with using firewood include the emission of black carbon and carbon dioxide (CO2), among others, which contributes to global warming (Kandlikar et al., 2009). The impacts of global warming in Bhutan are felt through changes in precipitation patterns, rises in temperature, glacial lake outburst floods, etc.(Hoy et al., 2016). The combustion of firewood is also a primary cause of indoor air pollution, leading to approximately 4.3 million premature deaths across the globe (WHO, 2015).

In Bhutan, 99% of electricity is generated through hydropower plants. The Ministry of Economic Affairs acts as the primary agency for constructing new power plants and negotiating bilateral or international agreements for financing. The daily operation of

[1] In Brooks et al. (2016), firewood consumption is reported in kilograms. For comparison purposes, I used the official conversion rate of 1 cubic meter of firewood = 200 kg used in Bhutan.

hydropower plants, including the production of electricity, is undertaken by Druk Green Power Corporation Limited (DGPC), and Bhutan Power Corporation Limited (BPC) is responsible for the distribution of electricity within the country and for developing an electricity distribution infrastructure (such as substations and distribution lines). DGPC and BPC are regulated by an autonomous agency called the Bhutan Electricity Authority (BEA)[2].

Bhutan's geography is dominated by deep valleys and tall mountains. The elevation in Bhutan ranges from 200 meters above sea level (asl) in the southern foothills to 7000 meters asl in the north. Therefore, Bhutan has very little or no plains. In other words, Bhutan's landscape is dominated by steep or very steep valleys and mountains. These geographic features, combined with rivers formed by snow felts (from tall mountains), provide opportunities for hydropower plants with sufficient river gradients for producing electricity. However, as pointed out by (Duflo and Pande, 2007) (in the case of agriculture dams in India), there exists a nonmonotonic relationship between the gradient and the hydropower feasibility, suggesting that in areas such as Bhutan (with only steep and very steep areas), steep areas are more likely to receive hydropower plants than very steep areas. (Similarly, plains are also less likely to receive hydropower plants than steep areas because of the lack of a sufficient gradient). There are two important reasons for this, which are relevant for mountainous countries such as Bhutan. First, according to engineering literature, power or electricity generation depends on the mass of water (usually measured as kg per second), acceleration (due to gravity), height and discharge (Zaidi and Khan, 2018), where mass and height depend on the gradient. It was learned from DGPC engineers that mass and discharge decrease with gradient in Bhutan because the volume of rivers is small on the top of mountains and hence less likely to receive hydropower plants. Second, mountainous areas do not have sufficient infrastructure (such as roads) to support hydropower development. Hence, (for places such as Bhutan), as the

[2]The BEA is responsible for the review of electricity tariffs and the approval of electricity tariffs proposed by BPC, and it regulates performance standards and prescribes technical and safety requirements for electricity utility companies in Bhutan.

gradient increases, the feasibility of hydropower plants decreases, and hydropower plants are less likely to receive hydropower plants.

2.2 Bhutan Rural Electrification Program

The rural electrification program in Bhutan started in the 1980s, although households' accessibility to the grid remained as low as 20% (ADB, 2004). The rural electrification program was intensified in the late 1990s and early 2000s (Kumar and Rauniyar, 2018), and less than 1% of households currently do not have access to grid electricity (BPC, 2016). The Asian Development Bank (ADB) was the key agency that financed the rural electrification program in Bhutan before 2005. Since 2005, the Japan International Corporation Agency (JICA) has been one of the key partners in terms of both financing and providing policy guidance on rural electrification. Rural electrification in Bhutan was predominantly targeted at improving living standards, education, and health; enhancing economic productivity; and reducing firewood consumption (ADB, 2003; JICA, 2005).

The rural electrification documents of the ADB do not provide clear information about the criteria used for connecting communities to the grid. However, Litzow et al. (2019) and JICA (2005, chapter 13) suggest that economically more efficient villages and villages closer to roads were prioritized. Notably, the major implementation of this rural electrification plan was undertaken during the 10^{th} Five-Year Plan (2008 – 2013), during which considerable institutional change occurred, and the first democratically elected political party formed the government[3]. In contrast to the previously planned target of achieving 100% electrification by 2020, the target of the newly elected government was to electrify all households by 2013 (GNHC, 2009). In addition, the ambitious plan of the elected government regarding road infrastructure substantially reduced the variation in road accessibility across subdistricts[4].

[3]Druk Phuensum Tshogpa (DPT) was the first democratically elected political party to form a government from 2008 to 2013.

[4]The emphasis on road development is also evident from the total budget overlay from the 10^{th} Five-Year Plan document. The Ministry of Works and Human Settlement, which is responsible for building roads in Bhutan, received approximately 19.23% of the total budget allocation, which was the

BPC suggested that it initially electrified areas that require minimal cost to connect, and cost is largely determined by the gradient, proximity to power plant (and distance from substation[5]). Furthermore, Kumar and Rauniyar (2018) states that before 2008, when the ADB was involved in the rural electrification program in Bhutan, BPC prioritized communities that required less budget. Obviously, the locations of hydropower plants were not randomly assigned. However, it was learned during discussions with the Ministry of Economic Affairs and BPC that engineering parameters such as ground stability, seismic fault lines, river velocity and water discharge play a crucial role in identifying the location of power plant sites. In addition, before the 2005 census, Bhutan did not have reliable household data that could be used for location sorting(Kumar and Rauniyar, 2018). This suggests that the locations of power plants may not be correlated with firewood consumption and other household and community characteristics.

In addition, the rural electrification program in Bhutan was bundled with subsidies of free initial connection. It was learned from BPC that this subsidy program substantially reduced the burden on high initial connection costs, and once electricity arrived in the community, the initial connection cost did not prevent households from connecting to the grid. Therefore, this partially resolves concerns over self-selection at the household level. Furthermore, our data show that approximately 88 percent of households did not have electricity because they did not have the option to connect. However, approximately 1.30 and 2.78 percent of households responded "no need" and "too expensive", respectively, while approximately 8% cited others as reasons for not having electricity[6].

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second highest resource allocation among ministries (see GNHC, 2009, page 66).

[5]In fact, during discussions with BPC, its representatives did not mention the proposed criterion and instead repeatedly indicated that the availability of the budget and cost played crucial roles. Additionally, note that distance from the substation may seem a possible instrument, but substation may also be correlated with factors that affect firewood consumption, e.g., wealth.

[6]Others may include houses under construction or renovation or household electrification in progress, etc.

3 Data

I use three waves of the Bhutan Living Standard Survey (BLSS) conducted in 2007, 2012 and 2017 as pooled data for the main analysis. In this study, I use a subsample of rural households since the use of firewood is associated with rural households. I use administrative data from the DGPC regarding the location of the power plant to construct the IV. I also use census data from the Population and Housing Census of Bhutan 2005 and data on forest coverage in each subdistrict published by the Ministry of Agriculture and Forestry to test the validity of the IV.

After omitting urban households and those that did not respond to the firewood consumption question, the pooled data consist of households from 204 of 205 subdistricts from all twenty districts in Bhutan. The pooled data used for this study have households from 199, 195 and 198 subdistricts in BLSS 2007, 2012 and 2017, respectively. In the BLSS 2007, 2012 and 2017 surveys, 6,856, 4,986 and 6,854 households from rural areas were surveyed, respectively. In contrast, only 3,558 and 5,345 households reported firewood consumption in BLSS 2012 and 2017, respectively. In addition, I omitted the households that reported firewood consumption above the 99^{th} percentile as outliers and 64 households that reported unrealistically high per capita household expenditures. These exclusions resulted in a final sample of 15,502 households. Approximately 4% of the households also reported consuming zero units of firewood.

In the BLSS surveys, the dependent variable was collected via face-to-face interviews by directly asking households, “How many backloads or truckloads of firewood do you consume per month or year?” I used the official conversion factor to convert the firewood consumption reported in backloads and truckloads into cubic meters. The summary statistics and definitions of the other control variables are reported in Table 1A. The simple average of firewood consumption over time shows that firewood consumption decreased from approximately 2 cubic meters per month in 2007 to approximately 1.5 cubic meters in 2017 as the percentage of households connected to grid electricity increased from approximately 56% to 80% and 97% in 2007, 2012 and 2017, respectively. Another main dependent variable is a binary variable indicating whether the lighting fuel is kerosene because information about the quantity of kerosene consumption was not collected. A simple average suggests that approximately 37 percent of households used kerosene as lighting fuel in 2007, while only 1% of households reported using kerosene as lighting fuel in 2017. The monthly per capita household expenditure is deflated to 2017 prices by using the consumer price index of the respective year.

The instrument land gradient was computed from a 90 meter Shuttle Radar Topography Mission (SRTM) global digital elevation model using ArcGIS software. The land gradient in this study is measured in degrees that range from 0 to 90 (i.e., plain to complete steep). The overall average land gradient in Bhutan is 24 degrees, and approximately 88% of the subdistrict lies above the 20 degree land gradient. The gradient in Bhutan ranges from a minimum (average) of 2.01 degrees to a maximum (average) of 72.68 degrees[7]. Another instrument, plant, is a dummy variable that takes the value of 1 if the household belongs to a subdistrict that has a hydropower plant and 0 otherwise. In Figure 1, I report the subdistricts that have power plants (which include both mini hydel and mega hydropower plants) and population density. The summary statistics of power plants included in this study are reported in Appendix Table A1.

Along with the summary statistics in Table 1A, the group mean tests between households with and without electricity are reported. The mean differences from the pooled data between households with and without electricity are highly significant, and households without electricity consume approximately 0.73 cubic meters more firewood than electrified households. Moreover, the mean difference (and proportion of dummy variables) of a significant number of the other household characteristics are significantly different from zero (in Table 1B). A critical examination of these results suggests strong evidence of endogeneity. In the next section, I discuss the estimation strategy.

[7]The maximum average degree is computed as the average of the maximum land gradient of each subdistrict.

4 Effect of Electricity on Firewood and Kerosene

4.1 Estimation Strategy

There are two different levels of the nonrandomness of rural electricity provision: community and household. Which community receives electricity provision depends on the political importance (Dinkelman, 2011) of the community. In addition, in developing countries, mega infrastructure developments (such as hydropower plants) are usually financed through borrowing; hence, government and utility firms might have to consider recovering both capital and operating costs. Therefore, governments and utilities may prioritize electricity provisions to affluent communities for affordability reasons. Once a community is connected to the grid, the second source of nonrandomness is the household decision to obtain a grid connection (Litzow et al., 2019). As discussed in Section 2, rural electrification in Bhutan was bundled with the subsidy of free initial connection, and such schemes did not prevent households from connecting to electricity due to high initial connection cost, once the community has the option to connect. Data also show that the majority (88%) of households did connect to electricity because they did not have the option to connect to the grid, while approximately 8% reported other reasons that may include households under construction or renovation. Therefore, bias due to nonrandomness at household may be minimal or ignorable. To circumvent the nonrandom assignment of electricity provision, I estimate the effect of grid electricity for household h in subdistrict d on outcome variable y_{hd} as follows:

$$\mathrm{y}_{hd} = \beta_0 + \beta_1 \mathrm{electricity}_{hd} + \mathrm{x}_{hd}\theta + u \tag{1A}$$

The household electrification status is instrumented on the land gradient (subdistrict) and availability of power plants in the first stage as follows:

$$\mathrm{electricity}_{hd} = \alpha_0 + \alpha_1 \mathrm{gradient}_d + \alpha_2 \mathrm{plant}_d + \mathrm{x}_{hd}\theta + v \tag{1B}$$

The two main outcome variables are firewood consumption and (binary variable) kerosene as lighting fuel. As described in Section 2, there are two different channels through which the land gradient affects electricity provision. First, for mountainous regions (such as Bhutan with steep and very steep areas), as the land gradient increases, the feasibility of developing hydropower plants decreases. In Table 2, I present major hydropower plants by their location and the gradient of subdistrict in which the plant is located, which would have had a huge impact on rural household accessibility due to high installed capacity. As evident, no subdistricts with gradients above 27 degrees received major hydropower plants[8]. Second, as pointed out by Dinkelman (2011) and learned during the discussion with utility in Bhutan, as the land gradient increases, the cost of constructing (electricity) infrastructure (such as distribution lines and substations) increases; thus, subdistricts with high land gradients are less likely to have the option to connect to the grid, and hence, I expect α_1 to be negative. The binary IV plant takes value 1 if mega hydropower plants or minihydel is located in the subdistrict and zero otherwise.

In this study, I expect the variation in household electricity due to proximity to hydropower plants to be explained by variable plants, and gradient explains the variation in electrification status due to it's effect on the cost of expanding electricity networks. Furthermore, I also estimate a bivariate probit model for kerosene as a lighting fuel using the same IVs, and the same discussion applies. However, the identification strategy relies on the assumption that households living in the steep subdistrict and households living in the subdistrict with power plants are electrified earlier than those living in the very steep subdistrict and subdistricts without plants. As reported in Figure 2, the numbers of households electrified in steep subdistricts are higher than those in very steep subdistricts in both 2007 and 2012. Similarly, the number of households electrified in subdistricts where power plants are located is higher than that in subdistricts that do not have power plants, suggesting that IVs explain the variation in electricity provision. An additional check for the validity of IV is discussed in Section 4.4.

[8] Approximately 25% of subdistricts lie above the gradient of 27 degrees.

The vector of other controls includes whether households have adopted LPG as a cooking fuel since LPG adoption can also affect the amount of firewood consumption. Other control variables include household characteristics, such as whether the head of household can read or write, the age and gender of the head of household, the presence of children younger than six years old, the household size and cattle ownership. The fuel adoption literature has well-documented evidence suggesting that women show greater preferences for clean fuel (Dendup and Arimura, 2019; Rahut et al., 2017). In addition, firewood collection and cooking in developing countries are usually performed by women and children; thus, having children younger than the age of six prevents women from performing this daily household work. Household size measures the availability of a labor force to collect firewood. Additionally, firewood is used for preparing cattle feed in developing countries (Nepal et al., 2011; Heltberg et al., 2000); thus, I also control for cattle ownership. When estimating the kerosene model, variable LPG and cattle are also included to capture the wealth effect.

In addition, to control for the financial constraints that rural households face, I control for access to financing, which is measured in terms of having access to loan services from banks. Household expenditures are also used as a proxy for income. The distance to markets and forests controls for access to alternative fuels. Household density controls for the pressure on the total amount of fuel available in the community. In addition, I control for district and year fixed effects. In the next subsection, I discuss the results of the (electricity) reduced form equation.

4.2 First Stage Results: Effect of IV on Electrification

The results from the reduced-form electricity equation 1B are reported in Table 3 (along with the second stage results). In Panel A, IV results of the firewood are reported and bivariate probit results of kerosene are reported in Panel B. In Panel A, column 2, results results show that with 10 degree increase in gradient, households are approximately 10 – 20 percentage points less likely to connect to electricity. In Panel A, column 4, households in the subdistrict with power plants are likely to be electrified by approximately 9 – 19 percentage points when only plants are used as IVs. Similarly, when both IVs are used (in column 6), the results show that a 10 degree increase in gradients decreases the likelihood of connecting to electricity by approximately 10 – 20 percentage points, while living in a subdistrict with a power plant increases the likelihood of connecting to electricity by 7 – 17 percentage points. In column 8, I used gradient as binary which takes value of 1 if gradient (of a subdistrict) is $\leq$ 25 degree, zero otherwise. Therefore, the control group is households in very steep subdistricts. The results indicate that households in steep areas are approximately 1 – 11 percentage points more likely to be electrified than households in very steep areas. Plant is also significant and shows that households in subdistricts with plants are approximately 8 – 19 percentage points more likely to connect to the grid than those in subdistricts that do not have plants.

In Panel B, the coefficient of gradient is negative in column 2, suggesting a negative relationship between gradient and electricity, while the coefficient of plant is positive in column 4, suggesting a positive relationship between electrification and plants. Similarly, when both IVs are used in column 6 (of Panel B), the coefficient of gradient is negative, while the coefficient of plant is positive, and the results are consistent with the results in Panel A. When the gradient is binary, the coefficient is positive, suggesting a positive correlation between steep area and electricity provision. The coefficient of plant is positive as expected. The coefficients of IVs in panels A and B are significant at the conventional level, indicating that IVs are correlated with household electricity provision.

The variables of read/write, age and female are positive and significant, suggesting that literate household heads and senior citizens are more likely to obtain electricity connections. Variable expenditure is positive and significant, signifying that wealthier households are more likely to connect to electricity. The distance from the market is negative and significant, while the distance from the nearest forest is positive, indicating that households located farther from urban areas are less likely to connect to electricity, while households located closer to urban areas (or farther from forests) are more likely to connect to electricity. The full first-stage results of both the firewood and kerosene equations are reported in appendix Table A2 and Table A3, respectively.

4.3 Second Stage Results

4.3.1 Effect of Electricity on Firewood Consumption

In Table 3, Panel A, I report the result of the effect of electricity on firewood consumption, and full results are reported in appendix Table A2. The OLS results are reported in column 1, and IV results are reported in columns 2 through 9. All results are estimated by controlling for district and year fixed effects, and all the variables are reported in Table 1A. In column 3, only the gradient is used as IV, and in column 5, only the plant is used as IV. In columns 7 and 9, the effect of electricity on firewood consumption is estimated using both IVs. However, in column 7, gradient is used as continuous and in column 9, gradient is used as binary taking value of 1 if gradient (subdistrict) is ≤ 25 degree.

The OLS results in column 1 show that households connected to electricity consume approximately 0.37 – 0.58 cubic meters per month less firewood than households without electricity. In column 3 (of Panel A), when only gradient is used as IV, the results show that electrified households consume less firewood by approximately 0.82 – 2.45, and likewise, in column and 5 (of Panel A), when only plant is used as IV, electrified households consume less firewood by approximately 0.32 – 2.15 cubic meters compared to unelectrified households. The IV results reported in column 7 suggest that firewood consumption decreases by approximately 0.83 – 2.09 cubic meters per month compared to households without electricity. When the gradient is used as binary along with the plant (in column 9), the results show that electrified households consume less firewood, approximately 0.57 – 2.50 cubic meters per month[9]. The effect size and significance level

[9]In column 9, I classified subdistricts with $\leq$25 degrees as steep and $>$ 25 degrees as very steep areas. Based on this classification, approximately 50% of subdistricts are classified as steep and very steep. I also estimated by creating binary gradients at 27, 20 and 15 degrees and estimated the same model as in column 9. The results show that when 27, 20 and 15 degrees are used, the coefficients of electricity

of IV results are comparable across all four specifications, I use results from column 7 in the subsequent analysis later. However, this result does not suggest that electricity completely replaces the use of firewood; instead, the data indicate that households are stacking fuels. For example, approximately 38% of electrified households report firewood as the primary cooking fuel[10]. Figure 3 clearly shows that households consume firewood even when electricity, LPG, and kerosene are reported as the primary cooking fuels. Similarly, as reported in Figure 4, as the proportion of households connected to electricity increases, the average consumption of firewood by electrified households declines at a decreasing rate, although electricity does not completely replace firewood.

The IV result indicates that the OLS results underestimate the effect of electricity on firewood consumption, potentially due to the heterogeneous effect of electricity provision. Similar estimates of downward bias from the OLS estimates are reported by Card (1993) with respect to returns to education[11]. In line with Card (2001), the downward bias in OLS results could be due to the underlying heterogeneity in firewood consumption, and the result of returns to firewood conservation in this study may be capturing the effect of the subset of the population with the highest returns on firewood conservation. Therefore, I interpret the IV results as upper bound estimates[12]. I examine the heterogeneous effect by income and years of electrification in Subsection 4.7.

However, IV results are the local average treatment effect (LATE) for the units whose behaviors can be altered by varying the values of the IV (Angrist and Imbens, 1995; Angrist et al., 1996). That is, the causal effect of grid electricity on firewood consumption based on the IV strategy represents the effect on compliers (i.e., households in lower

are -1.435, -1.400 and -1.176, respectively, and all are significant at the one percent significance level.

[10]When firewood users are redefined as households that have reported positive firewood consumption, our data show that approximately 96% of electrified households still use firewood.

[11]A survey of similar results is reported in Card (2001) along with possible explanations for such downward bias in the OLS results.

[12]Another possible concern is that the development of mega-hydropower power plants can affect the wealth of households within their vicinity and thus might also affect firewood consumption through changes in wealth. However, it does not bias the IV results because I control for household income. Furthermore, I re-estimated the IV results by eliminating households from subdistricts with mega-hydropower plants, and the coefficient of electricity was -1.575, which is significant at 1% and lies within the 95% confidence interval of the results reported in Table 3

gradient and residents of subdistricts with power plants connects to an electricity, while households located in higher gradient and farther away from plant did not obtain an electricity connection). Therefore, following Angrist and Imbens (1995); Angrist et al. (1996), the effect of electricity on firewood consumption does not represent the causal effect of the entire population but only the compliers. However, one important assumption in the LATE is that there are no defiers (i.e., households that refuse to obtain a grid connection when living in a lower gradient and households that obtain a connection when living in subdistricts with a higher gradient). In this study, the assumption of no defiers is reasonable for two reasons. First, for households located farther away or residing in a higher gradient, the provision for connecting to electricity simply did not exist (at this specific time). Second, current universal access to electricity would not have been achieved in the presence of defiers.

The coefficient of the variable LPG is also negative and significant, indicating that LPG is negatively correlated with firewood consumption[13]. Similarly, literate household heads are negatively correlated with firewood. On the other hand, households headed by elderly individuals are positively correlated with firewood, possibly due to more heating requirements and a stronger preference for firewood. Similarly, having a greater number of household members is positively correlated with firewood consumption due to the greater labor supply for firewood collection and the higher energy requirements. In rural areas, firewood is also used to prepare cattle feed, and the results show that cattle ownership is positively correlated with firewood consumption. Additionally, wealthier households are positively correlated with firewood consumption, possibly because the energy requirements for richer households are greater since richer households have different cooking habits and can own larger residences that require more heating. Similar observations are reported by Hanna and Oliva (2015) in India. Furthermore, a higher density of households in a community means greater demand for firewood and more

[13]In this study, LPG is also a potential endogenous variable. However, due to a lack of IV, I estimate the firewood equation without including LPG as a control variable to assess the sensitivity of the coefficient of electricity. The results are reported in appendix Table A4, and the coefficient of electricity is -1.547 and significant at 1%, similar to the IV result reported in Table 3.

pressure on the available firewood stock. The results show that higher household density is negatively correlated with firewood consumption, indicating that firewood scarcity is negatively correlated with firewood consumption[14]. In the next subsection, I discuss the results of the effect of electricity on kerosene lighting.

4.3.2 Effect of Electricity on Kerosene Lighting

The effect of electricity provision on the choice of kerosene as lighting fuel is reported in Table 3, Panel B. In my data set, I do not observe the quantity of kerosene consumption and only information about whether lighting fuel is kerosene or not was collected. Hence, probit and bivarate probit models are estimated for kerosene as a lighting fuel. In column 1, the result of naive porbit is reported, and in columns 2 through 9, the results of bivariate probit are reported. The same set of covariates controlled in Panel A are also controlled in Panel B.

In column 1 (of Panel B), naive probit results indicate that electrified households are 0.47 – 0.53 percentage points less likely to use kerosene as lighting fuel. The bivariate probit results in column 3, when gradient is used as IV, electrified households are approximately 58 – 70 percentage point less likely to use kerosene and similarly, in column 5, when plant is used as IV, the results show that electrified households are approximately 62 – 72 percentage point less likely to use kerosene as lighting fuel. When both IVs are used (in column 7), electrified households are 61 – 71 percentage points less likely to use kerosene. In column 9, when gradient is used as binary (along with plant), the results show that electrified households are approximately 62 – 71 percentage points less likely to use kerosene as lighting fuel. The bivariate probit results are comparable across all specifications. Overall, the results suggest that electricity reduces household reliance on kerosene for lighting[15].

Bensch et al. (2020) show that the impact of electricity is also driven by roads in

[14]The OLS results of the effect of electricity provision on firewood for each separate year are reported in appendix Table A5, and the results are consistent with the results reported in Table 3.

[15]I also estimated both firewood and kerosene models by including outliers, and the results are identical in terms of both effect size and significance.

South Africa, and the authors suggest that roads are post IV variables and should not be controlled for. In this study, roads are not controlled for and hence do not bias the result. However, I control for the distance to the nearest market and forest, which may capture the impact of roads. In the absence of the IV for the distance to market and forest, I dropped the variables market and forest and estimated both firewood and kerosene equations. The results are comparable both in terms of effect size and significance level. When estimating IV regression after dropping distance to road and forest, the firewood consumption reduces by approximately 0.837 – 1.928 cubic meters per month, and similarly the result of bivariate probit suggests that electrified households are approximately 60 – 71 percentage points less likely to use kerosene, which includes all the point estimates reported in Table 3.

External Validity: Following List (2020), I now discuss the external validity of the effect of electricity on firewood consumption and kerosene. BLSS data were collected from all twenty districts in Bhutan and are a representative sample of the population. Therefore, differences in terms of observables between the households that are included and not included in the study may be ignorable. In other words, factors that affect individuals/households preferences and constraints may be similar between households that are included in our study and those not. Therefore, similar results can be obtained using different samples from the same population. One of the important and peculiar aspects of this study may be in terms of the treatment assignment or electricity distribution policy. In Bhutan, households were not charged for the initial connection fee. This free initial connection scheme may have attributed to compliance with treatment (or connecting to electricity once the option is available). This compliance with treatment may have contributed to a reduction in firewood consumption, switching to electricity for lighting and the adoption of basic cooking appliances. In addition, rural households in Bhutan receives free electricity of 100 kWh per month which relaxes the concerns over high electricity bill.

The external validity of the effect of electricity on firewood consumption will also largely depend on dietary habits and whether electrical appliances are available for cooking local foods because rural households cannot afford to purchase expensive electrical ovens. For instance, in Bhutan, the staple food is rice, which households can cook with basic electrical appliances, such as rice cookers. In addition, electrical appliances such as rice cookers are available at rural places at reasonable and affordable prices. Therefore, a similar impact of rural electrification on firewood consumption in developing countries could be observed in areas with similar food cultures. In the next subsection, I examine the validity of the instruments in greater detail.

4.4 Robustness Check for IV

The asymptotic distributions of the IV estimators are different when the correlation between the endogenous variable(s) and instrument(s) is weak, rendering the standard test statistics invalid (Staiger, 1997). Weak IV statistics reported in Panel A (in columns 3, 5, 7 and 9) correspond to t-statistics in columns 3 and 5 and F-statistics for joint significance in columns 7 and 9. The t-statistics reported in columns 3 and 5 are 5.25 and 5.42, respectively, which are slightly above Stock-Yogo's t-critical of 3.20 when number of IV is one. The F test for the joint significance of instruments gradient and plant in columns 7 and 9 are 212.13 and 131.55, respectively, which is way greater than Yogo and Stock's critical value of 10 (when the number of instruments is two), thus rejecting the null hypothesis of no joint significance. Overall, the results suggest that bias due to weak instruments may be minimal or ignorable in this study. In addition, having two instruments in a reduced-form equation results in one overidentifying restriction, which allows for the testing of the exclusion restriction. The Sargan-Hausman test statistic for the overidentification test is χ^2 (1,15,481)=1.134 when gradient is used as continuous (along with plant in column 7) and test statistics is χ^2 (1,15,481)=4.351 (when binary gradient is used along with plant in column 9), which is less than the critical critical value=6.635, thus, I fail to reject the null hypothesis that one of the instruments fails the exclusion restriction. However, the test does not provide evidence for or against the violation of exogeneity of IVs.

Furthermore, in this study, the exclusion restriction could be violated if the locations of power plants were related to factors that also enter the firewood equation. One such variable could be the availability of firewood or the health of the forest in a particular community. Of course, the locations of plants are largely determined by exogenous geological factors, and the possibilities of location sorting are difficult to exclude since Bhutan has a long history of following very strict conservation policies. This possibility is further supported by the objective of rural electrification, which clearly states the reduction of firewood consumption as one of the objectives of the rural electrification program. To assess this possibility, I estimate the following equation:

$$\text{plant}_d = \rho_0 + \rho_1 \text{forest}_d + \delta + \epsilon \tag{2}$$

where $plant_d$ indicates whether a power plant or mini hydel is located in subdistrict d, $forest_d$ is the percentage of forest cover in subdistrict d, and ρ_1 is the coefficient to be estimated. I also include district fixed effects δ to control for the differences in income among districts[16]. Therefore, if ρ_1 is different from zero, the variable substation is not a valid instrument.

Another possible criticism for using plants as instruments is that if the locations of power plants were determined based on the income or wealth of households in particular communities, the exclusion restriction assumption would be violated. Such location sorting could occur if the plants or mini hydels were constructed near affluent households for affordability and cost recovery reasons. To test for this possibility, I constructed a wealth index (w_{ij}) using the PHCB 2005 data set, which was collected before the data that I use for the main analysis, as follows: $w_{ij} = 1/11 \sum_{j=1}^{11} A_{ij}$, where $A_{ij} = 1$ if a household owns assets j and 0 otherwise. The assets included in computing w_{ij} are

[16]A subsequent poverty report published by the National Statistics Bureau of Bhutan suggests that there are differences in income among districts, and district dummies are included to capture such differences.

ownership of radios, phones, land, livestock, houses with metal roofs, concrete walls, and flush toilets, access to piped drinking water, whether the primary income source is the household's own business, household size and number of rooms[17]. Using this wealth index, I categorized subdistricts into poor, middle and wealthy and re-estimated equation 2 by using the wealth index as an explanatory variable. Next, I discuss the results of equation 2.

The results of equation 2 are reported in Table 4. In Panel A, I report the results from equation 2 with forest cover as an explanatory variable, and in Panel B, I report the results from equation 2 with the wealth index (poor, middle and wealthy) as the explanatory variables. In column 2 of panels A and B, the linear probability model is estimated without controlling for district fixed effects, while district fixed effects are controlled for in column 3. The coefficient of forest cover is close to zero and not significantly different from zero, indicating that there is no evidence of location sorting based on forest coverage. In Panel B, the excluded category is poor subdistrict; therefore, ρ_1 is the probability of installing a plant in medium and wealthy subdistricts compared to poor subdistricts. However, the coefficients are not distinguishable from zero. Therefore, based on these results, I do not find evidence of location sorting based on the income of the community[18].

Although the strong correlation between IVs and endogenous variable electricity (and the test that I conducted above) reinforces some confidence in the IVs, yet it is difficult to exclude the possibility of violation of exclusion restriction and exogeneity of IVs. Therefore, I first assess the bounds of IV estimates under mild deviation from the exclusion restriction following Conley et al. (2012). For this sensitivity analysis of IV estimates, consider a regression equation 1A, which allows an instrument to directly

[17]For the number of rooms and household size, I created a binary variable for rooms if a household owns more than one room and a binary variable for household size if the total household members number fewer than five. Note that poor households are associated with larger household sizes in developing countries.

[18]As a robustness check, I also estimated equation 2 for each of the 11 wealth indicators used in computing the wealth index separately, and the results are reported in appendix Table A6, Panel A. Some of the coefficients of wealth indicators are significant; therefore, I use propensity score matching as an alternative identification strategy to account for the nonrandom assignment of electricity. The results are reported in Panel B of Table A6, and both the average treatment effect on treated and average treatment effect are negative and significant.

affect the outcome with coefficient γ. It is equivalent to allowing land gradients and plants to linearly affect firewood consumption or kerosene directly. If γ is known, we can estimate consistent estimates of interest variable (i.e., electricity)[19]. Applying Conley et al. (2012) by specifying support for $\gamma^g \in [-0.03, 0.03]$ and $\gamma^p \in [-0.07, 0.07]$, where γ^g and γ^p are coefficients of gradient and plant, respectively, in the structural equation, the 95% confidence interval of the effect of electricity on firewood consumption is [-0.442 – -2.510] and the effect of electricity on kerosene is [-0.022 – -1.449]. The results show that by allowing a reasonable amount of deviation from perfect exclusion restriction, the effect of electricity on firewood and kerosene is negative. Note that we have the option to specify any values for γ, however this test is designed for the mild deviation from exclusion restriction and choosing larger value of γ will rather invalidate IVs instead of assuming the mild deviation from exclusion restriction[20].

Second, following Nevo and Rosen (2012), I estimate the bounds for IV estimates relying on a weaker form of instrument exogeneity, i.e., correlation between IV and error term is of the same direction as the correlation between an endogenous variable and error term. Another important assumption when applying Nevo and Rosen (2012) is that the correlation between the IV and error terms is smaller than the correlation between the endogenous variable and error term. In this study, as discussed above, one of the unobservables that may be correlated with electricity provision is political importance, which may be positively correlated with electricity. Similarly, error term may be positively correlated with plant because plant location can be sorted based on political importance, suggesting positive correlation between plant and error term[21]. Applying Nevo and Rosen (2012), our results suggest that on mild deviation from exogeneity, the effect of electricity of firewood lies between -0.535 and -2.158, and similarly, the effect of electricity on kerosene lighting lies between -0.674 and -0.794. The result suggests that the effect of

[19]For details, refer Conley et al. (2012).

[20]I also checked the resilience of IV results by varying many values of arbitrarily chosen γ^g and γ^p, and under mild deviation of exclusion restriction, the effect of electricity on firewood and kerosene are negative.

[21]It is difficult to guess the relationship between error term and gradient, therefore, it is likely that gradient is more exogenous than plant in this study.

electricity on firewood consumption and kerosene is negative, as the IV result suggests, and the bounds include all the point estimates reported in Table 3. Having developed some confidence in the IV results, in the next subsection, I examine whether the impact of electricity is also driven by road.

4.5 Is Road Driving the Effect of Electricity?

The distant road data in this study were collected by directly asking households in terms of (walking) distance to the nearest road point. In 2007, the average distance to the nearest road was 113 minutes, and it decreased to mean distances of 39 and 20 minutes in 2012 and 2017, respectively. To examine whether the impact of electricity depends on the road, following Bensch et al. (2020), I first dropped the households within the distance of 15 minutes and estimated the firewood and kerosene models using both IVs and by controlling the same set of covariates controlled in Table 3. Then, I dropped households within 30 minutes and estimated the same models and followed the same by dropping households with an increment of 15-minute intervals up to 90 minutes. The results are reported in Figure 5 and full results are reported in appendix Table A7 and Table A8.

In Figure 5, the coefficient of electricity from the firewood model is reported on the left, and on the right, the average partial effect of electricity on kerosene from the bivariate model is reported. The first result (i.e., All) is the same as the results of the firewood model and bivariate probit model reported in column 7 of Table 3. In the firewood model, the results show that the effect of electricity remains constant until a distance of 45 minutes and gradually increases thereafter. This result may suggest that the effect of electricity on firewood consumption is also driven by road accessibility. One possible explanation is that it may be due to the availability of substitution. In Bhutan, households closer to roads have access to alternative cooking fuels such as LPG and electricity (in addition to firewood), while households distant from roads only have the option to use firewood or electricity (after connecting to grid becomes available). Additionally, in

Bhutan, most households prefer using LPG over electricity because LPG can cook all food, while electrical appliances such as rice or curry cookers can be used for specific purposes only. Therefore, the increase in the impact of electricity with increases as distance from the road may suggest that in the absence of LPG, households rely more on electrical appliances for cooking[22].

On the other hand, the effect of electricity on kerosene does not seem to be driven my road. Based on the partial effect of electricity on kerosene on the right side of Figure 5, we do not see any clear pattern. Why roads drive the effect of firewood consumption and not kerosene is an interesting question to explore in detail. One of the possible explanations is that electricity is very pervasive in terms of replacing lighting fuel but not in terms of replacing firewood as cooking fuel. If alternative fuels such as LPG become available, households may prefer to use LPG rather than electricity as cooking fuel. However, it is beyond the scope of this study to explore this phenomenon in detail. In next subsection I examine the underlying mechanism.

4.6 Mechanism

In this subsection, I examine the underlying mechanism of the reduction in firewood consumption and dependence on kerosene. If the underlying mechanism of the reduction in firewood consumption operates via a change in household technology, households must shift from the use of traditional fuel (firewood) to electricity for household production and adopt basic electrical appliances that enable the household to derive benefits from electricity. To examine this mechanism, I estimate bivariate probit models for the adoption of cooking fuel, lighting fuel and electrical appliances of household h in

[22] My data show a negative relationship between LPG adoption and distance to road. Households within distances of ≤ 15, [15, 30), [30, 45), [45,60), [60,75) and [75,90) minutes, the adoption of LPG is 47, 28, 20, 17, 15, and 15%, respectively. The adoption of rice cooker by distance to road by ≤ 15, [15, 30), [30, 45), [45,60), [60,75) and [75,90) minutes is 77, 71, 51, 52, 48 and 47%, respectively. However, information about the intensity of the use of appliances was not collected.

subdistrict d as follows:

$$\mathrm{y}^*_{hd} = \Phi(\delta \mathrm{electricity}_{hd} + \mathrm{x}_{hd}\gamma + \epsilon) \tag{3A}$$

$$\mathrm{electricity}^*_{hd} = \Phi(\alpha_1 \mathrm{gradient}_d + \alpha_2 \mathrm{plant}_d + \mathrm{x}_{hd}\gamma + \nu) \tag{3B}$$

where $y_{hd} = 1[y^*_{hd} > 0]$, Φ is the standard normal cumulative distribution function and equations 3A and 3B are jointly estimated. The binary outcome variables are adoption of electricity and firewood as cooking fuel, adoption of electricity for lighting and adoption of three different cooking appliances: rice cooker, curry cooker and water boiler. The vector x includes the same set of controls included in Table 3 except that the variables cattle and density are excluded when estimating the bivariate probit model for all three appliances.

In Table 5, Panel A, I report the results of the adoption of cooking fuel and lighting fuel, and in Panel B, I report the results of the adoption of electrical appliances. The bivariate probit results of electricity and firewood reported in Panel A are positive and negative, respectively, suggesting that electrified households are approximately 63% more likely to adopt electricity as a cooking fuel and approximately 35% less likely to adopt firewood. Similarly, electrified households are 87% more likely to use electricity as a lighting fuel. Similar results for the effect of electricity on lighting fuel were reported by Bharadwaj et al. (2021); Lee et al. (2020) and Barron and Torero (2017). The results indicate that the mechanism underlying the reduction in kerosene use is replacement for lighting fuel. The overall results suggest that households shift from using traditional fuels to conventional electricity in response to electricity provision. Full results are reported in appendix Table A9.

All coefficients of bivariate probit models of (electrical) appliances reported in Panel B (of Table 5) are positive and significant, suggesting that electrified households are more likely to adopt rice cookers, curry cookers and water boilers. The results show that households are approximately 63, 67 and 56% more likely to adopt rice cookers, curry cookers and water boilers, respectively[23]. Full results are reported in appendix Table A10. The adoption of these simple electrical appliances in rural settings has direct effects on household production technology. As a result, the energy obtained via firewood (and other traditional fuels) could be reduced in places such as rural Bhutan, where the main ingredient cooked using firewood is rice. Therefore, one of the mechanisms of the reduction in firewood consumption from electricity provision in rural developing countries may operate through changes in household technology.

I also report the results of a bivariate probit model of all three cooking appliances for one to eight years of electrification in Figure 6. The data about the number of years a subdistrict is electrified are collected from the local administrative office of each subdistrict. I use the year in which electricity provision became available in the village where subdistrict headquarters is located, as year in which a subdistrict is electrified[24]. The coefficient of year one (in Figure 6) is estimated by restricting the sample of households living in the subdistrict that had been electrified for one year or less and similarly for the rest of the years. The coefficients of all three appliances are significant from years one through eight. The basic cooking appliances considered in this study are inexpensive and readily available in the rural markets of Bhutan; hence, such market accessibility would have contributed to the adoption of these appliances. Furthermore, the 95% confidence interval of all three appliances overlaps from years 1 through 8, suggesting no variation in the adoption of appliances over the years. This may be an indication that rural households may not adopt expensive electrical ovens that have multiple functions.

[23] I also estimated a bivariate probit model for adoption of refrigerators, and the results show that electrified households are approximately 20% more likely to adopt refrigerators and is significant at the 1% significance level. This result is only reported to show that households adopt appliances after electrification and study does not claim that refrigerators would reduce firewood consumption.

[24] In Bhutan, most of the subdistricts headquarters are located in the center of respective subdistrict boundaries, therefore, numbers of years of a subdistrict is electrified is equivalent to defining the subdistrict as electrified if the electricity provision have become available up to the center of subdistrict.

4.7 Heterogeneity of the Effect of Electricity

In this subsection, I examine the heterogeneous effect of electricity provision by income (proxied by expenditure) quartiles and by the number of years a subdistrict is electrified for two main outcome variables: firewood consumption and kerosene. The mean monthly consumption expenditures of the first, second, third and fourth quartiles are approximately $14, 31, 54 and 133 respectively[25]. The IV regression and multivariate probit models (for firewood and kerosene, respectively) are estimated by including the interaction term of electricity and binary quartile and interaction of electricity and binary years of electrification from year 2 through year 4 and above. Therefore, the excluded categories are interaction of electricity and first quartile in columns 1 and 2 of Table 6. Similarly in columns 3 and 4 (of the Table 6), interaction of electricity and one year of electrification is the excluded category. All the models are estimated by controlling for the same set of controls used in Table 3[26].

In columns 1 and 2 (of Table 6), the coefficients are negative and significant. The results from column 1 show that compared to electrified households in first quartile, electrified households in second, third and fourth quartile reduces more firewood by approximately 0.21, 0.34 and 0.37 cubic meters respectively. The overall effect of electricity increases with the increase in household income because richer households can afford to buy more electrical appliances that would displace firewood consumption. Data also show that only 21% of households in the first quartile own all three appliances, while 28, 45 and 66% of households in the second, third and fourth quartiles, respectively, own all three appliances. On the other hand, average partial effect of electricity on kerosene, reported in column 2 are similar for all three interaction terms, suggesting all three interaction terms are statistically different from the first quartile. For the fourth

[25] Monthly household expenditure was originally in local currency Ngultrum (Nu) and converted to US $ using an exchange rate of US $ 1= Nu 72 following the official exchange rate on September 2, 2021.

[26] The interaction variables are also an endogenous variables. I use interaction of gradient and binary quartile and interaction of plant and binary quartile as IV for the interaction term of electricity and binary quartile. I followed the same strategy for interaction term of electricity and years of electrification. I also estimated linear probability models for kerosene and results are consistent with multivariate probit models.

quartile, the effect of electricity reduces slightly. This may be capturing the fact that high-income households may not depend on kerosene even in the absence of an electricity grid because they can afford solar or generators for lighting, which may attenuate the effect of electricity on kerosene lighting[27].

In columns 3 and 4, I report the heterogeneous effect by years of electrification for both firewood and kerosene. The coefficient of interaction term of electricity and 2 and 3 years of electrification are not significant suggesting that the effect is not statistically different from one year of electrification. This result is consistent with the adoption of appliances reported in Figure 6. However, for four and more years of electrification, the coefficient is significant suggesting that effect is statistically different from one year of electrification. Similarly my data show that in the first, second, third and fourth year of electrification approximately 44, 52, 59 and 80% of households adopt rice cooker respectively. Thus results is suggesting that impact of electricity on firewood may depend number of years a household is electrified. On the other hand, the impact of electricity on lighting is significantly different from one year of electrification. Overall results suggests that the impact of electricity is heterogenous for both firewood and kerosene lighting. In the next section, I examine the climate effect of rural electrification from displaced firewood consumption.

5 Climate Impact of Rural Electrification from Displaced Firewood and Kerosene

The IV results suggest that electricity provision reduces firewood consumption, and similarly, bivariate probit results suggest that electricity also reduces household dependence on kerosene as lighting fuel. In the case of firewood reduction due to electricity, the impact on the climate can be from the reduced emissions from displaced

[27]However, the BLSS dataset did not collect information about lighting fuel before connecting to the electricity grid and hence does not allow us to verify this claim.

firewood consumption and simultaneously from the trees saved/uncut (due to reduced dependence on firewood). To compute the emissions saved per household due to reduced dependency on firewood, I follow Somanathan and Bluffstone (2015) and use the same emission factors, originally collated by Pandey et al. (2014). In this study, I focus on two important pollutants: carbon dioxide and black carbon. Following Somanathan and Bluffstone (2015), I use emission factor of 1358 gram of carbon dioxide per kg of firewood and 0.7 gram of black carbon per kg of firewood and multiplied the emission factor with 100-year global warming potentials (GWP) and computed tons of CO2e saved per kg of firewood [28]. Finally, annual tCO2e saved per household is computed as product of the coefficient of 1.5 cubic meters reported in Table 3 of column 7, assuming one cubic meter of firewood weighs approximately 500 kg[29]. Based on the econometric results and emission factors used, one electrified household saves emission of approximately 5.9 tCO2 and 5.2 tCO2e of CO2 and black carbon per year, respectively.

Another benefit of rural electrification is the replacement of traditional lighting fuel kerosene. The byproduct of incomplete combustion of kerosene is black carbon in addition to the emission of CO2. In my data set, information about the quantity of kerosene consumption was not collected, and I use the annual consumption of kerosene reported by ADB (2010) in Bhutan as 37 liters per year. I use an emission factor of 90 gram of black carbon per kg of kerosene and 2770 gram of CO2 per kg of kerosene following Lam et al. (2012), and I follow the same procedure described above for firewood. The results show that electricity saved emission of approximately 2.45 tCO2e black carbon and approximately 0.084 tCO2 annually per household. Overall, the results show that electricity provision also has climate benefits from displaced emissions.

[28] 100-year GWP of carbon dioxide is 1 and black carbon is 900 following Somanathan and Bluffstone (2015)

[29] According to the discussion with forester in Bhutan, one cubic meter of firewood would range between 350 and 750 kg depending on whether it is hard or soft wood. Such information about firewood in the data set is not available; hence, I choose 500 kg.

6 Conclusions

This study examines the effect of household electrification on firewood consumption and kerosene. I address the issue of endogenous household electricity provision by using the land gradient of the subdistrict and proximity to power plants as instruments in the reduced form equation. The results indicate that electrified households consume approximately 0.83 – 2.09 fewer cubic meters of firewood per month than unelectrified households. I also conduct numerous checks for the validity of the instruments and show that, conditional on controlling for potentially endogenous individual and household characteristics, the locations of power plants are not correlated with the factors that affect firewood use; rather, anecdotal evidence suggests that the locations of power plants are largely driven by exogenous factors, such as seismic fault lines, river velocity and ground stability. Furthermore, IV results reported in Table 3 still hold under mild deviation from exclusion restriction and exogeneity assumptions of IVs used in this study. However, I also find evidence that the effect of electricity on firewood consumption may be driven by the distance to the nearest road, while I do not find such evidence for the adoption of kerosene as lighting fuel. Similarly, I also find that the effect of electricity on firewood may also depend on household income, while I do not find evidence of heterogeneity by the years of electrification for either firewood or kerosene.

Furthermore, the results show that one possible mechanism for the reduction in firewood consumption operates through a change in household technology by adopting electricity for cooking and investing in electrical appliances. Rural households in Bhutan primarily use firewood for cooking (but a heating effect may also exist). However, the BLSS data enable us to examine the mechanism of firewood reduction through the replacement of cooking fuel only; therefore, the reduction mechanism is only through the replacement of firewood with electricity and the adoption of cooking appliances, namely, rice cookers, curry cookers and water boilers. To support this claim, I show that households switch from traditional cooking fuel to conventional electricity for cooking.

Electrified households are approximately 60–67% more likely to use electricity as cooking fuel, while 31–38% less likely to use firewood than unelectrified households. Similarly, electrified households are approximately 59–67%, 65–69% and 54–58% more likely to adopt rice cookers, curry cookers and water boilers, respectively.

Similarly, the results indicate that households shift from traditional lighting fuel (kerosene) to electricity; thus, the mechanism underlying the reduction in the use of kerosene appears to be the replacement of lighting fuel. Electrified households are approximately 85–90% more likely to use electricity for lighting than unelectrified households. The overall results suggest that rural electricity programs help reduce firewood consumption and kerosene for lighting. Thus, based on the IV results of reduction in firewood consumption and the emission factor assumed in this study, electrified households saves approximately 5.9 tCO2 and 5.2 tCO2e of CO2 and black carbon annually, respectively. Similarly, from the displaced kerosene consumption due to electricity, approximately 2.45 tCO2e black carbon and approximately 0.084 tCO2 of CO2 are saved annually per household.

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Table 1A: Summary Statistics and Group Mean Comparison

		Pooled		2007		2012		2017		Group Mean		
Variables	Definition	Mean	SD	Mean	SD	Mean	SD	Mean	SD	No	Yes	(No−Yes)
Firewood	Firewood consumption in cubic meters	1.748	1.544	1.960	1.564	1.686	1.599	1.519	1.441	2.30	1.57	0.731***
Kerosene	1 if lighting fuel is kerosene	0.194	0.396	0.370	0.483	0.133	0.340	0.012	0.107	0.72	0.02	0.700***
Electricity	1 if connected to grid electricity	0.753	0.431	0.559	0.497	0.799	0.400	0.970	0.172			
LPG	1 if LPG is used for cooking	0.328	0.470	0.125	0.330	0.372	0.484	0.558	0.497	0.07	0.41	-0.347***
Read/write	1 if head can read and write	0.300	0.458	0.275	0.446	0.285	0.451	0.342	0.474	0.23	0.32	-0.097***
Age	Age of head of household	49.86	14.53	48.62	14.59	51.05	14.74	50.66	14.19	49.13	50.10	-0.975**
Female	1 if head is female	0.369	0.483	0.345	0.475	0.358	0.480	0.409	0.492	0.29	0.39	-0.102***
Children	1 if child below age 6 is present	0.378	0.485	0.416	0.493	0.372	0.483	0.333	0.471	0.41	0.37	0.040***
Size	Household size	4.943	2.280	5.269	2.400	4.983	2.231	4.501	2.073	5.24	4.85	0.392***
Loan	1 if availed loan from bank	0.227	0.419	0.154	0.361	0.221	0.415	0.325	0.468	0.12	0.26	-0.145***
Cattle	1 if owns cattle	0.738	0.440	0.721	0.449	0.768	0.422	0.739	0.439	0.75	0.73	0.016
Expenditure	Per capita monthly household expenditure	4,170	3,998	3,385	2,947	2,143	3,053	6,532	4,545	2815	4613	-1798***
Market	Distance to market in hours	1.956	5.696	2.883	6.955	1.771	5.862	0.898	2.930	4.88	1.00	3.886***
Forest	Distance to forest in hours	1.245	2.185	1.312	1.887	1.093	2.250	1.261	2.471	1.33	1.22	0.114
Density	Household density	7.170	8.688	7.886	9.735	7.187	8.090	6.245	7.491	5.11	7.84	-2.734***
Gradient	Mean gradient of subdistrict (in degree)	24.23	4.015	24.15	4.132	24.23	4.065	24.32	3.824	25.37	3.258	1.511***
Plant	1 if power plant located in a subdistrict	0.148	0.355	0.138	0.345	0.145	0.352	0.164	0.370	0.08	0.17	-0.093***
N		15,502		6711		3531		5260				

Note: No and Yes refer to households not connected and connected to electricity, respectively. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. Standard errors for the group mean test are clustered at the subdistrict level (but not reported for brevity purposes).

Table 1B: Summary Statistics With and Without Electricity over Year

	2007					2012					2017				
	No Grid (a)		Grid (b)		(a-b)	No Grid (a)		Grid (b)		(a-b)	No Grid (a)		Grid (b)		(a-b)
Variables	Mean	SD	Mean	SD		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Firewood	2.295	1.525	1.696	1.544	0.599***	2.340	1.667	1.522	1.539	0.817***	2.173	1.829	1.498	1.422	0.675***
Kerosene	0.781	0.414	0.047	0.211	0.734***	0.579	0.494	0.021	0.144	0.558***	0.269	0.445	0.004	0.059	0.265***
LPG	0.046	0.209	0.187	0.390	-0.141***	0.0847	0.279	0.445	0.497	-0.360***	0.362	0.482	0.564	0.496	-0.202**
Read/write	0.226	0.418	0.313	0.464	-0.087***	0.220	0.415	0.301	0.459	-0.080***	0.263	0.441	0.344	0.475	-0.082***
Age	48.93	14.39	48.36	14.74	0.570	50.00	14.87	51.31	14.70	-1.306*	48.84	13.52	50.71	14.21	-1.87
Female	0.295	0.456	0.384	0.486	-0.089***	0.275	0.447	0.379	0.485	-0.104***	0.331	0.472	0.411	0.492	-0.080
Children	0.426	0.495	0.408	0.492	0.018	0.357	0.480	0.376	0.484	-0.018	0.294	0.457	0.334	0.472	-0.041
Size	5.328	2.478	5.222	2.335	0.107	5.113	2.452	4.951	2.172	0.162	4.131	2.210	4.512	2.067	-0.381
Loan	0.115	0.319	0.185	0.388	-0.071***	0.126	0.332	0.245	0.430	-0.119***	0.156	0.364	0.330	0.470	-0.174***
Cattle	0.763	0.425	0.687	0.464	0.076***	0.750	0.433	0.773	0.419	-0.023	0.512	0.501	0.746	0.435	-0.234**
Expenditure	2,850	2,531	3,807	3,175	-956.2***	1,712	2,945	2,250	3,071	-538.0**	7,050	5,723	6,516	4,502	533.7
Market	5.092	9.535	1.143	2.826	3.949***	4.460	11.70	1.096	2.535	3.364***	2.894	12.57	0.835	1.950	2.059
Forest	1.266	2.339	1.348	1.433	-0.083	1.220	3.960	1.061	1.548	0.159	3.016	4.942	1.206	2.331	1.809***
Density	5.479	6.006	9.782	11.53	-4.303***	4.018	3.652	7.982	8.681	-3.964***	3.137	5.139	6.343	7.533	-3.206***
Gradient	25.26	3.337	23.28	4.476	1.979***	26.06	2.703	23.77	4.217	2.287***	24.25	3.502	24.32	3.834	-0.074
Plant	0.082	0.274	0.183	0.386	-0.101***	0.058	0.234	0.167	0.373	-0.109***	0.106	0.309	0.165	0.372	-0.059
N	2,958		3,753			708		2,823			160		5,100		

Note: “No Grid” and “Grid” indicate nonelectrified and electrified households, respectively. N is the number of observations, and (a-b) is the mean difference between nonelectrified and electrified households for each year. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. Standard errors for the group mean test are clustered at the subdistrict level (but not reported for brevity purposes).

Table 2: Mega Hydropower Plants by Gradient

Plant	Capacity (MW)	Year	District	Subdistrict	Gradient
Basochu HP I	24	2005	Wangdi	Gatsewom	23
Basochu HP II	40	2005	Wangdi	Dagar	26
Chukha HP	336	1988	Chukha	Darla	26
Kurichu HP	60	2001	Mongar	Mongar	25
Tala HP	1020	2006	Chukha	Bjachog	27
Dagachu HP	126	2015	Dagana	Gozhi	20
Mangdechu HP	720	2019	Trongsa	Drakteng	23
Punatsangchu HP I	1200	Progress	Wangdi	Dagar	26
Punatsangchu HP II	1020	Progress	Wangdi	Dagar	26

Note: HP stands for hydropower plant and capacity is the installed capacity of hydropower plant in megawatt (MW). Year refers to the year of commission of the plant. Gradient (in degree) is the average gradient of subdistrict in which hydropower plant is located. For Punatsangchu HP I and II, 'Progress' indicate work in progress or it is under construction. Note that last three hydropower plants would not have affected in this study but presented as an evidence that gradient affects the sitting of power plant.

Table 3: Effect of Electricity on Firewood and Kerosene

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
		IV							
	OLS	1 Stage	2 Stage	1 Stage	2 Stage	1 Stage	2 Stage	1 Stage	2 Stage
Variables	Firewood	Electricity	Firewood	Electricity	Firewood	Electricity	Firewood	Electricity	Firewood
Panel A									
Electricity	-0.473***		-1.636***		-1.233***		-1.462***		-1.534***
	(0.054)		(0.416)		(0.467)		(0.322)		(0.494)
Gradient		-0.016***				-0.015***			
		(0.003)				(0.003)			
≤ 25 Gradient (0/1)								0.057**	
								(0.027)	
Plant				0.137***		0.123***		0.136***	
				(0.025)		(0.026)		(0.026)	
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weak IV			5.250		5.420		212.130		131.55
Panel B									
	Naive Probit	Bivariate Probit							
	Kerosene	Electricity	Kerosene	Electricity	Kerosene	Electricity	Kerosene	Electricity	Kerosene
Electricity	-2.301***		-2.743***		-2.850***		-2.812***		-2.835***
	(0.072)		(0.117)		(0.104)		(0.103)		(0.105)
Gradient		-0.068***				-0.062***			
		(0.015)				(0.015)			
≤ 25 Gradient (0/1)								0.218*	
								(.125)	
Plant				0.630***		0.569***		0.623***	
				(0.147)		(0.153)		(0.152)	
APE	-0.497***		-0.636***		-0.671***		-0.659***		-0.666***
	(0.014)		(0.031)		(0.025)		(0.025)		(0.024)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ρ			0.294***		0.383***		0.354***		0.371***

Note: ≤ 25 Gradient is a binary variable taking a value of 1 if the gradient is ≤ 25 degrees and 0 otherwise. Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. Full results of both panels A and B are reported in Table A2 and Table A3, respectively. Controls include district and year fixed effects, LPG, read/write, age, female, children, size, loan, cattle, expenditure, market, forest and density. N=15502. APE stands for average partial effect, and standard errors (of APE) are bootstrapped with 500 replications by setting the seed at 123. ρ (in Panel B) is the correlation between the errors of electricity and the kerosene equation.

Table 4: Effect of Forest Cover and Wealth on the Locations of Plants

Variables	(1) Mean (SD)	(2)	(3)
		Dep Var: Plant (0/1)	
Panel A			
Forest	78.177	0.001	0.002
	(18.933)	(0.001)	(0.001)
District FE		No	Yes
Observations		205	205
Panel B			
Middle	0.234	0.029	0.039
	(0.426)	(0.053)	(0.050)
Rich	0.049	0.002	0.083
	(0.216)	(0.109)	(0.121)
District FE		No	Yes
Observations		205	205

Note: Robust standard errors appear in parentheses. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. In Panel B, subdistricts are first categorized as poor, middle and wealthy based on the wealth index, which is first calculated at the household level using eleven different wealth indicators as $1/11 \sum_{j=1}^{11} A_{ij}$ using whether the house has a metal roof, concrete walls, toilet facilities, and a piped water connection, number of rooms, household size, whether it owns a radio, phone, land, and livestock and whether the primary income is from a business or not. The wealth index at the subdistrict level is calculated as the average of the household level wealth index within each subdistrict. The base category is the poor subdistrict. All of the regression coefficients are estimated including intercepts but are not reported for brevity purposes.

Table 5: Effect of Grid Electricity on the Adoption of Cooking Fuel, Lighting Fuel and Appliances

	Cooking Fuel is Electricity	Cooking Fuel is Firewood	Lighting Fuel is Electricity
Panel A			
Electricity	2.671***	-1.868***	3.573***
	(0.183)	(0.164)	(0.078)
APE	0.631***	-0.346***	0.871***
	(0.019)	(0.018)	(0.012)
Controls	Yes	Yes	Yes
Observations	15,502	15,502	15,502
Mean (SD)	0.596(0.491)	0.514(0.500)	0.758 (0.428)
Panel B			
	Rice Cooker	Curry Cooker	Water Boiler
Electricity	2.522***	2.626***	2.389***
	(0.167)	(0.114)	(0.112)
APE	0.632***	0.669***	0.561***
	(0.021)	(0.011)	(0.011)
Controls	Yes	Yes	Yes
Observations	15,502	15,502	15,502
Mean (SD)	0.621(0.485)	0.536(0.499)	0.453(0.453)

Note: Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. The coefficients reported above are from bivariate probit models, and the full results are reported in appendix Table A9 and Table A10 . APE stands for the average partial effect, and standard errors are bootstrapped (by drawing a sample with replacement) with 500 replications by setting the seed at 123. Mean (SD) is the mean and standard deviation of the respective outcome variables. In Panel A, same set of controls as in Table 3 are included while in Panel B, household density and cattle ownership are excluded.

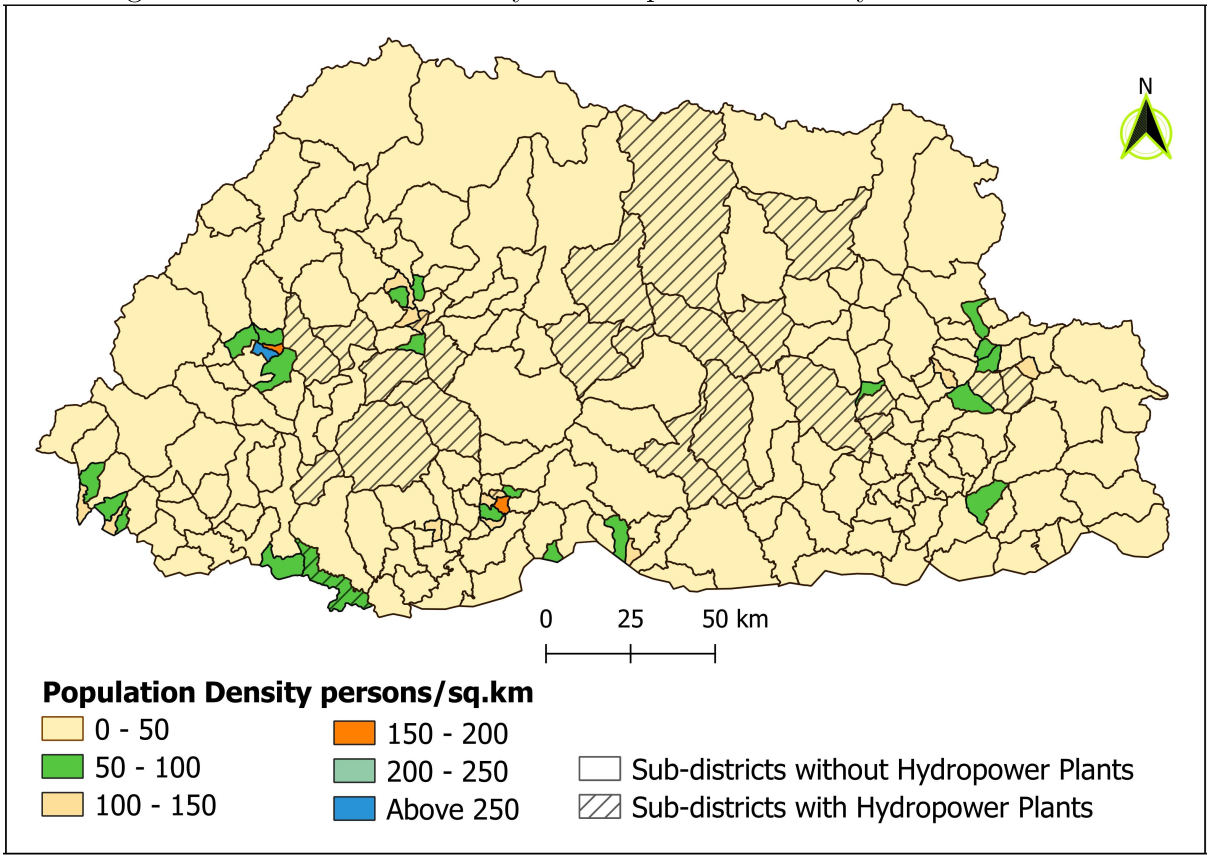
Table 6: Heterogeneity of Effect of Electricity

	(1) Firewood	(2) Kerosene	(3) Firewood	(4) Kerosene
Electricity × Q2	-0.210**	-0.207***		
	(0.091)	(0.0001)		
Electricity × Q3	-0.343***	-0.225***		
	(0.112)	(0.0003)		
Electricity × Q4	-0.376**	-0.221***		
	(0.154)	(0.0001)		
Electricity × Year2			-0.122	-0.150***
			(0.201)	(0.0007)
Electricity × Year3			-0.142	0.133***
			(0.200)	(0.0012)
Electricity × Year4			-0.425***	-0.220***
			(0.109)	(0.0004)
Controls	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
N	15502	15502	15502	15502

Note: Q2, Q3 and Q4 refers to second, third and fourth quartile respectively and year2, year3 and year4 refers to two, three and four and more years of electrification. Quartile 1 is the poorest household, and quartile 4 is the richest household classified based on consumption expenditure. Excluded category for firewood and kerosene models are "electricity × Q1" and "electricity × year1". The coefficients of kerosene models are estimated by multivariate probit model and coefficient reported are average partial effect and standard errors are bootstrapped with 500 replications. Standard errors of firewood equations are clustered at subdistrict.

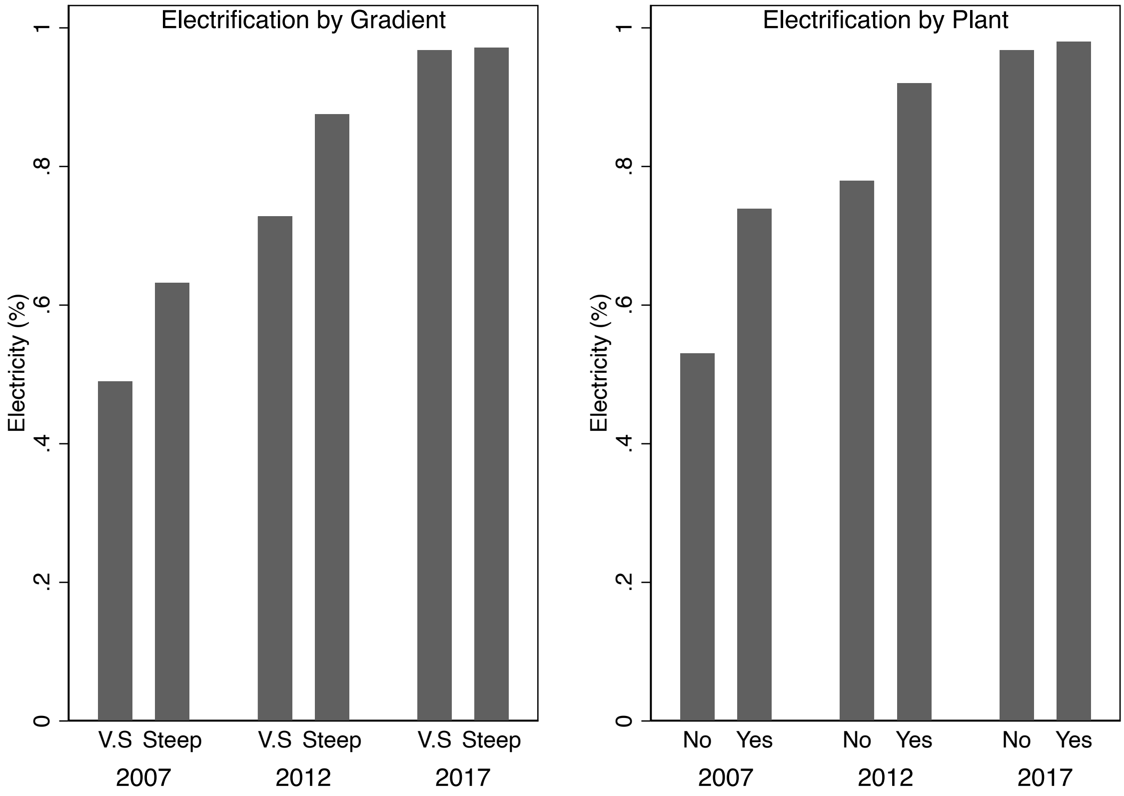
Figure

Figure 1: Subdistrict Boundary with Population Density and Power Plant



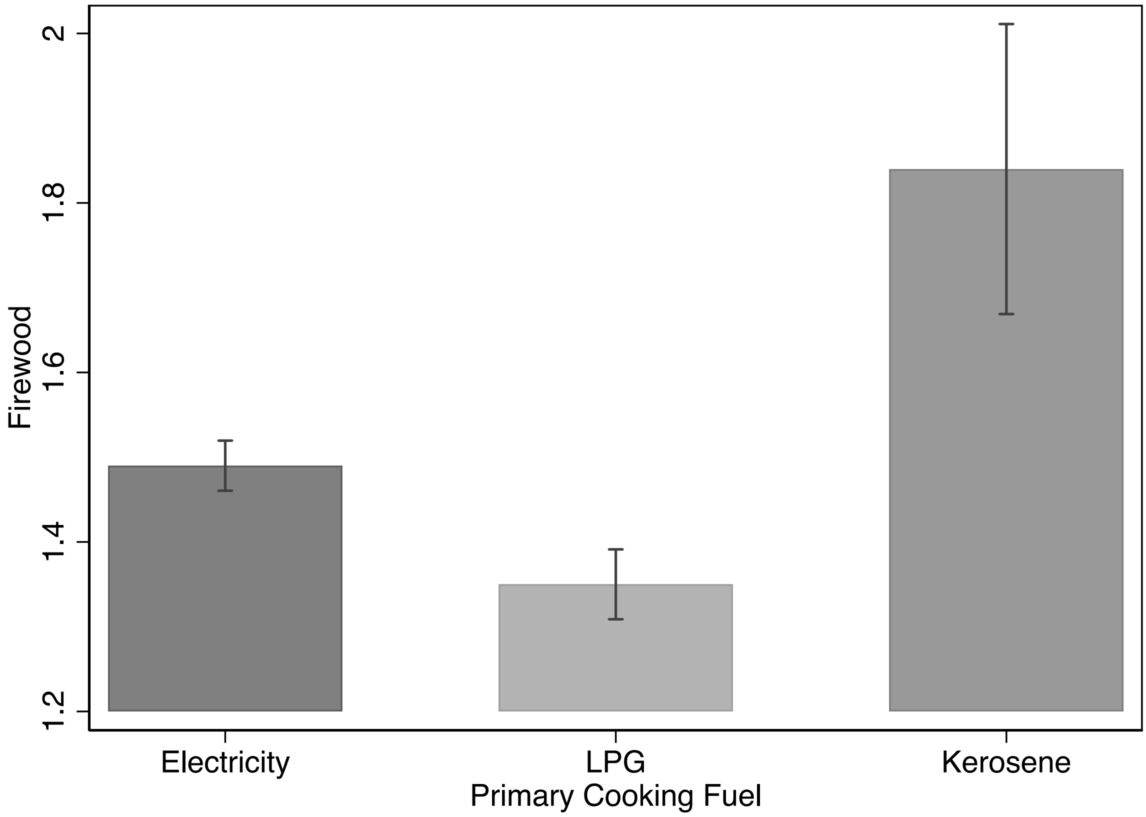
Note: Hydropower plants reported in appendix Table A1 are included in this figure (which includes both mini hydels and mega hydropower plants).

Figure 2: Household Electrification by Gradient and Plant



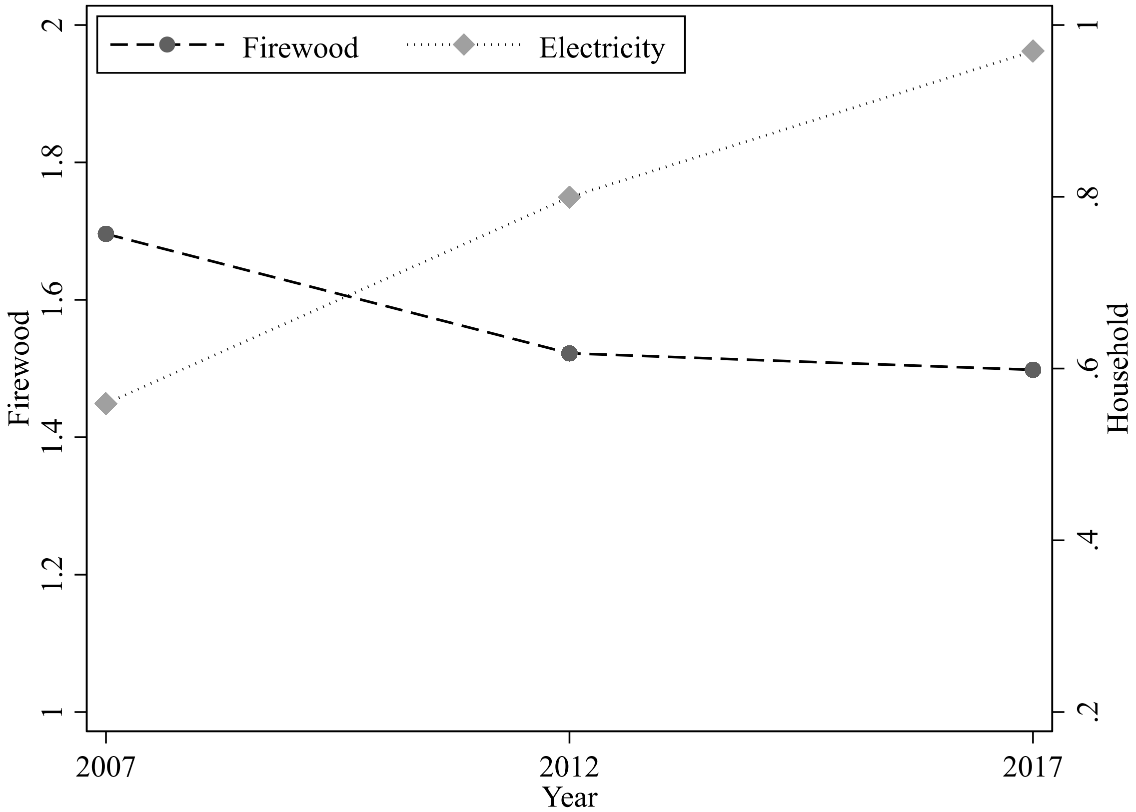
Note: V. S stands for very steep. No refer to households without electricity, and yes indicates households are electrified. The left figures show the percent of households electrified by gradient over years. Households are classified as living in very steep subdistricts if the gradient is above 25 degrees. (I use 25 degrees because this classifies approximately 50% of households into steep and very steep. As robustness check, I also used 15, 20 and 27 as cutoffs, and the results still hold). The right figure shows the percent of households electrified by whether households are living in subdistricts that have hydropower plants or hydels.

Figure 3: Firewood Consumption Compared to Other Cooking Fuels



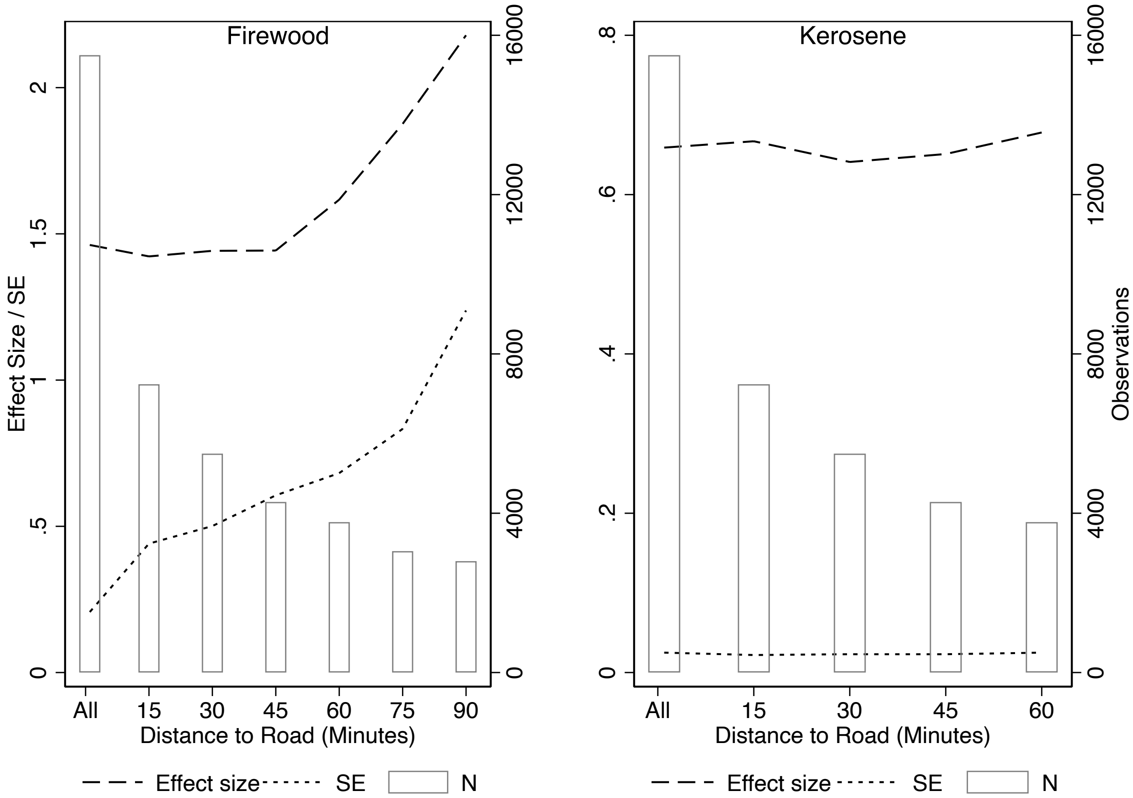
Note: Firewood consumption is the average consumption (in cubic meters) by households that have reported their primary cooking fuel as electricity, LPG and kerosene.

Figure 4: Change over Years in Firewood Consumption by Electrified Households



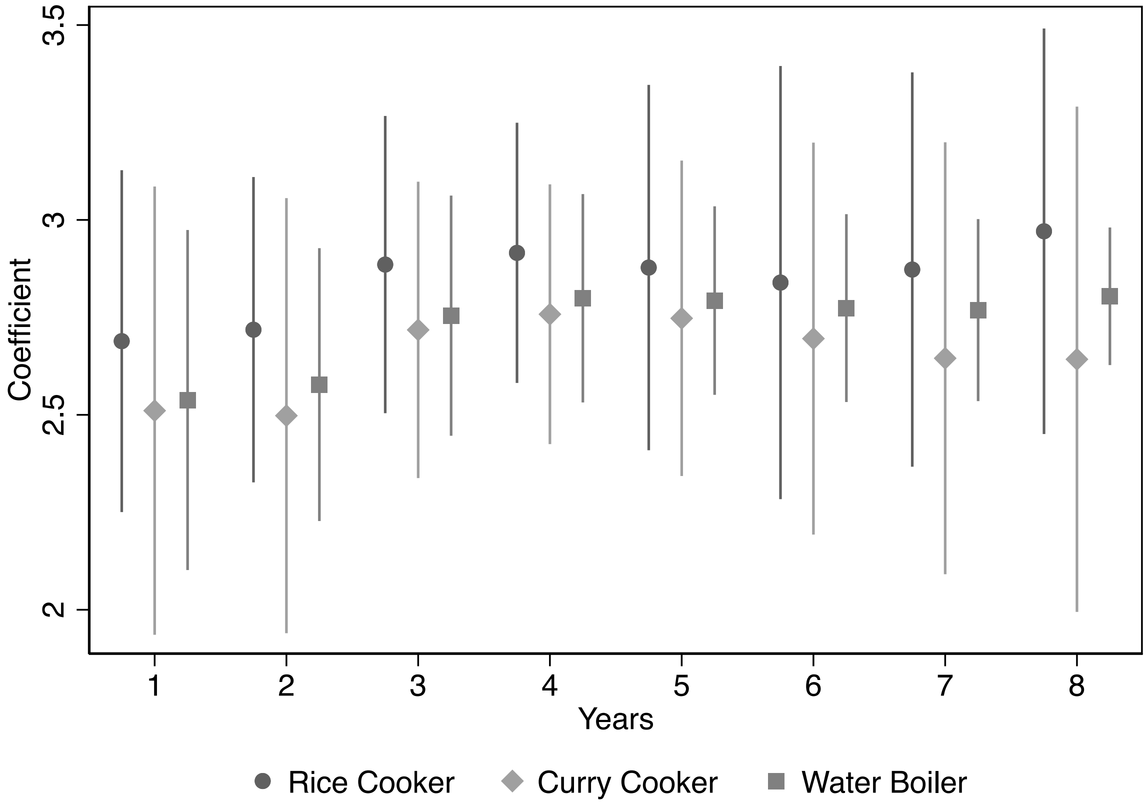
Note: Firewood consumption is the monthly firewood consumption by electrified households only (while the proportion of electrified households includes both electrified and nonelectrified). The primary axis (or left y-axis) is monthly firewood consumption in cubic meters, and the secondary axis (or right y-axis) is the proportion of households connected to grid electricity.

Figure 5: Effect of Electricity on Firewood and Kerosene by Distance to Road



Note: All indicates all the samples are included. Distance to road on the horizontal axis "15" indicates that households whose distance to the nearest road is less than 15 minutes are dropped and similarly for those 30 through 90. At 75 and 90 mins, only plants were used as IVs, as the gradient was not significant. The bivariate model for 75 and 90 did not converge and hence was not reported. In both figures, the primary y-axis presents the coefficient of electricity, and the secondary y-axis represents the sample size. In the figure on the right, the average partial effect and bootstrapped standard error are plotted. The full results are reported in appendix Table A7 and Table A8.

Figure 6: Effect of Electrification on Appliance Adoption by Years of Electrification



Note: The y-axis in the figure is the coefficient of the bivariate probit model. Each coefficient (and 95% CI) is plotted from a separate bivariate probit model for rice cooker, curry cooker and water boiler. In all the models, the same set of covariates as in Table 5 are controlled for except cattle ownership and density. The coefficient of year 1 is estimated by restricting the sample households living in the subdistrict that had been electrified for less than or equal to one year and similarly for the others.

Table A1: Summary Statistics of Hydropower Plants

Sl	Name	Capacity	Built Year	District	Subdistrict
1	Basochu Hydropower Plant	64 MW	2005	Wangdiphodang	Gatetshowom & Daga
2	Chukha Hydropower Plant	336 WM	1988	Chukha	Darla
3	Kurichu Hydropower Plant	60 WM	2001	Mongar	Drepong
4	Tala Hydropower Plant	1020 MW	2006	Chukha	Bjachog
5	Ura Mini Hydel	50 kW	1987	Bumthang	Ura
6	Tamzhing Mini Hydel	30 kW	1987	Bumthang	Chumey
7	Chumey Mini Hydel	150 kW	1989	Bumthang	Chumey
8	Darachu Mini Hydel	200 kW	1992	Dagana	Tseza
9	Gangzur Mini Hydel	120 kW	2000	Lhuntse	Gangzur
10	Khalangzi Mini Hydel	300 kW	1992	Mongar	Mongar
11	Sengor Mini Hydel	100 kW	1992	Mongar	Saling
12	Thimphu Mini Hydel	360 kW	1967	Thimphu	Mewang
13	Thinleygang Mini Hydel	30 kW	1987	Thimphu	Chang
14	Chenangri Mini Hydel	750 kW	1987	Tashigang	Samkhar
15	Rangjung Mini Hydel	2.2 MW	1996	Tashigang	Shongphu
16	Tangsibji Mini Hydel	30 kW	1987	Trongsa	Tangsibji
17	Trongsa Mini Hydel	50 kW	1987	Trongsa	Nubi
18	Bubja Mini Hydel	30 kW	1987	Trongsa	Dragteng
19	Chachey Mini Hydel	200 kW	1991	Tsirang	Gosarling
20	Rukhubji Mini Hydel	40 kW	1987	Wangdiphodang	Sephug
21	Khekhar Mini Hydel	20 kW	1987	Zhemgang	Nangkhor
22	Tintibi Mini Hydel	200 kW	1992	Zhemgang	Trong

Note: The hydropower plants that were completed after 2017 are not included in the above list, and no plants were completed between 2007 and 2017.

Table A2: Effect of Grid Electricity on Firewood Consumption

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	OLS				IV				
Variables	Firewood	Electricity	Firewood	Electricity	Firewood	Electricity	Firewood	Electricity	Firewood
Electricity	-0.473***		-1.636***		-1.233***		-1.462***		-1.535***
	(0.054)		(0.416)		(0.467)		(0.322)		(0.494)
Gradient		-0.016***				-0.015***			
		(0.003)				(0.003)			
$\leq$ 25 Gradient								0.057**	
								(0.027)	
Plant				0.137***		0.123***		0.136***	
				(0.025)		(0.026)		(0.026)	
LPG	-0.398***	0.041***	-0.346***	0.042***	-0.364***	0.039***	-0.353***	0.041***	-0.350***
	(0.046)	(0.012)	(0.053)	(0.011)	(0.053)	(0.011)	(0.051)	(0.011)	(0.057)
Read/write	-0.133***	0.044***	-0.080**	0.046***	-0.098**	0.044***	-0.088**	0.045***	-0.084**
	(0.031)	(0.008)	(0.039)	(0.008)	(0.039)	(0.008)	(0.037)	(0.008)	(0.042)
Age	0.003***	0.001**	0.004***	0.001***	0.003***	0.001**	0.003***	0.001**	0.004***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
Female	0.017	0.026***	0.049	0.026***	0.038	0.025***	0.044	0.027***	0.046
	(0.032)	(0.010)	(0.034)	(0.010)	(0.035)	(0.009)	(0.034)	(0.010)	(0.036)
Children	0.025	0	0.025	-0.001	0.025	-0.001	0.025	-0.002	0.025
	(0.031)	(0.007)	(0.033)	(0.007)	(0.032)	(0.007)	(0.032)	(0.007)	(0.032)
Size	0.064***	0.002	0.066***	0.001	0.065***	0.002	0.066***	0.002	0.066***
	(0.007)	(0.002)	(0.008)	(0.002)	(0.007)	(0.002)	(0.008)	(0.002)	(0.008)
Loan	-0.016	0.007	-0.002	0.012	-0.007	0.008	-0.004	0.01	-0.004
	(0.033)	(0.009)	(0.036)	(0.009)	(0.035)	(0.009)	(0.036)	(0.009)	(0.036)
Cattle	0.329***	0.005	0.337***	0.007	0.334***	0.005	0.336***	0.008	0.337***
	(0.040)	(0.010)	(0.043)	(0.010)	(0.041)	(0.010)	(0.042)	(0.010)	(0.043)
Expenditure (ln)	0.008	0.015*	0.026	0.012	0.02	0.012	0.023	0.012	0.025
	(0.030)	(0.009)	(0.034)	(0.009)	(0.032)	(0.009)	(0.033)	(0.009)	(0.033)
Market (ln)	0.039**	-0.067***	-0.045	-0.069***	-0.016	-0.065***	-0.032	-0.068***	-0.038
	(0.018)	(0.006)	(0.038)	(0.006)	(0.039)	(0.006)	(0.031)	(0.006)	(0.044)
Forest (ln)	-0.219***	0.139***	-0.111	0.081*	-0.148*	0.125***	-0.127	0.082*	-0.12
	(0.072)	(0.043)	(0.092)	(0.048)	(0.089)	(0.043)	(0.086)	(0.047)	(0.102)
Density	-0.015***	0.003*	-0.009**	0.005**	-0.011***	0.003*	-0.010***	0.005**	-0.009**
	(0.003)	(0.002)	(0.004)	(0.002)	(0.004)	(0.002)	(0.003)	(0.002)	(0.004)

Note: Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively. District FE (fixed effect), year FE and constant are included in all models but not reported for brevity purposes. N=15502. $\leq$ 25 Gradient equals 1 if less than or equal to 25 degrees and zero otherwise.

Table A3: Effect of Electricity on Kerosene Lighting

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	OLS				Bivariate Probit				
Variables	Kerosene	Electricity	Kerosene	Electricity	Kerosene	Electricity	Kerosene	Electricity	Kerosene
Electricity	-2.301***		-2.743***		-2.850***		-2.812***		-2.835***
	(0.072)		(0.117)		(0.104)		(0.103)		(0.105)
Gradient		-0.068***				-0.062***			
		(0.015)				(0.015)			
$\leq$ 25 Gradientgrad								0.218*	
								(0.125)	
Plant				0.630***		0.569***		0.623***	
				(0.147)		(0.153)		(0.152)	
LPG	-0.336***	0.480***	-0.287***	0.474***	-0.275***	0.480***	-0.281***	0.481***	-0.277***
	(0.083)	(0.063)	(0.081)	(0.062)	(0.078)	(0.062)	(0.079)	(0.062)	(0.079)
Read/write	-0.174***	0.202***	-0.142***	0.215***	-0.132**	0.205***	-0.136**	0.211***	-0.133**
	(0.055)	(0.040)	(0.054)	(0.040)	(0.054)	(0.040)	(0.054)	(0.040)	(0.053)
Age	0.000	0.003***	0.001	0.004***	0.001	0.003***	0.001	0.004***	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Female	-0.014	0.154***	0.007	0.148***	0.014	0.144***	0.011	0.151***	0.013
	(0.049)	(0.048)	(0.048)	(0.046)	(0.047)	(0.045)	(0.048)	(0.046)	(0.047)
Children	0.036	0.000	0.035	0.001	0.034	-0.002	0.034	0.003	0.034
	(0.044)	(0.035)	(0.044)	(0.036)	(0.044)	(0.035)	(0.044)	(0.035)	(0.044)
Size	-0.039***	0.020**	-0.036***	0.017*	-0.036***	0.017*	-0.036***	0.017*	-0.036***
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)
Loan	-0.096	0.074	-0.082	0.094*	-0.077	0.079	-0.079	0.087	-0.077
	(0.059)	(0.055)	(0.058)	(0.053)	(0.057)	(0.055)	(0.057)	(0.053)	(0.057)
Cattle	0.100*	0.041	0.100*	0.057	0.100**	0.050	0.099**	0.064	0.100**
	(0.053)	(0.047)	(0.051)	(0.048)	(0.050)	(0.048)	(0.051)	(0.048)	(0.050)
Expenditure (ln)	-0.157***	0.112***	-0.141***	0.097**	-0.139***	0.099**	-0.139***	0.097**	-0.139***
	(0.042)	(0.039)	(0.042)	(0.040)	(0.041)	(0.039)	(0.041)	(0.039)	(0.041)
Market (ln)	0.033	-0.280***	-0.011	-0.286***	-0.022	-0.270***	-0.018	-0.279***	-0.021
	(0.020)	(0.025)	(0.021)	(0.026)	(0.021)	(0.026)	(0.020)	(0.025)	(0.021)
Forest (ln)	0.482***	0.834***	0.542***	0.568***	0.549***	0.760***	0.551***	0.576***	0.547***
	(0.132)	(0.201)	(0.143)	(0.202)	(0.144)	(0.203)	(0.144)	(0.203)	(0.143)
Density	0.001	0.043***	0.006	0.055***	0.007*	0.042***	0.007	0.052***	0.007*
	(0.005)	(0.010)	(0.004)	(0.009)	(0.004)	(0.010)	(0.004)	(0.010)	(0.004)
ρ			0.294***		0.383***		0.354***		0.371***

Note: Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at 1%, 5% and 10%, respectively. District FE (fixed effect), year FE and constant are included in all models but not reported for brevity purposes. N=15502. $\leq$ 25 Gradient equals 1 if less than or equal to 25 degrees and zero otherwise.

Table A4: Effect of Electricity on Firewood Consumption without LPG

Variabbles	(1) Electricity	(2) Firewood
Electricity		-1.547***
		(0.322)
Gradient	-0.015***	
	(0.003)	
Plant	0.124***	
	(0.026)	
Read/write	0.048***	-0.115***
	(0.008)	(0.038)
Age	0.001**	0.004***
	(0.000)	(0.001)
Female	0.027***	0.029
	(0.009)	(0.034)
Children	-0.001	0.021
	(0.007)	(0.033)
Size	0.002	0.061***
	(0.002)	(0.008)
Loan	0.011	-0.027
	(0.009)	(0.037)
Cattle	0.004	0.350***
	(0.010)	(0.041)
Expenditure (ln)	0.018**	-0.022
	(0.009)	(0.033)
Market (ln)	-0.066***	-0.029
	(0.006)	(0.032)
Forest (ln)	0.126***	-0.119
	(0.043)	(0.085)
Density	0.003*	-0.011***
	(0.002)	(0.004)
Constant	0.057	2.796***
	(0.181)	(0.382)
Observations	15502	15502
Year FE	Yes	Yes
District FE	Yes	Yes

Note: Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at the 1%, 5% and 10% levels, respectively.

Table A5: OLS Results of the Effect of Grid Electricity on Firewood by Year

Variables	(1) Pooled	(2) 2007	(3) 2012	(4) 2017
Electricity	-0.473***	-0.370***	-0.481***	-0.421**
	(0.054)	(0.070)	(0.100)	(0.181)
LPG	-0.398***	-0.448***	-0.474***	-0.224***
	(0.046)	(0.071)	(0.087)	(0.066)
Read/write	-0.133***	-0.191***	-0.069	-0.089**
	(0.031)	(0.047)	(0.062)	(0.044)
Age	0.003***	0.004***	0.004*	-0.001
	(0.001)	(0.001)	(0.002)	(0.002)
Female	0.017	-0.006	0.049	-0.023
	(0.032)	(0.044)	(0.065)	(0.043)
Children	0.025	0.037	0.001	0.038
	(0.031)	(0.039)	(0.062)	(0.048)
Size	0.064***	0.068***	0.046***	0.040***
	(0.007)	(0.012)	(0.016)	(0.014)
Loan	-0.016	-0.014	-0.065	-0.010
	(0.033)	(0.059)	(0.065)	(0.047)
Cattle	0.329***	0.489***	0.149**	0.182***
	(0.040)	(0.060)	(0.074)	(0.049)
Expenditure (ln)	0.008	-0.086*	0.016	0.021
	(0.030)	(0.045)	(0.037)	(0.057)
Market (ln)	0.039**	0.006	0.073***	0.065***
	(0.018)	(0.024)	(0.027)	(0.024)
Forest (ln)	-0.219***	-0.324***	-0.147	-0.130
	(0.072)	(0.110)	(0.095)	(0.096)
Density	-0.015***	-0.018***	-0.016***	-0.011***
	(0.003)	(0.005)	(0.004)	(0.003)
Constant	2.526***	4.820***	1.271**	2.161***
	(0.359)	(0.601)	(0.512)	(0.579)
Observations	15,502	6,711	3,531	5,260
R-squared	0.140	0.207	0.161	0.151
Year FE	Yes			
District FE	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at the 1%, 5% and 10% respectively.

Table A6: Effect of Wealth Indicators on the Locations of Plants

Variables	Mean (SD)	Dep Var: Plant (0/1) No District	Dep Var: Plant (0/1) District	
PanelA: Wealth Indicators				
Roof	0.529	0.173**	0.339***	
	(0.212)	(0.076)	(0.095)	
Wall	0.381	0.007	-0.041	
	(0.251)	(0.080)	(0.119)	
Room	2.524	0.068***	0.062*	
	(0.696)	(0.025)	(0.033)	
Toilet	0.838	0.089	0.066	
	(0.136)	(0.090)	(0.118)	
Water	0.741	0.284***	0.271***	
	(0.190)	(0.074)	(0.090)	
Size	4.682	-0.009	-0.027	
	(0.573)	(0.032)	(0.043)	
Radio	0.649	0.260**	0.172	
	(0.121)	(0.130)	(0.184)	
Business	0.030	0.654	0.563	
	(0.036)	(0.677)	(0.917)	
Phone	0.063	0.579**	1.209***	
	(0.100)	(0.267)	(0.332)	
Land	0.742	-0.178	-0.158	
	(0.181)	(0.110)	(0.118)	
Livestock	0.562	-0.158	-0.220*	
	(0.179)	(0.117)	(0.113)	
Observations		205	205	
	NNM w/ ematch	NNM w/o ematch	OTO	OLS
PanelB: Propensity Score Matching				
ATE	-0.536***	-0.551***	-0.545***	-0.602***
	(0.060)	(0.062)	(0.104)	(0.104)
ATT	-0.640***	-0.646***	-0.621***	
	(0.062)	(0.075)	(0.134)	
Controls				Yes

Note: In PanelA, the coefficients of all of the wealth indicators are estimated from each separate regression with the intercept but are not reported for brevity purposes. In PanelB, the first three columns are estimated using treatment effect syntax "teffects" implemented in Stata. NNM stands for nearest neighbor matching, and OTO stands for one to one matching. NNM w/ is estimated using the nearest neighbor matching estimator by comparing households from the same district, while NNM w/o does not impose this restriction. ATE and ATT stand for average treatment effect and average treatment effect on treated of electricity on firewood consumption, respectively. The propensity score is estimated using the logit model by conditioning on the following covariates: gradient, plant, read/write, age, female, children, size, cattle, expenditure, market, forest, district dummy and year dummy. For the last column, I first matched each connected household with one unconnected households using the propensity score. Then, using only matched samples, the effect of electricity on firewood consumption is estimated by controlling for the same set of covariates included in Table 2 by linear regression. The standard errors of first three columns are default robust Abadie-Imbens standard errors, and standard errors of the last column are clustered at the subdistrict level. For all of the coefficients, ***, ** and * indicate significance at 1%, 5% and 10%, respectively.

Table A7: Effect of Electricity on Firewood Consumption by Road

Variables	15 Mins	30 Mins	45 Mins		60 Mins		75 Mins		90 Mins	
	Firewood	Firewood	Electricity	Firewood	Electricity	Firewood	Electricity	Firewood	Electricity	Firewood
Electricity	-1.423***	-1.442***		-1.443**		-1.617**		-1.876*		-2.179*
	(0.440)	(0.500)		(0.607)		(0.682)		(0.965)		(1.235)
Gradient			-0.013**		-0.012*					
			(0.006)		(0.007)					
Plant			0.163**		0.175**		0.185**		0.156*	
			(0.075)		(0.080)		(0.089)		(0.089)	
LPG	-0.426***	-0.368***	0.074***	-0.474***	0.079**	-0.497***	0.098***	-0.392**	0.112***	-0.349
	(0.069)	(0.095)	(0.028)	(0.115)	(0.033)	(0.127)	(0.037)	(0.167)	(0.039)	(0.212)
Read/write	-0.042	-0.043	0.062***	-0.080	0.065***	-0.056	0.071***	-0.034	0.069***	-0.010
	(0.059)	(0.070)	(0.017)	(0.085)	(0.018)	(0.090)	(0.019)	(0.115)	(0.021)	(0.126)
Age	0.004***	0.004***	0.001**	0.003	0.001**	0.004*	0.002***	0.004	0.002***	0.006**
	(0.001)	(0.002)	(0.000)	(0.002)	(0.001)	(0.002)	(0.001)	(0.003)	(0.001)	(0.003)
Female	0.027	0.046	0.068***	0.055	0.068***	0.103	0.059***	0.140	0.058***	0.144
	(0.049)	(0.064)	(0.018)	(0.076)	(0.020)	(0.081)	(0.019)	(0.097)	(0.020)	(0.110)
Children	0.000	-0.005	0.002	-0.038	0.004	-0.034	0.014	-0.042	0.013	-0.034
	(0.045)	(0.053)	(0.014)	(0.058)	(0.015)	(0.061)	(0.014)	(0.065)	(0.016)	(0.069)
Size	0.099***	0.094***	0.004	0.101***	0.004	0.100***	0.003	0.097***	0.001	0.090***
	(0.011)	(0.012)	(0.004)	(0.014)	(0.004)	(0.015)	(0.004)	(0.017)	(0.004)	(0.018)
Loan	0.010	0.036	0.025	0.069	0.032	0.078	0.043	0.167	0.041	0.161
	(0.065)	(0.077)	(0.025)	(0.090)	(0.026)	(0.098)	(0.032)	(0.123)	(0.032)	(0.138)
Cattle	0.270***	0.279***	0.010	0.212***	-0.005	0.193**	-0.013	0.206**	-0.001	0.206**
	(0.057)	(0.071)	(0.023)	(0.080)	(0.025)	(0.081)	(0.027)	(0.091)	(0.028)	(0.102)
Expenditure (ln)	0.120***	0.084*	0.030*	0.075	0.022	0.078	0.011	0.015	0.009	0.004
	(0.044)	(0.051)	(0.016)	(0.059)	(0.017)	(0.064)	(0.019)	(0.072)	(0.019)	(0.075)
Market (ln)	-0.077*	-0.087*	-0.058***	-0.085	-0.051***	-0.100*	-0.043***	-0.105	-0.042***	-0.120*
	(0.046)	(0.052)	(0.010)	(0.057)	(0.011)	(0.058)	(0.010)	(0.065)	(0.010)	(0.072)
Forest (ln)	0.014	0.012	0.252***	0.027	0.286***	0.067	0.369***	0.204	0.369***	0.283
	(0.128)	(0.151)	(0.083)	(0.206)	(0.097)	(0.260)	(0.080)	(0.443)	(0.082)	(0.540)
Density	-0.006	-0.005	0.006*	-0.008	0.006**	-0.007	0.006**	-0.006	0.012***	-0.000
	(0.006)	(0.006)	(0.003)	(0.006)	(0.003)	(0.007)	(0.003)	(0.008)	(0.005)	(0.020)
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	7,239	5,497		4,283		3,777		3,049		2,798

Note: First-stage results for 15 and 30 mins are not reported for brevity purposes. At 75 and 90 mins, only plants were used as IVs because the gradient was not significant. ***, ** and * indicate significance at 1%, 5% and 10%, respectively, and standard errors in parentheses are clustered at the subdistrict level.

Table A8: Bivariate Probit on Adoption of Kerosene as Lighting Fuel by Road

Variables	15 Mins		30 Mins		45 Mins		60 Mins	
	Electricity	Kerosene	Electricity	Kerosene	Electricity	Kerosene	Electricity	Kerosene
Electricity		-0.649***		-0.763***		-0.901***		-0.806***
		(0.225)		(0.267)		(0.274)		(0.276)
Gradient	-0.055***		-0.054***		-0.052**		-0.043*	
	(0.019)		(0.020)		(0.024)		(0.026)	
Plant	0.556**		0.540**		0.526*		0.552*	
	(0.217)		(0.244)		(0.276)		(0.288)	
LPG	0.471***	-1.610***	0.483***	-1.573**	0.396***	-2.233***	0.383***	-2.035***
	(0.104)	(0.505)	(0.128)	(0.615)	(0.137)	(0.547)	(0.146)	(0.540)
Read/write	0.145***	0.111	0.170***	0.113	0.230***	0.072	0.241***	0.093
	(0.053)	(0.095)	(0.059)	(0.108)	(0.068)	(0.128)	(0.070)	(0.133)
Age	0.004**	0.004	0.005***	0.003	0.005***	0.003	0.006***	0.004
	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)	(0.004)	(0.002)	(0.004)
Female	0.198***	-0.054	0.219***	-0.026	0.278***	-0.049	0.280***	-0.049
	(0.058)	(0.092)	(0.063)	(0.101)	(0.069)	(0.112)	(0.075)	(0.114)
Children	-0.038	-0.191*	-0.019	-0.220*	0.007	-0.268**	0.013	-0.241*
	(0.048)	(0.107)	(0.053)	(0.118)	(0.057)	(0.134)	(0.060)	(0.143)
Size	0.023*	0.019	0.011	0.022	0.018	0.036	0.018	0.044
	(0.012)	(0.024)	(0.013)	(0.024)	(0.013)	(0.028)	(0.014)	(0.028)
Loan	0.040	0.051	0.086	0.064	0.086	0.140	0.111	0.150
	(0.081)	(0.111)	(0.090)	(0.130)	(0.097)	(0.137)	(0.098)	(0.142)
Cattle	0.062	-0.029	0.067	-0.120	0.032	-0.169	-0.023	-0.162
	(0.065)	(0.106)	(0.073)	(0.116)	(0.088)	(0.121)	(0.093)	(0.122)
Expenditure (ln)	0.154***	0.102	0.109**	0.039	0.119**	0.104	0.088	0.189
	(0.051)	(0.102)	(0.053)	(0.115)	(0.056)	(0.124)	(0.060)	(0.126)
Market (ln)	-0.254***	-0.021	-0.236***	-0.035	-0.220***	-0.034	-0.199***	-0.046
	(0.030)	(0.034)	(0.033)	(0.037)	(0.035)	(0.038)	(0.036)	(0.040)
Forest (ln)	1.049***	-0.198	1.065***	-0.161	1.106***	-0.164	1.131***	-0.125
	(0.298)	(0.183)	(0.330)	(0.196)	(0.384)	(0.206)	(0.411)	(0.224)
Density	0.052***	-0.003	0.058***	-0.006	0.058***	-0.020	0.057***	-0.013
	(0.012)	(0.008)	(0.013)	(0.011)	(0.017)	(0.016)	(0.018)	(0.018)
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N		7,239		5,497		4,283		3,777

Note: Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at 1%, 5% and 10%, respectively. The bivariate probit results for 75 and 90 minutes did not converge and were not reported.

Table A9: Bivariate Probit on the Adoption of Cooking & Lighting Fuel

Variables	(1) Electricity	(2) Cooking Fuel is Electricity	(3) Electricity	(4) Cooking Fuel is Firewood	(5) Electricity	(6) Lighting Fuel is Electricity
Electricity		2.671***		-1.868***		3.573***
		(0.183)		(0.164)		(0.078)
Gradient	-0.064***		-0.065***		-0.064***	
	(0.016)		(0.016)		(0.015)	
Plant	0.549***		0.541***		0.582***	
	(0.158)		(0.155)		(0.153)	
LPG	0.469***	-0.673***	0.461***	-2.689***	0.482***	0.165**
	(0.063)	(0.098)	(0.063)	(0.079)	(0.062)	(0.078)
Read/write	0.204***	0.144***	0.206***	-0.139***	0.203***	0.083
	(0.039)	(0.041)	(0.039)	(0.037)	(0.039)	(0.052)
Age	0.003***	-0.006***	0.003***	0.006***	0.004***	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
Female	0.146***	0.107***	0.146***	-0.090**	0.147***	0.058
	(0.046)	(0.037)	(0.045)	(0.037)	(0.045)	(0.048)
Children	-0.001	0.016	-0.002	-0.013	0.000	-0.010
	(0.036)	(0.034)	(0.036)	(0.034)	(0.035)	(0.047)
Size	0.016	0.051***	0.017*	-0.023**	0.018*	0.018
	(0.010)	(0.009)	(0.010)	(0.009)	(0.010)	(0.011)
Loan	0.081	0.104***	0.084	-0.106**	0.077	0.008
	(0.055)	(0.038)	(0.055)	(0.042)	(0.055)	(0.051)
Cattle	0.045	0.040	0.049	0.255***	0.045	-0.071
	(0.048)	(0.047)	(0.048)	(0.046)	(0.048)	(0.053)
Expenditure (ln)	0.095**	0.326***	0.096**	-0.208***	0.100**	0.090**
	(0.039)	(0.030)	(0.040)	(0.035)	(0.040)	(0.041)
Market (ln)	-0.267***	-0.112***	-0.267***	0.062***	-0.267***	-0.014
	(0.025)	(0.018)	(0.025)	(0.020)	(0.026)	(0.020)
Forest (ln)	0.758***	0.014	0.758***	-0.127	0.770***	-0.451***
	(0.204)	(0.094)	(0.204)	(0.090)	(0.200)	(0.147)
	(0.124)	(0.092)	(0.125)	(0.097)	(0.123)	(0.107)
ρ		-0.123		0.163*		-0.607***
		(0.093)		(0.092)		(0.068)
Observations	15,502	15,502	15,502	15,502	15,502	15,502
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at 1%, 5% and 10%, respectively.

Table A10: Bivariate Probit Results of the Adoption of Appliances

Variables	(1) Electricity	(2) RC	(3) Electricity	(4) CC	(5) Electricity	(6) WB
Electricity		2.522***		2.626***		2.389***
		(0.167)		(0.114)		(0.112)
Gradient	-0.090***		-0.091***		-0.090***	
	(0.015)		(0.015)		(0.015)	
Plant	0.570***		0.551***		0.589***	
	(0.158)		(0.154)		(0.154)	
LPG	0.486***	0.387***	0.485***	0.331***	0.479***	0.557***
	(0.062)	(0.047)	(0.059)	(0.039)	(0.061)	(0.035)
Read/write	0.200***	0.203***	0.203***	0.168***	0.204***	0.291***
	(0.039)	(0.038)	(0.039)	(0.032)	(0.039)	(0.030)
Age	0.004***	-0.004***	0.004***	-0.005***	0.004***	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Female	0.155***	0.085**	0.162***	0.062*	0.159***	0.077***
	(0.046)	(0.038)	(0.046)	(0.033)	(0.046)	(0.027)
Children	-0.009	0.043	-0.003	0.036	-0.011	0.038
	(0.035)	(0.035)	(0.035)	(0.033)	(0.035)	(0.030)
Size	0.017*	0.070***	0.016	0.050***	0.016	0.069***
	(0.010)	(0.009)	(0.010)	(0.007)	(0.010)	(0.007)
Loan	0.084	0.057	0.087	0.084**	0.090	0.000
	(0.057)	(0.046)	(0.057)	(0.036)	(0.057)	(0.033)
Expenditure (ln)	0.083**	0.395***	0.088**	0.297***	0.077**	0.432***
	(0.039)	(0.032)	(0.039)	(0.025)	(0.039)	(0.028)
Market (ln)	-0.281***	-0.092***	-0.283***	-0.033**	-0.280***	-0.031**
	(0.026)	(0.018)	(0.025)	(0.014)	(0.025)	(0.015)
Forest (ln)	0.618***	0.097	0.641***	0.006	0.630***	-0.034
	(0.193)	(0.079)	(0.188)	(0.081)	(0.189)	(0.063)
ρ		-0.233**		-0.569***		-0.507***
		(0.099)		(0.084)		(0.078)
Constant	-1.999***	-6.334***	-2.089***	-4.963***	-2.009***	-6.199***
	(0.752)	(0.419)	(0.734)	(0.413)	(0.738)	(0.395)
Observations	15,502	15,502	15,502	15,502	15,502	15,502
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes

Note: Standard errors in parentheses are clustered at the subdistrict level. ***, ** and * indicate significance at the 1%, 5% and 10% respectively. Column heading RC, CC and WB stands for rice cooker, curry cooker and water boiler respectively.