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# Evaluating Rural Electrification

## *Illustrating Research Gaps with the Case of Bhutan*

**Erin Litzow, Subhrendu K. Pattanayak, and Tshering Thinley**

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# Evaluating Rural Electrification: Illustrating Research Gaps with the Case of Bhutan

Erin Litzow, Subhrendu K. Pattanayak, and Tshering Thinley

## Abstract

Electrification, especially rural electrification (RE), is a core component of the Sustainable Development Goals and a major focal point of the global development community. Despite this focus, more than one billion people worldwide do not have access to electricity, and electrification growth rates are not keeping pace with population growth. In this paper, we posit that lack of progress is partly driven by a misalignment between academic research and energy planners' and policy makers' needs. A majority of the studies measuring the impacts of electrification focus on precise estimation of a few outcomes, specifically health, education and productivity impacts. Other important impacts, e.g. environmental, have remained largely unstudied. As a consequence, quantifying the full set of costs and benefits of expanding electricity access is difficult and rarely done. When cost benefit analyses are done, they are often incomplete, and conclusions are highly susceptible to unavailable or uncertain parameter estimates. We illustrate these arguments in the case of Bhutan, where RE rates have expanded rapidly in the past few decades. We show that RE had positive impacts related to fuelwood consumption, education, and employment, but we do not find an effect on health. We then use these impact estimates to conduct cost-benefit analyses. Because there are more parameters in these calculations than we have data for from Bhutan, we transfer reasonable estimates from related contexts. However, to acknowledge the uncertainty induced by this process, we conduct Monte Carlo analyses to see if the NPV calculations are robust to alternative parameter values. Based on this exercise, we highlight research gaps that are preventing 1) thorough accounting of the net present value of RE in diverse settings and 2) financial investment in the sector.

**Key Words:** rural electrification, cost benefit analysis, Bhutan

**JEL Codes:** O13, O22

## Contents

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## 1. Why Another Study on Rural Electrification?

By recent estimates, more than 1 billion people globally live without electricity access, and more than 3 billion are reliant on biomass to meet their household cooking needs (IEA and WB 2017). The problem is heavily concentrated in rural areas, where only 73 percent of people globally have access to electricity, compared to 96 percent in urban areas (IEA and WB 2017). Lack of electricity access is one component of energy poverty; the other is reliance on polluting fuels, such as firewood, dung, agricultural waste, or kerosene, to meet household energy needs (IEA 2011). The consequences of energy poverty are wide-ranging and multi-scalar (Jeuland and Pattanayak 2012) and include air quality and climate (Jetter et al. 2012), human health (Rückerl et al. 2011; Anderson et al. 2012; Adair-Rohani et al. 2016), productivity (Kammila et al. 2014), forest degradation (Hofstad et al. 2009; Köhlin et al. 2011; Pattanayak et al. 2004), and education (Khandker et al. 2012). Many of these burdens disproportionately fall on women and children, primarily girls (Adair-Rohani et al. 2016; Köhlin et al. 2011).

Extending electricity access to rural areas is an important part of ending energy poverty, and there is an increasingly diverse set of technologies available for rural electrification (RE). These include extension of the national grid as well as mini-grids and stand-alone systems (World Bank and KTH Royal and Institute of Technology 2017). But simply extending electricity access does not guarantee that the negative consequences of energy poverty will be mitigated. In recent years, there have been

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multiple efforts to compile and review electrification impact evaluations (Köhlin et al. 2015; Bonan et al. 2017; Peters and Sievert 2016). The 39 studies reviewed, published between 2004 and 2015, provide evidence that electricity access can lead to improvements in productivity, employment, labor, and/or income. The pathways through which electrification can impact these and other outcomes is illustrated in Figure A1. As shown in Figure 1, the places/regions studied and the likelihood of observing a positive impact vary greatly across space. There is weak evidence regarding the impacts of electrification on health and education outcomes, and impacts are highly context specific. On the other hand, in terms of productivity, we see positive effects from RE across the majority of contexts. Below we provide examples for each major outcome category.

***Health***. Electrification addresses health impacts by reducing reliance on kerosene and biomass fuels which reduces indoor air pollution. Consider some examples. Electrification was seen to reduce the number of respiratory infections in children under six years of age because of reduced kerosene use and lower particulate matter concentrations in electrified households in El Salvador (Barron and Torero 2017). In another case, solar home systems were associated with improved health, particularly for women and girls in Bangladesh (Samad et al. 2013).

***Education.*** Electrification can impact education because of increased time for studying and/or for more activity in general (as the “day” expands). Lipscomb et al. (2013) found that electrification at the county level led to improvements in both enrollment and literacy rates in Brazil. Khandker et al. (2012) find that household-level electrification led to increases in both completed years of schooling and daily study time in Bangladesh, with impacts almost twice as high for boys compared to girls. In the African context, studies find an increase in study time *after* nightfall, but only in Senegal are researchers able to identify an increase in total study time (Peters and Sievert 2016).

***Household Productivity***. Electrification can also impact employment, labor supply, income and other productive uses of energy (Köhlin et al. 2011, Bonan et al. 2017). Using panel data, Khandker et al. (2009a) find that electrification led to a twenty-five percent increase in household income in Vietnam, most of which came from increases in farm income. Dinkleman (2011) found positive impacts on female employment in South Africa, likely due to less time spent doing housework, but found no increase in wages due to no change in labor demand. Peters and Sievert (2016) find that electrification did not lead to increases in employment in Sub-Saharan African, and that households rarely use electric appliances for productive uses. In their review, they also fail to observe a shift in time use from household tasks to income earning activities in any of the African contexts they studied. They hypothesize that these effects are muted, relative to other contexts, due to lack of market connectivity, i.e., new firms will not take hold because they cannot access markets for their goods. In the few contexts where they do find positive effects on new enterprise (Rwanda and Benin), these effects are observed in business centers with established market connections.

***Firm Productivity***. At the community level, electrification can promote the growth of energy-intensive enterprises and bring about increases in labor demand and wage-earning opportunities (Figure A1). A small set of studies that assess the impact of electrification on firms find positive impacts on (i) the quantity and diversity of firms and (ii) output (Rud 2012; Peters et al. 2011). Others find that unreliable electricity has negative effects on firms' productivity and revenue (Allcott et al. 2016; Fisher-Vanden et al. 2012; Reinikka and Svensson 2002).

***Local Environment.*** Only one of the three reviews considers local environmental outcomes, such as fuelwood extraction, and that review finds very few studies that focus explicitly on environmental outcomes (Köhlin et al. 2015). For example, a study of electrification via solar photovoltaic panels in Peru found that households with solar PV spent less on firewood, but this does not necessarily mean a reduction in amount of firewood consumed, as many households also collect firewood (Arráiz and Calero 2015).

A handful of the impact evaluations reviewed above conduct simple, "back of the envelope" calculations to compare their identified impacts to the costs of rural electrification. Khandker et al. (2009a) show that the present value of monthly benefits from improved income [$18.90 per household per month] were almost four times greater than the costs of grid extension and household connection, and the marginal costs of generation and transmission in Vietnam. Khandker et al. (2009b) identified similar results in Bangladesh, estimating a per household electrification cost of $4.50 per month and comparing it to the income gain from grid connection, which was $12 per month. This value understates the full benefits for health and education, for example. With respect to off-grid solutions in Bangladesh, Khandker et al. (2014) find that household benefits from reduced kerosene consumption and increased income are 500 percent higher than the cost of the solar home system. In their preceding impact analysis, the authors identify impacts on health and time use, but they do not include these as benefits categories in their CBA.

A number of past studies have undertaken a more detailed accounting of the costs of RE. Mahapatra and Dassapa (2012) compare the cost of different rural electrification technologies in sub-Saharan Africa, accounting for both infrastructure costs and carbon emissions. Mulder and Tembe (2008) take the analysis the next step, calculating benefits and comparing them to costs in Mozambique. They find that RE results in positive net benefits, but they make many, sometimes arbitrary, assumptions about parameter values and omit key benefits because of "limited data availability." Additionally, they fail to account for the opportunity cost of extending the grid. A state-level assessment of infrastructure spending and rural wages in India between 1970 and 1993 found that expenditure on energy infrastructure reduced rural poverty, but the magnitude of the reduction was small compared to investments in things like roads and agricultural research and development (Fan et al. 2000). Jeuland and Pattanayak's (2012) analysis of global clean cooking solutions consider the widest range of benefits and costs, including health improvements, time savings, and reduced carbon emissions. In our study, we apply a similar methodology to the question of rural electrification.

In the light of this review, two patterns emerge. First, most evaluations address only one or two categories of outcomes, even though plausibly all outcomes were impacted.[1] Thus, in this paper, we attempt to assess a larger set of impacts of Bhutan's national RE program. Second, few studies check whether benefits of RE exceed the cost. We undertake a more complete accounting of the private and social costs and benefits of Bhutan's RE program.

In the following section, we outline the data and methods that we used for both our impact analysis of Bhutan's RE program and the private and social cost benefit analyses (CBAs). We use regression and quasi-experimental methodologies to assess the impact of Bhutan's RE program on firewood use, non-subsistence employment, health, and education. In Section 3, we find that Bhutan's national RE program reduced fuelwood use, improved education outcomes, and increased the likelihood of being employed outside of subsistence agriculture, but, apparently, did not improve self-reported health outcomes. We then use as many context-specific parameter values as possible (including these estimated impacts) to conduct a full cost-benefit analysis, including some environmental outcomes. We find that the private benefits of RE outweigh the private costs to the individual household, and this finding is robust to

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[1] Exceptions in the peer-reviewed literature are Samad et al. (2013) in Bangladesh, Barron and Torero (2017) in El Salvador, and Lipscomb et al. (2013) in Brazil.

uncertainty about the true parameter values. However, the net benefits at the social level are less clear: NPV is marginally positive, but this estimate is very sensitive to parameter uncertainty. We conclude in Section 4 by calling for more research on previously unmeasured outcomes of electrification, including environmental outcomes, as well as better and more geographically diverse estimation of parameters needed to value these outcomes.

## 2. Data and Methods

Starting in the early 1990s, when less than five percent of Bhutan's total population had access to electricity (WB SE4All 2016), Bhutan's national RE program planned to harness domestic hydropower generation capacity to decrease reliance on biomass at the household level and improve health and education (Perera et al. 2010). These are important development goals in the case of Bhutan, which falls in the medium human development category (UNDP 2015) and whose citizens are some of the highest biomass consumers in the world (UNDP 2012). The program was successful at increasing rural grid-electrification rates, which increased to 25% in 2003 and 83% in 2012. However, grid expansion did not happen evenly across the entire country (Figure 2). Verifying that this expansion impacted the targeted outcomes is important as, in the past, outcomes used to justify investments in electrification have been largely unmeasured (Bernard 2010).

In order to estimate the impact of electrification, we rely on household- and individual-level data from three rounds [2003, 2007, and 2012] of the Bhutan Living Standards Survey (BLSS). The BLSS sampling and data collection methodologies are based on the World Bank's Living Standard Measurement Survey. The data is not a panel, but a repeated cross section. BLSS questionnaires cover a wide range of topics (NSB and ADB 2013). This is important because it not only allows for estimation of the impacts of RE on the diverse array of outcomes targeted by the program, but also allows for the consideration of confounding factors. After pooling data across all three survey rounds, we arrive at a sample size of 12,893 rural households. For indicators collected at the individual level, the sample consists of 66,239 individuals in rural households.

In our analysis, we consider four outcomes explicitly mentioned by the Bhutanese government as targets of the RE program. These include 1) monthly firewood consumption, in kilograms, 2) years of completed schooling among children ages 7 to 18, 3) reported illness in children 5 years and under in the four weeks before the survey, and 4) employment status in a personal business or a wage-earning activity for adults ages 15 to 60. To assess whether or not a household has electricity access as a result of Bhutanese government activities, we consider "electrified" households to be those who report having access to electricity from the grid. Those who report no access to electricity or access to electricity from home generation or "other" sources are used as the comparison group in this analysis.[2] The construction of these variables is explained in more detail in Table A10.

The primary challenge to identifying the impacts of grid electrification is the non-randomness with which communities and households are connected to the grid. This non-randomness exists primarily on two scales. The first is at the community level, related to the question of which communities the transmission network reaches. Transmission lines are often extended to accessible, populated areas first, as they are costly to build and initially target areas where they can connect the most people to electricity for the least cost. This was the case in Bhutan, where communities close to existing roads were prioritized for grid extension (JICA 2005). The more populated areas are also likely to have better market access and better access to government services. Relatedly, households in these areas tend to be wealthier than those in less-densely populated areas (Rauniyar 2009). The second scale of non-randomness is the household level. Once the transmission network reaches a community, distribution lines are extended and households make the decision to connect to the electric grid. Endogenous household and community characteristics, i.e., characteristics that drive both grid electrification and outcomes of interest, can lead to bias if impacts are estimated via simple comparison of outcomes between grid-connected and non-grid-connected households, hereafter referred to as connected and unconnected. We first conduct regression analysis to examine the community and household-level drivers of grid extension. We estimate the following equation:

$$E_{hj} = {\beta^e}_0 + {\beta^e}_1 X_{hj} + {\beta^e}_2 Z_j + {\gamma^e}_t + {\delta^e}_d + {\gamma^e}_t {\delta^e}_d + {\varepsilon^e}_{hj} \qquad (1)$$

where $E_{hj}$ is an indicator variable that takes the value of one if a household $h$ in community $j$ is connected to the electric grid.[3] $X_{hj}$ is a vector of household level characteristics and $Z_j$ is a vector of community characteristics. ${\gamma^e}_t$ and ${\delta^e}_t$ are a set of

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[2] In the pooled sample, 4 percent of households report getting electricity from a source other than the grid.

[3] This indicator takes the value of 1 if the response to the household-level question "Do you have electricity?" was "Yes, from the grid." The question was the same in the BLSS 2003, 2007, and 2012.

year and district indicator variables, respectively, which are included, along with the interaction between them, to account for unobserved characteristics in each year, each district, and each district-year that may be simultaneously driving grid electrification and other household and community outcomes. The parameters of interest from the above demand equation, ${\beta^e}_1$ and ${\beta^e}_2$, are estimated via logistic regression.[4]

To then account for the non-randomness of the 'treatment' we use two methods for each of the four outcomes identified above. The first is regression, with controls for household and community characteristics, including fixed effects for district and year. In the case of individual-level outcomes, we also include individual characteristics. We estimate the following equation:

$$y_{ihj} = \beta_0 + \beta_1 E_{hj} + \beta_2 X_{hj} + \beta_3 Z_j + \beta_4 V_{ijh} + \gamma_t + \delta_d + \gamma_t \delta_d + \varepsilon_{ihj} \qquad (2)$$

where $y_{ihj}$ is the outcome of interest and $V_{ijh}$ is a set of individual characteristics for individual $i$ in household $h$ in community $j$. We estimate this equation using a number of regression models. In the case of firewood consumption, a continuous variable, we use linear regression. In the case of health and employment outcomes, respectively measured as binary outcomes equal to 1 if an individual reported being ill or being employed in a personal business or wage-earning activity, we use logistic estimation. In the case of education outcomes, measured as a count variable of years of completed schooling, we use a negative binomial.

As an additional estimate as well as a robustness check, we apply propensity score matching techniques. This is an increasingly popular approach in practical evaluations of development and environment outcomes (Pattanayak 2009). In applying this technique, we first calculate a household's probability of treatment, i.e., connection to the grid, conditional on a set of household and community characteristics based on the model we described above (Equation 1). We then match connected households with unconnected households based on the calculated propensity score.[5] As shown in Table C2, the matched samples are balanced for 4 of 10 household covariates. For still unbalanced

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[4] Stata/SE 14.2 for Mac (64-bit Intel) was used to for all statistical analysis presented here.

[5] We test the robustness to both nearest neighbor with replacement and kernel density matching. In applying kernel density matching, we rely on the epanechnikov kernel (the default in Stata's -psmatch2- program), setting the bin width to 0.1 (Leuven and Sianesi 2003; Heckman et al. 1998b). We use the propensity score rather than the Mahalanobis distance, following the recommendation in the literature (Gu and Rosenbaum 1993; Rubin and Thomas 2000).

covariates, matching greatly reduced the bias coming from differences between connected and unconnected households.[6] Using this matched sample, we estimate the effect of electrification; in the case of individual outcomes, we additionally include age and gender as covariates.

The PSM method satisfies the unconfoundedness assumption, but it does not account for unobserved characteristics that may bias impact estimates. In the case of Bhutan, we are less concerned about unobservables for two reasons. First, we know and include the primary determinants of grid electrification at the community level, i.e., distance from roads. Second, the increase in electrification rates occurred quickly in Bhutan, as compared to other contexts. This rapid increase in electrification rates helps to reduce endogeneity bias because other factors that may be driving outcomes had less time to change over the restricted time period of this study.

After estimating the impacts of electrification using the above methodologies, we conduct CBAs to compare the magnitude of benefits with the costs of grid expansion and electricity generation. In this analysis, we consider costs and benefits at both the private and social levels, restricting the analysis to rural households and the government of Bhutan. The broad categories of costs and benefits considered are adapted from recent applications of CBA to energy interventions (Table 2; Jeuland and Pattanayak 2012; Jeuland et al. 2017). Some parameters of the CBA (from the 64 required) come from either estimates reported in the preceding impact analysis or from project- or location-specific documents. For example, fuel savings (e.g., time savings from reduced fuelwood collection and expenditure savings in the form of reduced kerosene consumption) are available from our setting. Other parameters have to be transferred, following a rich tradition of benefits transfer used to evaluate environmental policies (Smith et al. 2006). For example, even though we can report on additional years of schooling due to electrification, we need to value those quality changes in monetary terms, in this case based on a global review of how increased education increases adult earnings (Montenegro and Patrinos 2014). For other household costs, similarly, we either draw from Bhutan-specific literature or transfer from other contexts. These other categories

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[6] Matching led to a reduction in mean bias across all 11 covariates, plus district and time fixed effects and their interactions, from 20%, in the unmatched sample, to 5% and 6% when using nearest neighbor and kernel density matching, respectively. For the samples matched with both nearest neighbor and kernel density matching the Rubin's B ratio, which is the difference of the means of the propensity score in the matched treated and non-treated groups, is above the recommended 25%, but the R ratio, which is the ratio of matched treated to non-treated variances of the propensity score, is between the recommended 0.5 and 2 (Rubin 2001).

include the costs of acquiring and maintaining electric appliances, costs of additional years of school, and the cost of electricity itself.

We also consider social costs and benefits. Social costs, measured per household, now also include the cost of grid extension, operation and maintenance, and generation, which are reported in Asian Development Bank and World Bank documents (Khamudkhanov and Nunez 2008; PA Consulting Group 2011; NRECA Intl. Ltd. 2000). Grid extension also causes deforestation and forest degradation (NEC n.d.; Norbu et al. 2016). On the other side of the ledger, social benefits include savings from avoided kerosene subsidies (Khamudkhanov and Nunez 2008) and reduced greenhouse gas and black carbon emissions because of reduced fuelwood and kerosene combustion. A detailed discussion of the quantification and monetization of these costs and benefits is presented in Appendix B (for more details, see also Jeuland and Pattanayak 2012).

We consider a 50-year time span, assuming the operation and maintenance costs included in our estimation are sufficient to keep the grid running smoothly over these 50 years. We consider year zero to be the year in which the household is connected to the grid, with ongoing costs and benefits beginning to accrue in year 1. We discount the stream of costs and benefits to the present by applying the private discount rate in the case of the private analysis and the social discount rate in the case of the social CBA. Parameter values, their plausible ranges, and calculations used for each category of household and social costs and benefits are presented in Tables B1, B2, and B3. We use the base values reported in Table B3 and underlying equations reported in Table B2 to calculate the private ($p$) and social ($s$) NPV point estimates (Equations 3 and 4):

$$NPV_p = (fuel_{hh} + educ_{ben}) - (elec + app_1 + app_2 + educ_{cost} + emp) \tag{3}$$

$$\begin{aligned} NPV_s = \left(fuel_g + carb_w + carb_k + env + fuel_{hh} + educ_{ben} + emp\right) \\ - (grid + gen + land + elec + app_1 + app_2 + educ_{cost}) \end{aligned} \tag{4}$$

We conduct two types of sensitivity analyses to account for the uncertainty in the true value of the parameters used to quantify and monetize the costs and benefits referenced in the equations above. This uncertainty exists because 1) parameters are measured with error, 2) we have to transfer parameter values from other contexts, and/or 3) we predict, or make assumptions about, parameter values in the future. First, we conduct probabilistic sensitivity analysis using Monte Carlo simulations. In order to do this, we specify 1) the range of plausible values for each parameter, 2) the probability distribution of the parameter within this range, and 3) the correlations between parameters. Based on these specifications, outlined in Table B3, we run 10,000 simulations, repeatedly sampling parameter values from the specified distributions.[7] This analysis allows us to report on the probability distribution of the private and social NPVs across a range of values (Figure 4). Second, we conduct one-way sensitivity analysis to isolate the parameters that exert the most influence on our NPV estimates. This analysis involves varying parameters, one at a time, within the specified range. The tornado charts in Figure A9 illustrate which parameters most affect the private and social NPVs. These methods are similar to those applied to other environmental and health CBAs (Jeuland and Whittington 2009; Jeuland and Pattanayak 2012).

## 3. Results

At the time of the survey, 5,070 households were connected to the grid and 7,823 were without a grid connection (unconnected). Simply comparing to unconnected households, we see that connected households consume less fuelwood (166 kilograms per month), are more likely to be engaged in a personal business or wage-earning activity (30% compared to 20%), have more ill children under 5 (3 percentage points), and have children with more years of schooling (1.5 years). These differences are all statistically significant (Figure A2).

In addition to these differences in outcomes, connected and unconnected households are different in many characteristics (Table A3). Compared to connected households, unconnected households are poorer, larger, more likely to be headed by a female, less educated, more reliant on agriculture, and live in more remote communities. We find that many of the differences identified above are drivers of grid electrification (Table C1). At the community level, proximity to an existing road and to a district headquarter (which is more densely populated) is positively correlated with electrification, presumably because proximity is inversely correlated with the cost of grid electrification, both in terms of infrastructure construction and transmission of power (Barnes 2007). At the household level, we confirm that the expected factors such as wealth and use of other environmental health technology (e.g., improved water sources), explain connection status (Lewis and Pattanayak 2012; Khandker et al. 2012).

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[7] Sensitivity analysis was conducted using Oracle’s Crystal Ball tool for Microsoft Excel.

We present the results of both the regression-based and propensity score matching impact estimates in Table 2. Panel A presents results from the regression estimation methods. Column 1 presents results of a bivariate regression of the outcome of interest on grid electrification status. Columns 2 and 3 test the robustness of this estimate to the inclusion of individual, household and community level covariates and to the clustering of standard errors at the district level. We present PSM estimates in Table 2, Panel B, and find that the regression results are robust to alternative estimation techniques. [8]

***Fuelwood impacts***. We find that electrification led to a twenty percent reduction in fuelwood consumption at the household level. Using PSM, the estimated reduction is slightly larger and remains significant. The fact that electricity access does not cause firewood consumption to drop to zero is evidence of fuel stacking, which has been observed in many settings (Ruiz-Mercado and Masera 2015). While electricity access helps households move away from traditional fuels like kerosene for certain services like lighting, it may not be able to provide the energy required to meet other household needs like heating. Therefore, households "stack," or rely on multiple fuels and technologies to meet cooking, heating, lighting and other energy service needs.

***Education impacts.*** Grid electrification is associated with greater completed years of school among school-age children, leading to about 0.5 years of additional schooling (0.84 years in the case of PSM estimation). As demonstrated in Panel A, columns 4 and 5, this effect is stronger for girls than boys, with electrification increasing years of schooling by 0.75 years for girls, compared to 0.43 years for boys.[9] This may be due to the fact that girls bear heavier time burdens with regards to fuel collection and preparation. Electricity grid connections can reduce a portion of this time burden, allowing girls to spend more time studying or in school.[10]

***Health impacts*.** The small difference in incidence of illness among children under 5 between connected and unconnected households is not robust to the inclusion of covariates, including time and district fixed effects, nor to PSM estimation. There are at least two potential reasons for this finding. First, though electrification leads to a reduction in firewood consumption by the household, it does not *eliminate* firewood consumption. Biomass is still being used for fuel by connected households. The dose-

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[8] See Figure A4 for illustration that overlap assumption of propensity score matching is met.

[9] This effect is tested by including an interaction term between gender and grid electrification in the full model. The coefficient on this term is statistically significant at the 99.9 percent level.

[10] BLSS does not include data on daily activities and time budgeting needed to test this hypothesis.

response curve of $PM_{2.5}$ and other air pollutants and health outcomes has been estimated to be mostly flat at high concentration levels (Bruce and Smith 2014). Thus, changes in biomass use may not be reducing indoor air pollutant concentrations to very low levels. Second, the health indicator we use here is a survey self-report regarding whether *any* illness or injury occurred in the four weeks before the survey. Likely, this is not a precise enough measure of respiratory health to detect differences between the respiratory health of young children in connected and unconnected households.

***Productivity impacts.*** The point estimates in Table 2, Panel A indicate that grid electrification is associated with a three percent increase in the likelihood of being employed.[11] This effect is estimated to be driven by employment effects for men, and the effect for women is found to be insignificant (Table 2, Columns 5 and 6). This finding is robust to PSM estimation, although, when estimating the effect on female and male subsamples, the results are no longer significant, likely due to power limitations.

Taken together, these estimation methods provide evidence that Bhutan's RE program improved education and employment outcomes and reduced biomass consumption. The estimates of health impacts are insignificant.

***Cost benefit analysis.*** We next apply these impact estimates to conduct a CBA, using the framework presented in Section II. Based on this framework, we estimate that the private NPV is 880 USD per household (Figure 3, Panel A).[12] The majority of the benefits come from the increased earning capacity associated with improvements in schooling outcomes for children in connected households and the income from non-subsistence employment. Additionally, these households also spend less time collecting fuelwood and purchase less kerosene. The total benefits exceed the total costs, partly because of the subsidized electricity tariff (i.e., zero for consumption below 100 KWh/month in rural areas).

As described previously, we wish to examine the sensitivity of our NPV estimate to variation in key parameters (Table B3 for distributional assumptions associated with each parameter). First, we use Monte Carlo analysis to consider how this variation affects our conclusions. When we vary all parameters simultaneously, the distribution of the possible private NPV is overwhelmingly positive (almost the entire distribution is between 0 - 6,000 USD per household, Figure 4, Panel A). Second, we conduct one-way

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[11] See Tables A5-A8 for full estimation results.

[12] All monetary values are report in constant 2012 USD.

sensitivity analysis. Because the majority of private benefits are associated with increased income, from employment and education, variation in GDP growth has a significant effect on private NPV estimates. This is especially important given the volatile growth patterns in Bhutan over the past decade, with annual growth reaching 18 percent in 2007 and falling to 2 percent in 2013 (WB and OECD 2016). The NPV is sensitive to variation in GDP growth, but this variation alone is not enough to produce a negative value (Figure A9, Panel A). The NPV is also sensitive to variation in the private discount rate (Figure A9, Panel A).[13] Critically, none of the variation is sufficient to result in a negative private NPV (Table B3). This lack of sensitivity to variation in parameters, combined with the fact that the estimate presented here is likely a lower bound (see Appendix B), provides robust evidence that grid electrification results in a positive private NPV.

However, from a social perspective we must consider the infrastructure and generation costs of rural grid extension as well as the environmental benefits of reduced reliance on traditional fuels. In this case, we find that the NPV is 73 USD per household (Figure 3, Panel B). The majority of costs are the 1) high, one-time cost of grid extension and household connection and 2) recurring costs of grid operation and maintenance and electricity generation. The majority of these costs are borne by the government due to high electricity subsidies for rural households. However, because the households use less energy from kerosene, the government also saves on subsidies. A key component of the social benefits are the environmental benefits, mostly greenhouse gas emission reduction, which we estimate to be 2,543 USD (Figure 3, Panel B). Note, because electricity in Bhutan is generated by run-of-the-river hydropower (ADB 2014-2018), we do not subtract out the pollution costs of fossil fuel electricity generation or the methane associated with large, hydropower reservoirs (Tremblay et al. 2004).

When considering the sensitivity of our social NPV estimate to variation in multiple parameters, our Monte Carlo analysis shows that a little over half of the distribution of possible NPVs is in the positive range (52 percent). Critically, a non-trivial 48 percent is in the negative tail of the distribution of NPVs (Figure 4, Panel B). To better understand the source of these negative values, we conduct one-way sensitivity analysis. We find that our social NPV estimate is highly sensitive to variation in the social cost of carbon, which itself is subject to scientific disagreements (Nordhaus 2017). If the cost of

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[13] A recent review finds that empirical discounting studies often focus on U.S. and European populations, frequently relying on students as study subjects (Cohen et al. 2016). As rural Bhutan specific estimates are not available, assessing how variation in this parameter, and others like it, affects NPV estimates is very important.

carbon is valued at the high end of the range (95 USD per ton $CO_2$-equivalent), the estimated social NPV is highly positive (Figure A9, Panel B). In addition, this estimate is sensitive to assumptions about the annual operation and maintenance costs necessary to maintain the grid; if these costs are a little higher than the base case, the NPV will be negative. As in the private case, the social NPV estimate is sensitive to GDP growth rate, which greatly affects the estimated returns to education and employment. Thus, we cannot draw any strong conclusions about the social NPV for two reasons: (1) the sensitivity to parameters we have just discussed, and (2) the absence of estimates of household adoption of more advanced electrical appliances and of ecosystem service benefits from avoided deforestation.

## 4. Discussion and Conclusion

In this paper, we undertake a more comprehensive evaluation of rural electrification programs than previously conducted. First, we conduct an impact analysis of Bhutan’s RE program, similar to those done in other contexts, but we consider four outcomes – education, health, productivity, and fuelwood collection, the last of which is an often-ignored environmental outcome. We find the program decreased fuelwood consumption, improved educational outcomes, and increased the likelihood of non-subsistence employment. Second, we take the parameters from this analysis (and from other analyses) to answer the question of whether the government’s investment in RE resulted in positive *net* benefits. Our cost-benefit analysis shows that the private NPV of the program is positive. This finding is robust to variation in multiple parameters. At the social level, we calculate a small but positive NPV. Our sensitivity analysis reveals that the value of the social NPV is highly susceptible to variation in many parameters. Additionally, our estimate is likely a lower bound due to the omission of key benefits categories.

While our work expanded on past RE evaluation, we still faced many challenges in comparing the true and comprehensive costs and benefits of RE. First, despite the richness of the BLSS data from Bhutan, we cannot account for all the plausible impacts of electrification. For example, even though we are able to quantify GHG emissions and reduced biomass consumption, we cannot link reduced biomass consumption to the human welfare consequences of avoided forest degradation or ecosystem change generally. An example of these human welfare consequences was identified in a recent study in Malaysia. It was found that it is cheaper to operate municipal water treatment plants when a plant is located downstream from a forested area, as opposed to downstream from oil palm or rubber plantations (Vincent et al. 2016). Reducing deforestation and improving forest health can also protect biodiversity, preserve watershed services, and provide many other ecosystem services (Seymour and Busch 2016; Ferraro et al. 2011; Olivero et al. 2017). We were not able to account for these types of environmental outcomes because the links between unit reductions in firewood consumption and improvements in environmental services are not easily quantified. This is partly because such social-ecological links are complex and not accessible for decision making tools like CBA (Olander et al. 2017). In the future, researchers must fill this gap, for example by tapping novel and accessible data sources (e.g., the Global Survey for Multi-tier Energy Access Tracking and GeoQuery spatial data on land cover and forest resources).

Second, even if we had compelling estimates of all the impacts of RE, we need a second set of parameters to quantify the monetary benefits associated with these impacts. Typically, such parameters are drawn from methods that include averting behavior models, hedonic wage price, travel cost methods, and choice experiments (Pattanayak and Pfaff 2009). Even with our expanded impact analysis, we were still only able to use study-specific estimates for five of the sixty-four parameters required to value all costs and benefits considered. We partially offset this concern by obtaining Bhutan-specific estimates from other sources. When these were not available, we transferred estimates from other contexts based on a tradition of benefits transfer (Smith et al. 2006). For example, to value the increased education that accompanied rural electrification, we used estimates of the returns to primary education from other countries in the region (Montenegro and Patrinos 2014). Similarly, the shadow value of time is estimated based on authors' judgment as well as a 2010 study from Mozambique (Jeuland et al. 2010). Nonetheless, the transfer process remains somewhat ad hoc, with little clear guidance on how to adjust values for similarity between the study and policy context.

Third, for the reasons explained above (i.e., missing or transferred parameters), we explicitly incorporate uncertainty into our CBA through Monte Carlo simulations and one-way sensitivity analysis. However, even these methods require some understanding of the range of parameter values – if there is only one study, there is no range. This is especially important for environmental outcomes, which are dependent on a wide range of ecological and social variables. For example, in the case of Malaysia, there was significant heterogeneity in the reduction in water treatment costs depending on the type of forest located upstream (Vincent et al. 2016). Additionally, the climatic effects of GHG emissions across the world are not equal (Bond et al. 2013). This heterogeneity exacerbates the uncertainty already underlying the social cost of carbon (Van den Bergh and Botzen 2015). Thus, it is critical to expand the number and quality of primary studies on the estimation and valuation of environmental outcomes related to RE.

In sum, we show that Bhutan's RE program successfully delivered on many impacts that were used to justify the program – that is, the private NPV is positive, helping to improve welfare in poor, rural areas of Bhutan. At the social level, the returns to Bhutan's investment in expanding the grid were less clear. This is both because some of the parameters are noisy and because some are simply missing. Nonetheless, we are sufficiently confident about the overall worth of RE projects in practice; they will remain an important tool for combatting energy poverty. We believe that governments will continue to use RE programs to improve the quality of life in rural areas, and, as these programs continue, the policy research community has an important obligation to provide estimates of impacts and non-market values of the myriad impacts of RE. This could be through new primary studies or new methodological research for more accurate transfers (Smith et al. 2006). This work will to allow more comprehensive CBA, helping to spur investment and improve program design.

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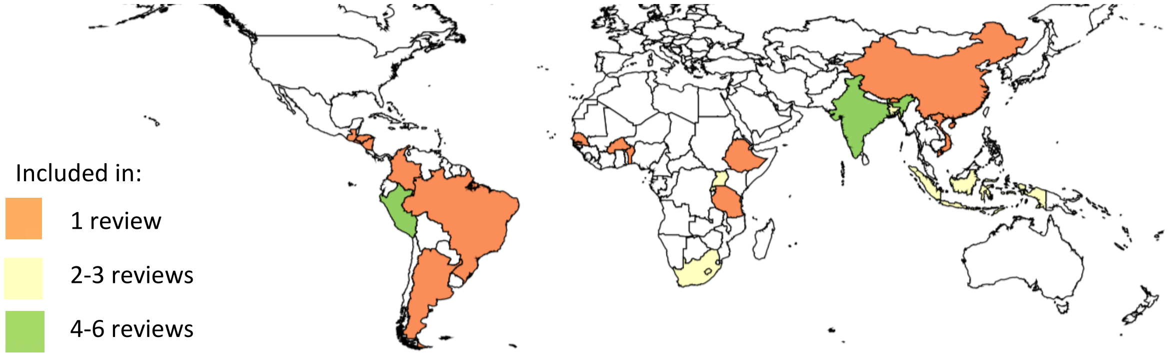
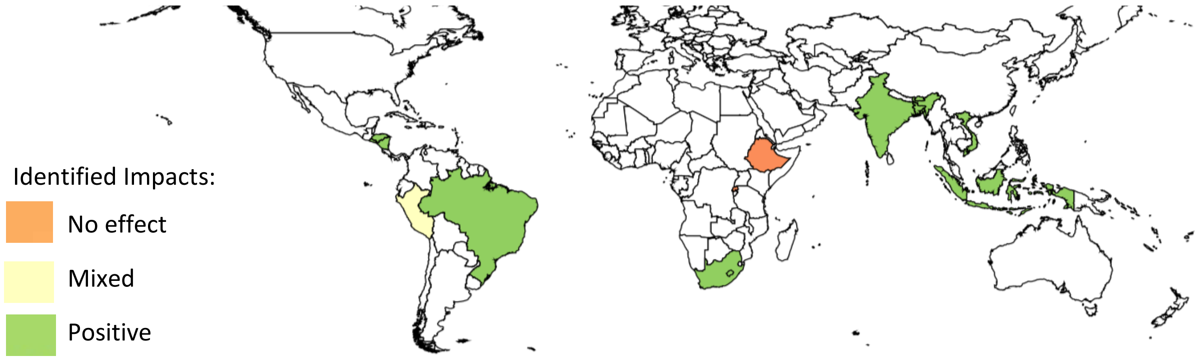
## Tables and Figures

### Figure 1a. Global Coverage of Electrification Studies Included in Köhlin et al., Bonan et al., and Peters and Sievert Reviews



### Figure 1b. Productivity Impacts of Electrification



### Figure 1c. Health Impacts of Electrification

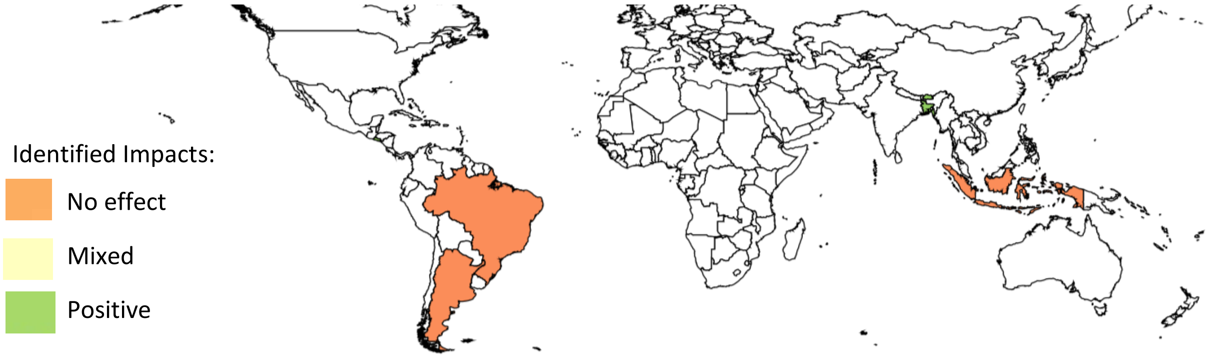


**Figure 1d. Education Impacts of Electrification**

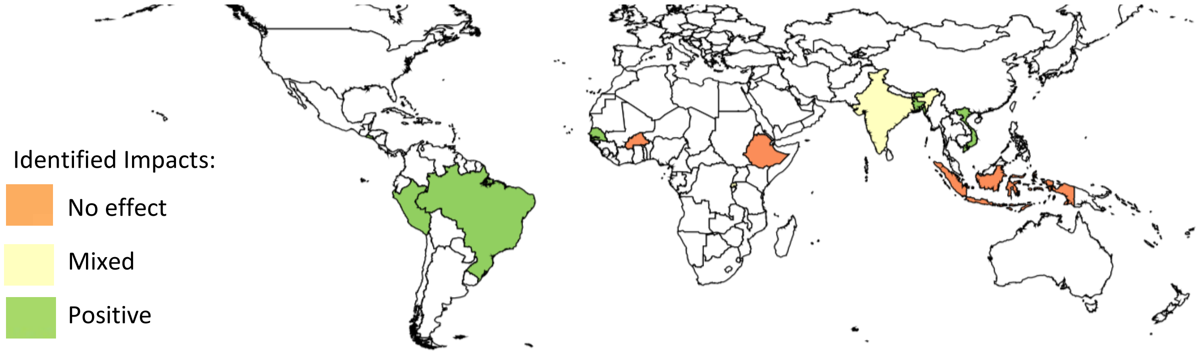
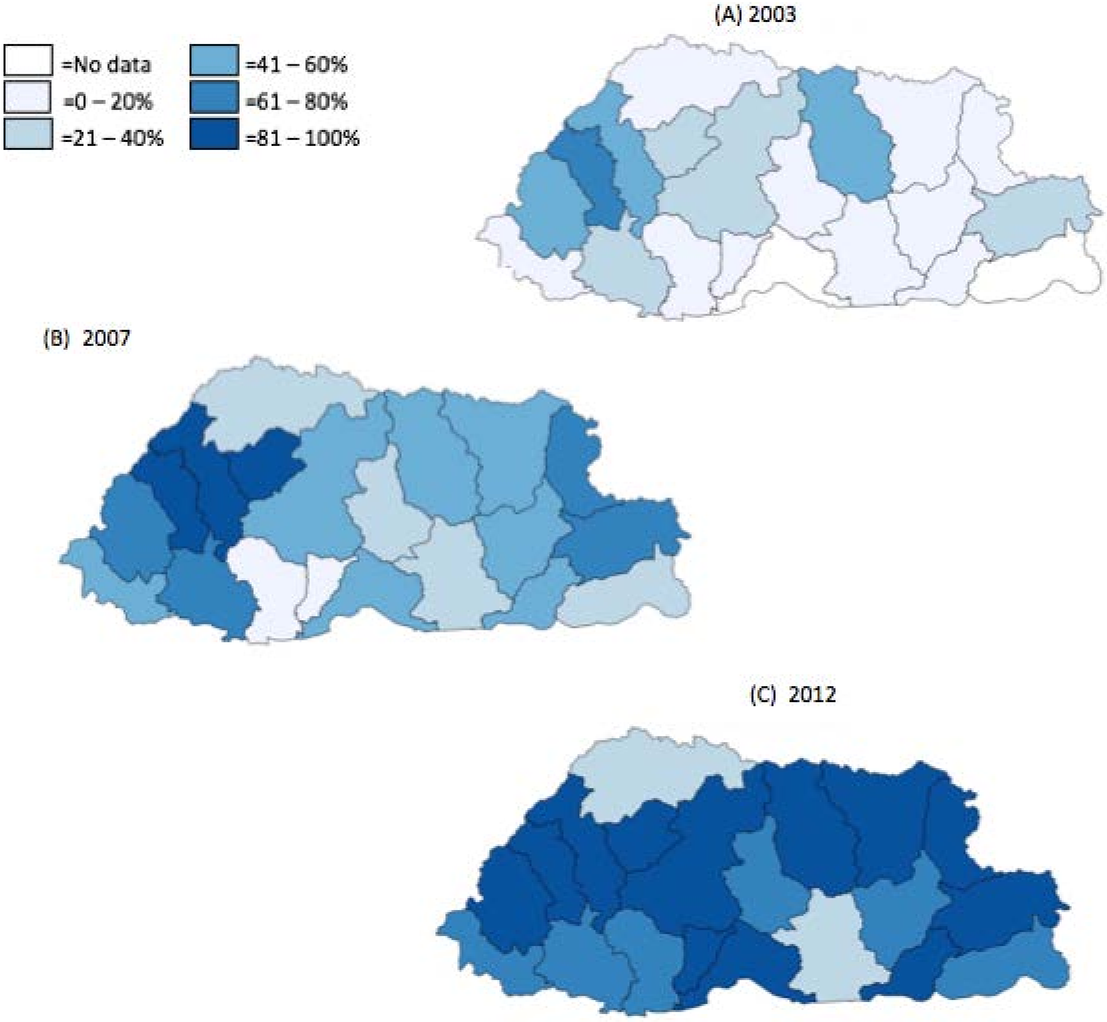


**Figure 2. Rural Electrification Rates by Dzongkhag, 2003-2012**[14]



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[14] Created in Stata/SE 14.2 for Mac (64-bit Intel), using Bhutan Living Standards Survey data from 2003, 2007, and 2012.

## Table 1. Costs and Benefits Considered[15]

| | Costs | | Benefits | |
|---|---|---|---|---|
| Private | Appliance costs | Purchase of electric cookers (curry, rice) and light bulbs; appliance maintenance | Fuel savings | Time savings from reduced fuelwood collection; monetary savings from reduced kerosene purchases |
| | Schooling costs | Notebooks, pencils, uniforms, transportation | Returns to education | Increased future earnings from increased educational achievement |
| | Electricity costs | Tariffs (cost per KWh) | Increased earnings | Increased earnings from non-subsistence employment |
| Social | Infrastructure costs | Grid extension/construction; operation and maintenance | Fuel savings | Reduced kerosene subsidies |
| | Generation and transmission costs | Opportunity cost of exporting power to India; cost of importing power from India | GHG emission reduction | Fewer emissions from reduced combustion of kerosene and firewood |
| | Forest conversion | Deforestation and forest degradation associated with grid extension | Other environmental benefits | Reduced cost of sustainable biomass harvest |

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[15] Adapted from recent analyses of household energy technologies by Jeuland and Pattanayak (2012) and Jeuland et al. (2017).

## Table 2. Estimated Impacts of Rural Electrification

| Outcome & Estimation Method | (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|---|
| A. Regression methods | Bivariate | Full controls | Clustered Std. Errors | Boys/Males | Girls/Females |
| Monthly firewood consumption | -165.73*** | -113.86*** | -113.86*** | -- | -- |
| (Linear regression) | (13.40) | (18.53) | (28.94) | | |
| Completed years of schooling | 1.51*** | 0.57*** | 0.57*** | 0.43*** | 0.75*** |
| (negative binomial regression) | (0.05) | (0.05) | (0.11) | (0.10) | (0.16) |
| Incidence of illness in children under 5 | 0.03*** | 0.01 | 0.01 | -0.00 | 0.02 |
| (logistic regression) | (0.01) | (0.01) | (0.02) | (0.02) | (0.02) |
| Employment status, personal business | 0.10*** | 0.03*** | 0.03** | 0.03*** | 0.02 |
| or wage-earning (logistic regression) | (0.00) | (0.01) | (0.01) | (0.01) | (.02) |

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| B. Propensity Score Matching | Nearest neighbor | Kernel density | Nearest Neighbor, boys/males | Nearest Neighbor, girls/females |
| Monthly firewood consumption | -134.46*** | -158.82*** | -- | -- |
| | (30.30) | (22.64) | | |
| Completed years of schooling | 0.82*** | 0.79*** | 0.68*** | 1.12*** |
| | (0.14) | (0.09) | (0.23) | (0.22) |
| Incidence of illness in children under 5 | 0.01 | -0.01 | -- | -- |
| | (0.03) | (0.03) | | |
| Employment status, personal business | 0.03** | 0.03*** | 0.03 | 0.03 |
| or wage-earning | (0.02) | (0.01) | (0.03) | (0.02) |

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Average partial effects are reported for education, health and employment outcomes

Panel A column 2 is estimated with the full set of individual (in the case of education, health and employment outcomes), household and community covariates. Panel A column 3 is estimated with full covariates and clustering standard errors at the district level. Panel A Columns 4 and 5 are estimated for gender-based subsamples.

Panel B Column 1 is estimated using the nearest neighbor (n=1) matched sample. Panel B Column 2 is estimated using the kernel density (bw=0.1) matched sample. Panel B Columns 3 and 4 are estimated using the nearest neighbor matched sample for gender-based subsamples.

**Figure 3. Net Present Value of Cost and Benefits of RE Program**

(A) Private (household) present value of benefits and costs

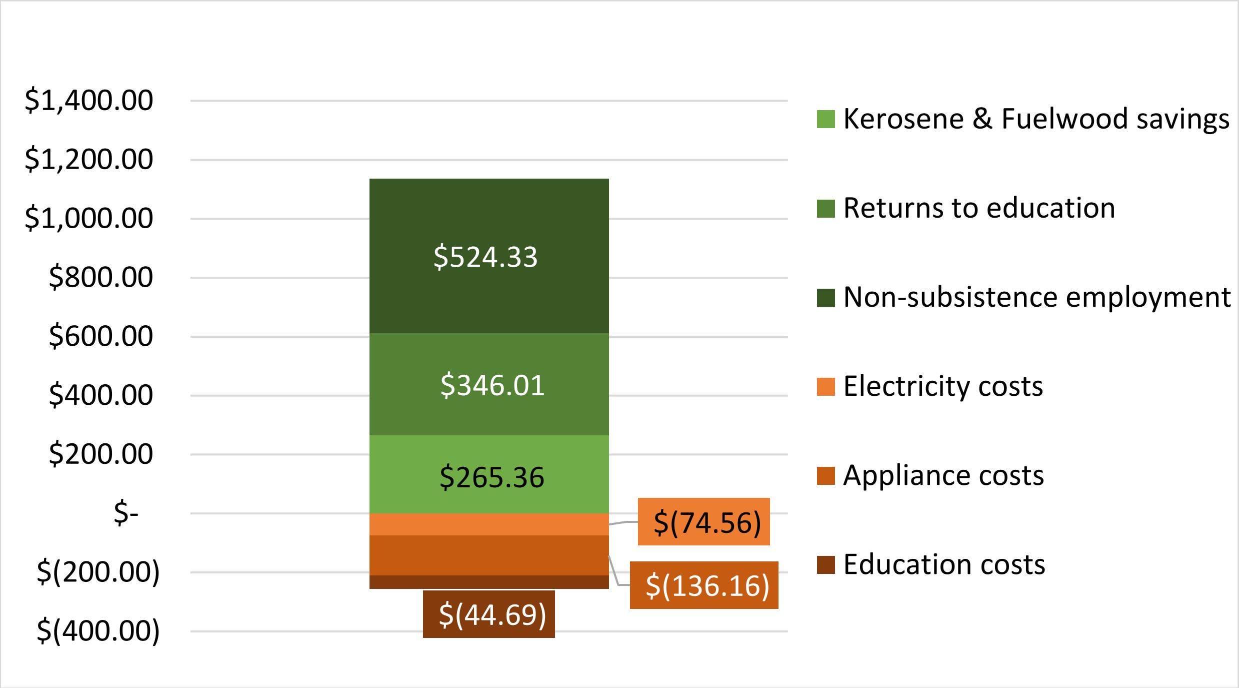


**Figure 3 continued. Net Present Value of Cost and Benefits of RE Program**

(B) Social present value of benefits and costs

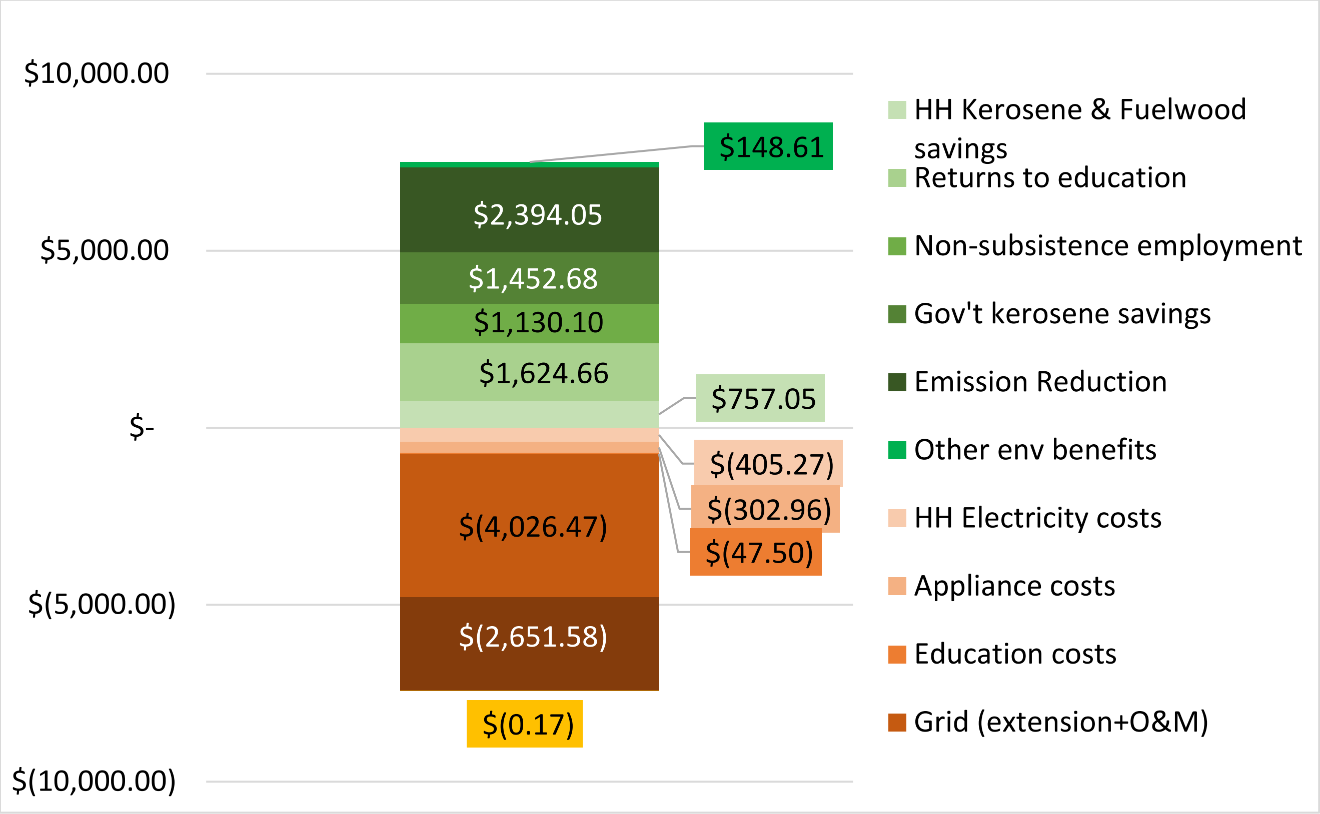
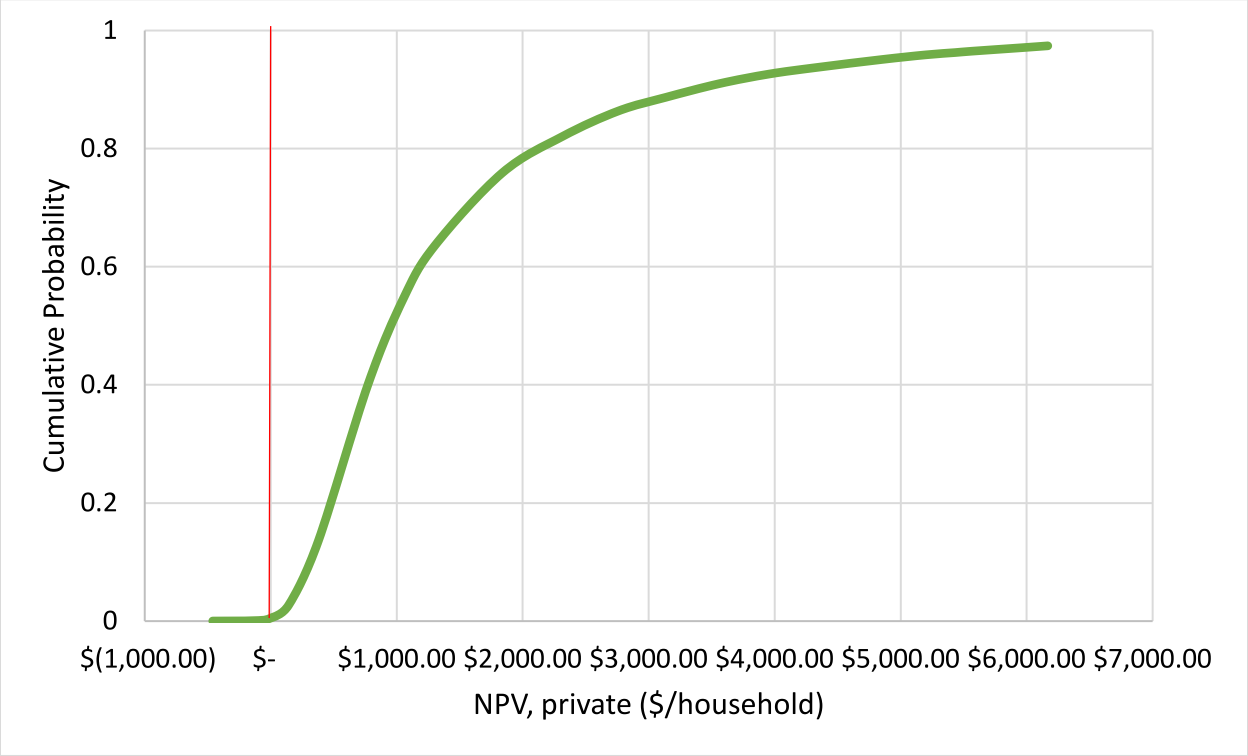
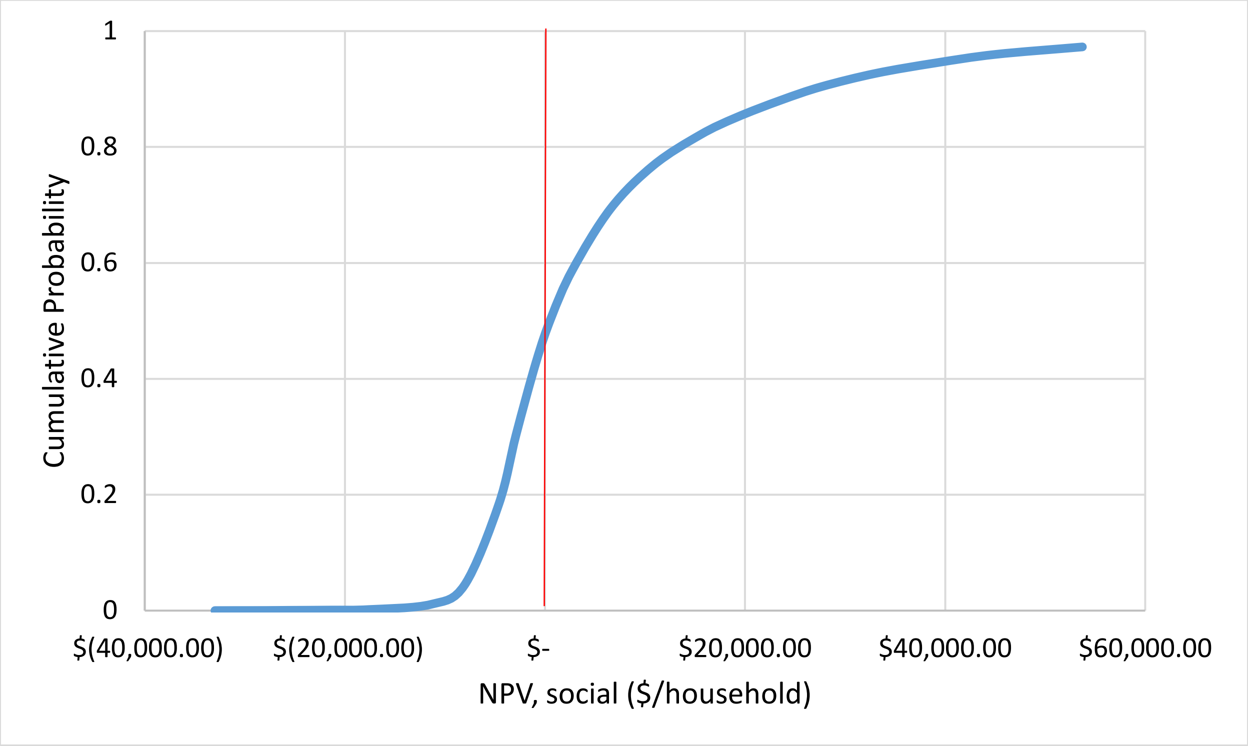


**Figure 4. Distribution of Present Value of Net Present Value Estimates**

(A) Private

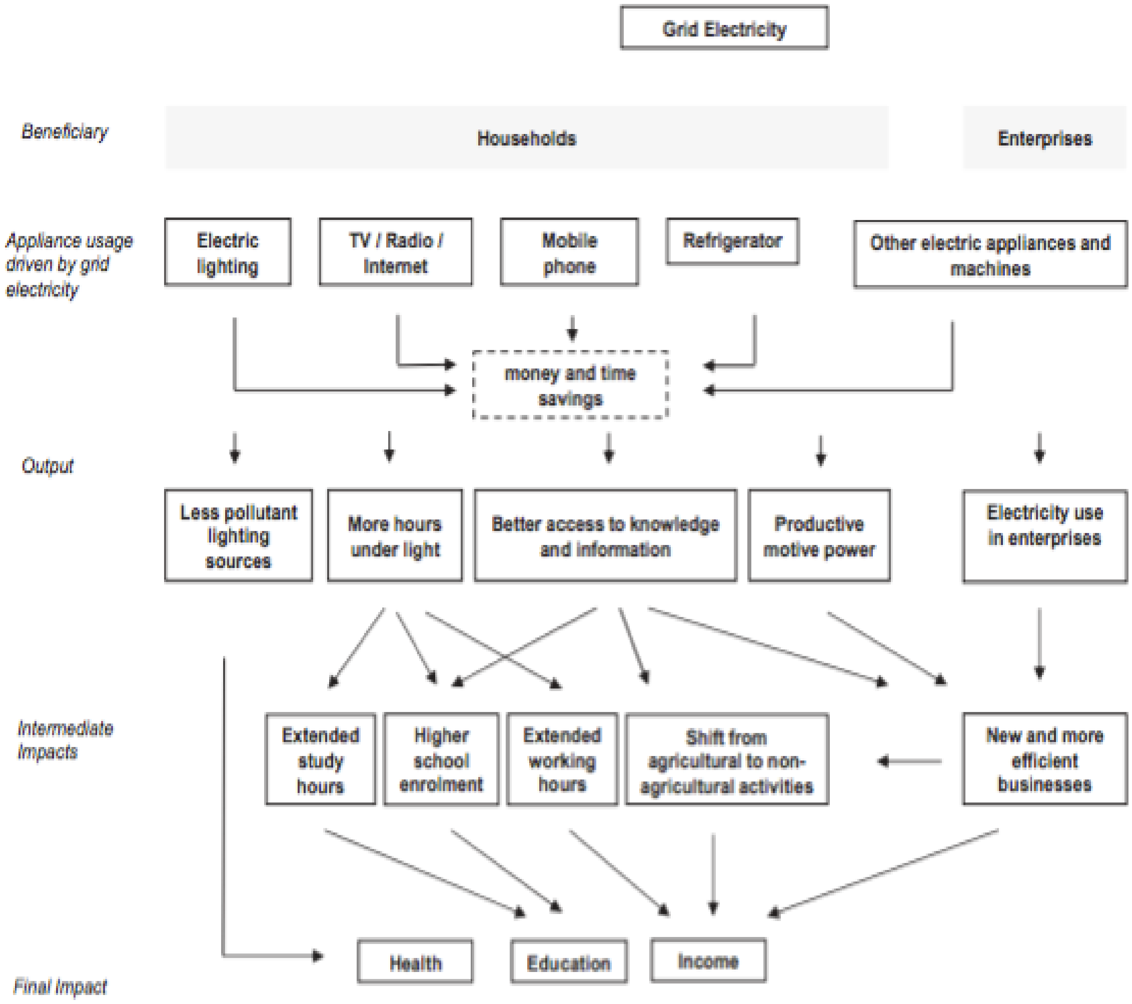


(B) Social

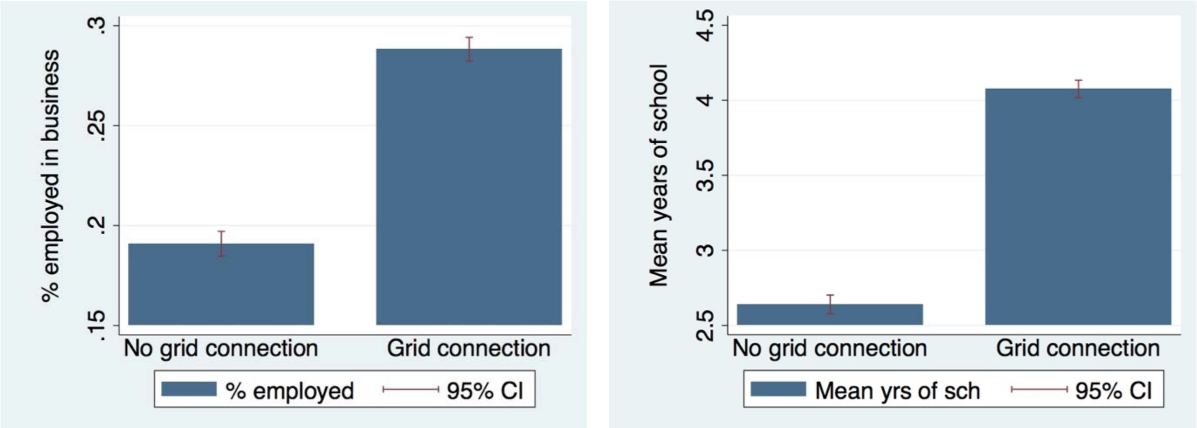


## Appendix A: Supplementary Tables and Figures

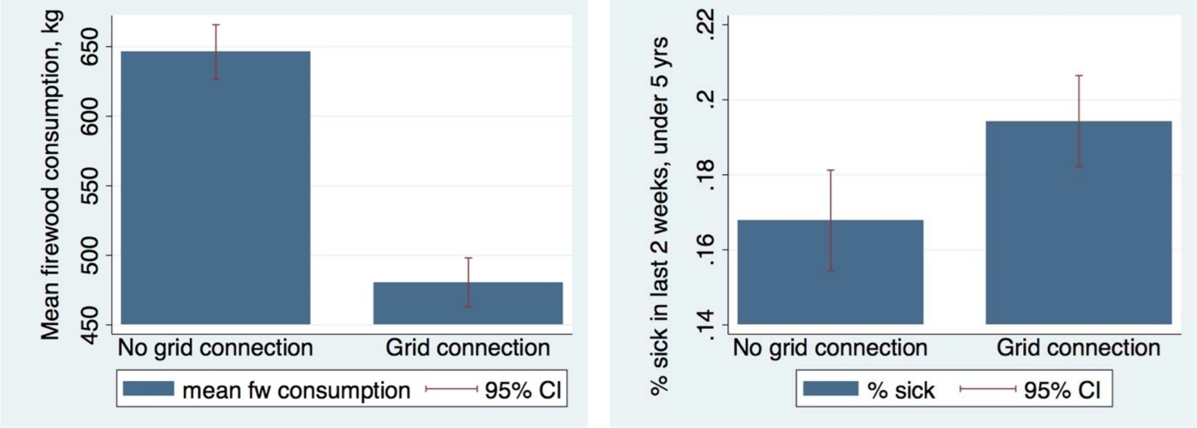
### Figure A1. Electricity Use and Outcomes in Rural Households (Peters and Sievert 2016)



## Figure A2. Comparison of Means of Key Outcomes, Unconnected v. Connected to Grid



(A) Non-subsistence Employment (B) Education



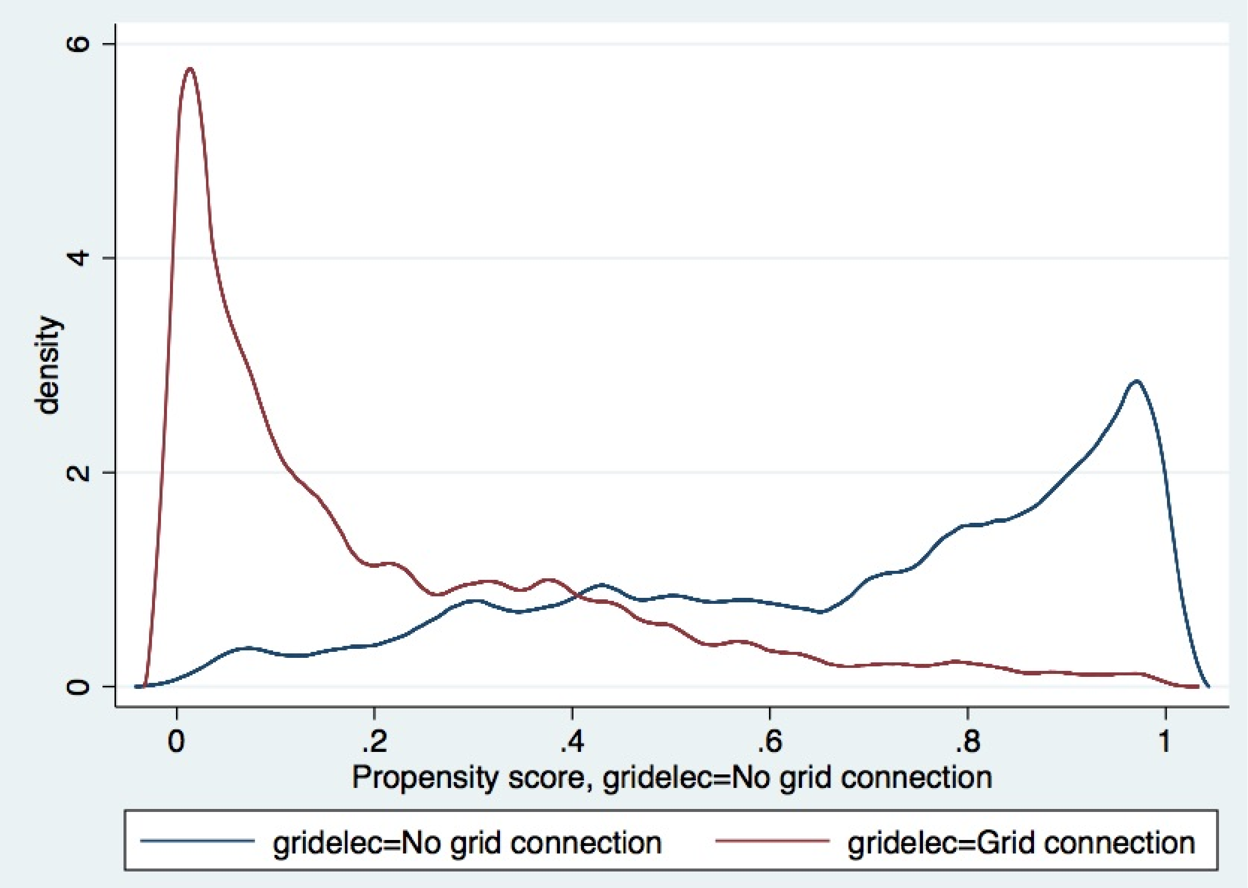
(C) Firewood Consumption (D) Children's Health

## Table A3. Means of Key Variables and Comparison of Connected and Unconnected Households

| | Not connected to grid | | Connected to grid | | |
|---|---|---|---|---|---|
| Variable | N | Mean | N | Mean | Difference |
| Outcomes | | | | | |
| Monthly firewood consumption, kg | 5,070 | 646.265<br>(708.299) | 7,823 | 480.532<br>(794.705) | 165.734*** |
| Working age adult employed in own business or wage-earning activity (1=yes) | 15,733 | 0.189<br>(0.392) | 22,682 | 0.286<br>(0.452) | -0.097*** |
| Child under 5 sick in last 4 weeks (1=yes) | 2,985 | 0.168<br>(0.374) | 4,086 | 0.194<br>(0.396) | -0.026*** |
| Years of completed school for children between 7 and 18 | 7,182 | 2.640<br>(2.686) | 9,800 | 4.075<br>(2.932) | -1.435*** |
| Household characteristics | | | | | |
| Household size | 5,070 | 5.355<br>(2.526) | 7,823 | 4.997<br>(2.284) | 0.358*** |
| Gender of household head (1=male; 2=female) | 5,070 | 1.309<br>(0.462) | 7,823 | 1.377<br>(0.485) | -0.068*** |
| Age of household head | 5,070 | 49.379<br>(14.439) | 7,823 | 48.792<br>(14.987) | 0.587** |
| Marital status of household head (1=married) | 5,070 | 0.781<br>(0.414) | 7,823 | 0.786<br>(0.410) | -0.005 |
| Household head can read & write in Dzongkha (1=yes) | 5,070 | 0.191<br>(0.393) | 7,823 | 0.305<br>(0.461) | -0.115*** |
| Acres of land owned | 5,069 | 3.165<br>(4.043) | 7,822 | 2.701<br>(3.639) | 0.465*** |
| Brick is main household construction material (1=yes) | 5,070 | 0.583<br>(0.493) | 7,823 | 0.694<br>(0.461) | -0.111*** |
| Improved water source (1=yes) | 5,070 | 0.807<br>(0.394) | 7,823 | 0.949<br>(0.221) | -0.141*** |
| Own chickens (1=yes) | 5,070 | 0.641<br>(0.480) | 7,823 | 0.429<br>(0.495) | 0.212*** |
| Community Characteristics | | | | | |
| Travel time to Dzongkhag HQ, in hours | 5,070 | 8.245<br>(9.761) | 7,823 | 2.953<br>(30368) | 5.292*** |
| Travel time to nearest tarred road, in hours | 5,070 | 6.188<br>(10.216) | 7,822 | 1.330<br>(2.610) | 4.858*** |
| Individual Characteristics | | | | | |
| Age | 27,150 | 28.201<br>(20.658) | 39,089 | 29.102<br>(20.939) | -0.901*** |
| Gender (1=male, 0=female) | 27,150 | 0.493<br>(0.500) | 39,089 | 0.487<br>(0.500) | 0.006 |
| Literacy status of working-age adults (ages 15-60, 1=literate in Dzongkha) | 15,800 | 0.338<br>(0.473) | 22,925 | 0.478<br>(0.500) | -0.140*** |
| Head of Household of working age adults (=1 if individual is HoH) | 15,881 | 0.248<br>(0.432) | 23,199 | 0.262<br>(0.439) | -0.013*** |

Standard deviations in parentheses; Stars indicate significance level of t-test of difference in means; *** p<0.01, ** p<0.05, * p<0.1.

**Figure A4. Distribution of Propensity Score, by Grid Connection Status**



## Table A5. Impact Estimates of Electrification, Firewood Consumption

| | Monthly firewood consumption, kg | | |
|---|---|---|---|
| | (1) | (2) | (3) |
| Household grid connection status (1=connected) | -165.73*** | -113.86*** | -113.86*** |
| | (13.40) | (18.53) | (28.94) |
| Household size | | 28.20*** | 28.20*** |
| | | (3.15) | (3.64) |
| Gender of household head (1=male; 2=female) | | 31.24* | 31.24 |
| | | (18.99) | (20.38) |
| Age of household head | | 1.40*** | 1.40*** |
| | | (0.51) | (0.39) |
| Marital status of household head (1=married) | | 57.81*** | 57.81*** |
| | | (15.85) | (17.75) |
| Household head can read & write in Dzongkha (1=yes) | | -55.87*** | -55.87*** |
| | | (16.62) | (16.24) |
| Acres of land owned | | 4.16** | 4.16* |
| | | (1.77) | (2.28) |
| Brick is main household construction material (1=yes) | | -13.66 | -13.66 |
| | | (14.31) | (17.20) |
| Improved water source (1=yes) | | -17.16 | -17.16 |
| | | (18.12) | (17.20) |
| Own chickens (1=yes) | | 81.59*** | 81.59*** |
| | | (13.82) | (18.55) |
| Household head employed outside of subsistence agriculture (1=yes) | | -60.73*** | -60.73*** |
| | | (15.02) | (17.06) |
| Log travel time to Dzongkhag HQ, in hours | | -6.41 | -6.41 |
| | | (12.64) | (22.00) |
| Log travel time to tarred road, in hours | | 6.83 | 6.83 |
| | | (8.97) | (17.14) |
| Time trend | | -3.96 | -3.96*** |
| | | (5.64) | (1.27) |
| District indicators | No | Yes | Yes |
| District/time interaction terms | No | Yes | Yes |
| Constant | 646.27*** | 272.46*** | 272.46*** |
| | (9.95) | (92.73) | (81.60) |
| Observations | 12,893 | 12,875 | 12,875 |
| R-squared | 0.01 | 0.09 | 0.09 |

Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Column 3 standard errors are clustered at the district level.

## Table A6. Impact Estimates of Electrification, Completed Years of Schooling

| | Years of completed school | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4)<br>Boys | (5)<br>Girls |
| Household grid connection status (1=connected) | 1.51*** | 0.57*** | 0.57*** | 0.43*** | 0.75*** |
| | (0.05) | (0.05) | (0.11) | (0.10) | (0.16) |
| Child's age | | 0.56*** | 0.56*** | 0.58*** | 0.54*** |
| | | (0.01) | (0.12) | (0.01) | (0.02) |
| Child's gender (1=male; 0=female) | | 0.17*** | 0.17** | | |
| | | (0.04) | (0.08) | | |
| Household size | | -0.03*** | -0.03*** | -0.03** | -0.03** |
| | | (0.01) | (0.01) | (0.01) | (0.01) |
| Gender of household head (1=male; 2=female) | | 0.30*** | 0.30*** | 0.20*** | 0.40*** |
| | | (0.04) | (0.07) | (0.08) | (0.10) |
| Age of household head | | 0.00** | 0.00** | 0.00 | 0.01*** |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| Marital status of household head (1=married) | | 0.07 | 0.07 | 0.04 | 0.14* |
| | | (0.05) | (0.06) | (0.08) | (0.07) |
| Household head can read & write in Dzongkha (1=yes) | | 0.64*** | 0.64*** | 0.59*** | 0.71*** |
| | | (0.04) | (0.09) | (0.09) | (0.12) |
| Acres of land owned | | 0.02*** | 0.02*** | 0.01** | 0.02** |
| | | (0.00) | (0.01) | (0.01) | (0.01) |
| Brick is main household construction material (1=yes) | | 0.20*** | 0.20* | 0.19* | 0.22* |
| | | (0.04) | (0.11) | (0.10) | (0.13) |
| Improved water source (1=yes) | | 0.71*** | 0.71*** | 0.53*** | 0.96*** |
| | | (0.08) | (0.11) | (0.12) | (0.15) |
| Own chickens (1=yes) | | -0.31*** | -0.31*** | -0.26*** | -0.37*** |
| | | (0.04) | (0.06) | (0.08) | (0.09) |
| Household head employed outside of subsistence agriculture (1=yes) | | 0.24*** | 0.24*** | 0.30*** | 0.19** |
| | | (0.04) | (0.06) | (0.05) | (0.09) |
| Log travel time to Dzongkhag HQ, in hours | | -0.08*** | -0.08 | -0.12* | -0.06 |
| | | (0.03) | (0.07) | (0.07) | (0.08) |
| Log travel time to tarred road, in hours | | -0.11*** | -0.11** | -0.03 | -0.17*** |
| | | (0.02) | (0.04) | (0.04) | (0.05) |
| Time trend | | 0.14*** | 0.14*** | 0.06*** | 0.23*** |
| | | (0.03) | (0.01) | (0.01) | (0.01) |
| District indicators | No | Yes | Yes | Yes | Yes |
| District/time interaction terms | No | Yes | Yes | Yes | Yes |
| Observations | 16,982 | 16,948 | 16,948 | 8,498 | 8,450 |
| Pseudo R-squared | 0.01 | 0.10 | 0.10 | 0.11 | 0.10 |

Average partial effects reported. Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Standard errors in columns 3-5 are clustered at the district level. Columns 4 and 5 are estimated for the sample of boys and girls only, respectively.

## Table A7. Impact Estimates of Electrification, Incidence of Children's Illness

| | Incidence of young child illness in the 4 weeks preceding the survey | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4)<br>Boys | (5)<br>Girls |
| Household grid connection status | 0.03*** | 0.01 | 0.01 | -0.00 | 0.02 |
| (1=connected) | (0.01) | (0.01) | (0.02) | (0.02) | (0.02) |
| Child's age | | -0.03*** | -0.03*** | -0.03*** | -0.03*** |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| Child's gender (1=male; 0=female) | | -0.01 | -0.01 | | |
| | | (0.01) | (0.01) | | |
| Household size | | -0.01*** | -0.01*** | -0.01*** | -0.01*** |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| Gender of household head (1=male; | | 0.02* | 0.02* | 0.02 | 2 |
| 2=female) | | (0.01) | (0.01) | (0.01) | (0.02) |
| Age of household head | | 0.00 | 0.00 | -0.00 | 0.00 |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| Marital status of household head (1=married) | | 0.02 | 0.02 | 0.02 | 0.02 |
| | | (0.01) | (0.01) | (0.02) | (0.02) |
| Household head can read & write in | | 0.04*** | 0.04*** | 0.04* | 0.04** |
| Dzongkha (1=yes) | | (0.01) | (0.01) | (0.02) | (0.02) |
| Acres of land owned | | -0.00 | -0.00 | -0.00 | -0.00 |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| Brick is main household construction | | -0.02* | -0.02* | -0.01 | -0.03** |
| material (1=yes) | | (0.01) | (0.01) | (0.02) | (0.01) |
| Improved water source (1=yes) | | -0.01 | -0.01 | -0.04* | 0.02 |
| | | (0.02) | (0.02) | (0.02) | (0.03) |
| Own chickens (1=yes) | | 0.01 | 0.01 | 0.00 | 0.01 |
| | | (0.01) | (0.01) | (0.02) | (0.01) |
| Household head employed outside of | | 0.00 | 0.00 | -0.01 | 0.01 |
| subsistence agriculture (1=yes) | | (0.01) | (0.01) | (0.01) | (0.02) |
| Log travel time to Dzongkhag HQ, in hours | | -0.01 | -0.01 | -0.01 | -0.01 |
| | | (0.01) | (0.01) | (0.02) | (0.02) |
| Log travel time to tarred road, in hours | | 0.00 | 0.00 | 0.01 | 0.00 |
| | | (0.01) | (0.00) | (0.01) | (0.01) |
| Time trend | | -0.00 | -0.00 | 0.01*** | -0.01*** |
| | | (0.01) | (0.00) | (0.00) | (0.00) |
| District indicators | No | Yes | Yes | Yes | Yes |
| District/time interaction terms | No | Yes | Yes | Yes | Yes |
| Observations | 7,071 | 7,065 | 7,065 | 3,601 | 3,464 |
| Pseudo R-squared | 0.01 | 0.06 | 0.06 | 0.06 | 0.07 |

Average partial effects reported. Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Standard errors in columns 3-5 are clustered at the district level. Columns 4 and 5 are estimated for the sample of boys and girls only, respectively.

## Table A8. Impact Estimates of Electrification, Employment

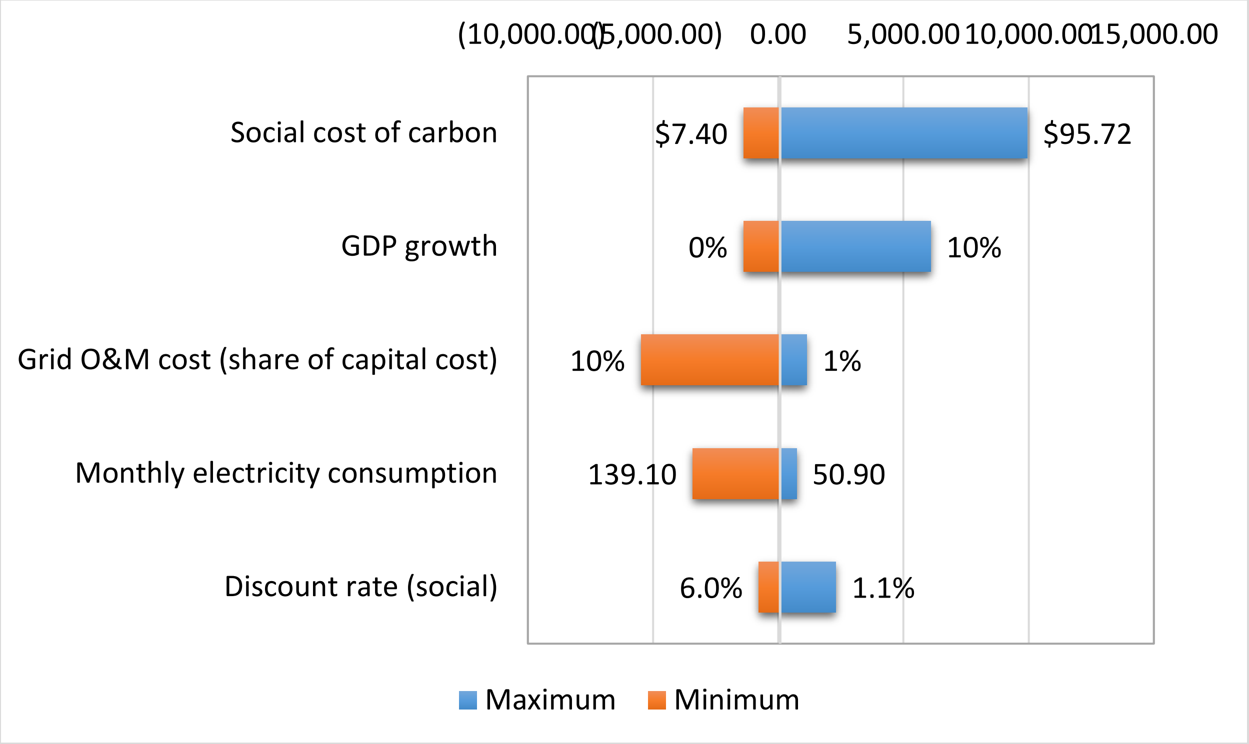
| | Employed in personal business or wage-earning activity (1=yes) | | | | |
|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4)<br>**Men** | (5)<br>**Women** |
| Household grid connection status (1=connected) | 0.10*** | 0.03*** | 0.03** | 0.03*** | 0.02 |
| | (0.00) | (0.01) | (0.01) | (0.01) | (0.02) |
| Individual's age | | 0.00*** | 0.00*** | 0.00*** | 0.00 |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| Individual can read & write in Dzongkha (1=yes) | | 0.00 | 0.00 | 0.00 | -0.00 |
| | | (0.01) | (0.01) | (0.01) | (0.01) |
| Individual gender | | 0.14*** | 0.14*** | | |
| | | (0.00) | (0.01) | | |
| Individual is head of household (1=yes) | | 0.08*** | 0.08*** | 0.11*** | 0.06*** |
| | | (0.01) | (0.01) | (0.01) | (0.01) |
| Household size | | -0.00*** | -0.00** | -0.00 | -0.00** |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| Gender of household head (1=male; 2=female) | | 0.01*** | 0.01** | 0.05*** | 0.00 |
| | | (0.01) | (0.01) | (0.01) | (0.01) |
| Age of household head | | -0.00*** | -0.00*** | -0.00*** | -0.00 |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| Marital status of household head (1=married) | | -0.02*** | -0.02** | -0.02** | -0.02** |
| | | (0.01) | (0.01) | (0.01) | (0.01) |
| Household head can read & write in Dzongkha (1=yes) | | 0.05*** | 0.05*** | 0.06*** | 0.05*** |
| | | (0.01) | (0.01) | (0.02) | (0.01) |
| Acres of land owned | | -0.00*** | -0.00*** | -0.01*** | -0.00* |
| | | (0.00) | (0.00) | (0.01) | (0.00) |
| Brick is main household construction material (1=yes) | | 0.02*** | 0.02* | 0.02* | 0.02 |
| | | (0.00) | (0.01) | (0.01) | (0.01) |
| Improved water source (1=yes) | | 0.04*** | 0.04** | 0.04** | 0.03* |
| | | (0.01) | (0.02) | (0.02) | (0.02) |
| Own chickens (1=yes) | | -0.05*** | -0.05*** | -0.08*** | -0.03*** |
| | | (0.00) | (0.01) | (0.01) | (0.01) |
| Log travel time to Dzongkhag HQ, in hours | | -0.02*** | -0.02*** | -0.02** | -0.02** |
| | | (0.00) | (0.01) | (0.01) | (0.01) |
| Log travel time to tarred road, in hours | | -0.00 | -0.00 | -0.01 | 0.00 |
| | | (0.00) | (0.00) | (0.00) | (0.01) |
| Time trend | | 0.01*** | 0.01*** | 0.02*** | 0.00 |
| | | (0.00) | (0.00) | (0.00) | (0.00) |
| District indicators | No | Yes | Yes | Yes | Yes |
| District/time interaction terms | No | Yes | Yes | Yes | Yes |
| Observations | 38,415 | 38,373 | 38,373 | 18,158 | 20,215 |
| Pseudo R-squared | 0.01 | 0.11 | 0.11 | 0.11 | 0.08 |

Average partial effects reported. Robust standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1. Standard errors in columns 3-5 are clustered at the district level. Columns 4 and 5 are estimated for the sample of men and women only, respectively.

**Figure A9. Sensitivity of Net Present Value Estimates to Variation in Individual Parameters**

(A) Variation in present value of private NPV ($/household)

(B) Variation in present value of social NPV ($/household)



## Table A10. Construction of Key Variables from BLSS Data

| Variable | Explanation of variable construction |
|---|---|
| Incidence of sickness | =1 if the individual was reported to have suffered from sickness or injury in the four weeks preceding the survey |
| Employment in personal business or wage-earning activity | =1 if an individual reported to have worked for money or have had a profitable business in the seven days preceding the survey |
| Years of completed schooling | Calculated as the highest year of schooling completed by an individual |
| Monthly firewood consumption, kg | Households reported firewood consumption as backloads per month or truck loads per year. These reported values were converted to kilograms by assuming a backload is 30 kg of firewood, while a truck load is 6000 kg. Truckloads were converted to a monthly value by dividing by 12. The total is the sum of the backloads, in kg, and truckload, in kg per month. |
| Household grid connection status | =1 if household reports to have access to electricity from the grid at the household |
| Marital status of household head | =1 if head of the household reports that he/she is currently married |
| Can read & write in Dzongkha | =1 if the head of the household reports that he/she is able to read and write a short text in Dzongkha |
| Acres of land owned | The sum of all wet, dry and orchard land the household reports to own |
| Brick is main household construction material | =1 if household reports that main building material of house is mud-bonded bricks/stones or cement-bonded bricks/stones |
| Improved water source | =1 if, in alignment with the World Health Organization's (WHO n.d.) categorizations, the household reports that their main source of water is a pipe in dwelling, neighbor’s pipe, public outdoor tap, protected well, protected spring, rainwater, or bottled water |
| Own chickens | =1 if the household indicates that they own one or more chickens |
| Travel time to Dzongkhag HQ, in hours | Calculated as the gewog/year-level[16] mean of all reported travel times by foot or foot/vehicle combination from the surveyed household to the nearest Dzongkhag HQ. |
| Travel time to tarred road, in hours | Calculated as the gewog/year-level mean of all reported travel times by foot or foot/vehicle combination from the surveyed household to the nearest tarred road. |

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[16] Gewog is the second highest administrative level in Bhutan, after the district, or Dzongkhag.

## Appendix B: Detailed Description of Cost Benefit Analysis Methodology

This appendix offers a detailed description of the calculation of the costs and benefit categories presented in Table 2 of the main text. The equations referred to below are outlined in Table B2.

The grid connection costs are calculated as the cost per household of both grid extension and household connection. Household connection costs were assumed to be borne by the government, based on ADB project descriptions, so this cost is included in the social costs category (Rauniyar et al. 2010). Operation and maintenance costs contain both a labor and non-labor share. Equation C1 assumes that the non-labor share of operation and maintenance costs is constant over time; the estimated labor share grows over time as wages grow, estimated by applying the GDP growth rate. The terminal value of the grid infrastructure at the end of the 50-year period is also included. We calculate this value as the resale value of the rural grid infrastructure itself, estimated as a share of the cost in year 0. We use the resale value because, given rapid technological change, we cannot predict what technology will be used after 50 years to bring electricity to Bhutan's rural areas. Generation costs are also heavily borne by the government, given that, currently, all rural household consumption below 100 KWh/month is completely subsidized by the government. Generation costs (Equation C2) are calculated based on household consumption, expected to start at only 65 KWh/month and grow at a rate of one percent per year (Khamudkhanov and Nunez 2008; Palacios 2008), the economic cost of generation, taking into account the opportunity cost of exporting electricity to India (PA Consulting Group 2011), and the tariff rate. The share of generation costs (per KWh) borne by the government is calculated as the economic cost of generation minus the tariff rate paid by households. Deforestation and forest degradation from grid expansion was estimated by Bhutan's National Environment Commission (NEC n.d.) and was monetized using Monga Bay estimates of the kilograms of biomass per hectare in Bhutanese forests as well as the cost of tree replacement (Equation C3) (Norbu et al. 2016; NEC 2008).[17] This cost was only applied to the estimated share of unsustainable biomass use in Bhutan (Drigo et al. 2014).

At the private level, electricity costs are a function of a household's electricity consumption and the tariff rate (Equation C4). Currently, in Bhutan, rural electricity

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[17] The literature on forest ecosystem services (biodiversity, watershed services, ecotourism) from avoided deforestation and degradation is not sufficiently rich and at scale in order to map and convert "kilograms of reduction in firewood" to social benefits (Ferraro et al. 2011). Such an analysis is part of a future extension of this project.

tariffs are set in a block system (BPC 2016; BEA 2016). All domestic rural electric consumers are charged a zero tariff for consumption below 100 KWh per month. This block is called the "lifeline" block and exists to ensure that poor rural households have access to electricity and to promote future growth in electricity demand. While this lifeline block is in place, annual household electricity cost in year *t*, Bhutanese ngultrum (BTN), is calculated in the following way if household energy consumption is below 1200 KWh/year,:

$$e * \left(1 + e_g\right)^{(t-1)} * tar_{<100} \qquad (B1)$$

where $tar_{<100}$ is the tariff rate for the lifeline block. This is assumed to be zero in the base case, but this parameter is varied in the sensitivity analysis. If household consumption is above 1200 KWh/year, the consumption above 1200 KWh is charged a higher tariff, while the first 1200 KWh of electricity consumption is still charged the lifeline tariff rate:

$$\left[\left(e * \left(1 + e_g\right)^{(t-1)}\right) - 1200\right] * tar_{>100}) + (1200 * tar_{<100}) \qquad (B2)$$

where $tar_{>100}$ is the tariff for consumption above the lifeline block, which, in the base case, is assumed to be 1.82 BTN/KWh. In the years after the lifeline block is discontinued, if, for example, rural households have reached income levels that no longer require subsidized electricity, all electricity consumption is assumed to be charged the higher tariff:

$$e * \left(1 + e_g\right)^{(t-1)} * tar_{>100} \qquad (B3)$$

The lifeline block is expected, in the base case, to last 15 years, after which the tariff rate for consumption above 100 KWh per month would be applied to all levels of consumption. This expectation is varied in the sensitivity analysis.

Appliance costs were estimated based on data from the BLSS 2003, 2007 and 2012. Purchase costs of electric cookers such as rice cookers, curry cookers, and water boilers (Equation C5) were estimated based on the average expenditure of rural households who reported buying an appliance in the year preceding the survey. The annual maintenance costs of these appliances were estimated as the annual expenditure of households who reported owning an electric cooking appliance but did not report purchasing one that year (Equation C6). Appliances were estimated to last 5 years, based on assumptions in Jeuland et al. (2017). Lighting costs per room were also based on household reporting from the BLSS (included in Equations C7 and C8). All of these costs were expected to remain constant over the 50-year time span. At the household level, we restrict our analysis to the costs and benefits of the technologies first adopted by households: electric light and electric cookers. These appliances are shown to be purchased by poor and wealthy households alike upon electrification (Khamudkhanov and Nunez 2008). While other appliances such as refrigerators, fans and TVs are purchased by wealthier households and may be purchased by poorer households at some point in the 50-year time span considered (Khamudkhanov and Nunez 2008), we assume the net benefits from these purchases to be zero or greater. This estimate of net benefits from household appliance adoption is therefore a lower bound, as net benefits from other appliances, in addition to the lighting and cookers considered here, may very well be positive. The final private cost considered is the cost of increases in education that stem from rural electrification. These estimates are based on rural households' reported education expenditure from the BLSS and the number of school-aged boys and girls in a household. We assume households will bear this cost in year 1, or the first year after receiving a grid connection, given that the majority of individuals in rural areas have not completed primary school and the average age of school-age boys and girls in rural Bhutan is 12 years old (NSB and ADB 2013; Author's estimate based on BLSS 2003, 2007 and 2012 data).

Social benefits are in the form of both fuel savings (Equation B8) and environmental benefits. The government heavily subsidizes kerosene purchased for household use, so reductions in kerosene use lead to government expenditure savings. Changes in kerosene consumption at the household level are estimated based on the methodologies presented above for changes in fuelwood consumption, using BLSS data.

To calculate the avoided greenhouse gas emissions associated with reduced kerosene and fuelwood combustion at the household level (Equations B9 and B10), we rely on the methodology adopted in Jeuland et al. (2017). We consider emissions of six climate pollutants: carbon dioxide ($CO_2$), carbon monoxide (CO), nitrous oxide ($N_2O$), methane ($CH_4$), black carbon (BC) and organic carbon (OC). The global warming potential (GWP) of each compound, in $CO_2$-equivalence, is measured as a stream of the radiative forcing of each pollutant over a period of 100 years (Shindell 2015). This stream is discounted to the period of emissions by applying the social discount rate. The calculation of the global warming potential for each pollutant, *p*, over the time period (100 years) is based on the following equation (equation A22 in Jeuland et al. (2017)):

$$GWP_p = \frac{\sum_{t=1}^{100} \frac{RF_{j,t}}{(1+\delta_S)^{t-1}}}{\sum_{t=1}^{100} \frac{RF_{CO2,t}}{(1+\delta_S)^{t-1}}} \qquad (B4)$$

To then calculate the GWP of the emissions of these six pollutants, in total $CO_2$-equivalence, from the combustion of fuelwood (in traditional stoves) and kerosene, we combine the above GWP values, per pollutant, with the emission factors of pollutants from each fuel. The total global warming potential from both kerosene and fuelwood is calculated as follows:

$$GWP_w = \varepsilon_{CO2,w} * \lambda + \varepsilon_{CO,w} * GWP_{CO} + \varepsilon_{CH4,w} * GWP_{CH4} + \varepsilon_{N2O,w} * GWP_{N2O} + \varepsilon_{BC,w} * GWP_{BC} + \varepsilon_{OC,w} * GWP_{OC} \qquad (B5)$$

$$GWP_k = \varepsilon_{CO2,k} + \varepsilon_{CO,k} * GWP_{CO} + \varepsilon_{CH4,k} * GWP_{CH4} + \varepsilon_{N2O,k} * GWP_{N2O} + \varepsilon_{BC,k} * GWP_{BC} + \varepsilon_{OC,k} * GWP_{OC} \qquad (B6)$$

where $\varepsilon_{p,k}$ and $\varepsilon_{p,w}$ are the emission factors for pollutant, $p$, in kerosene, $k$, or fuelwood, $w$, and $\lambda$ is the share of harvested biomass that is non-renewable. This parameter is included because renewable biomass harvesting does not affect emissions of $CO_2$, i.e., it sequesters carbon as quickly as it is consumed. This global warming potential is then applied to the reduction in the amount of kerosene or fuelwood that is combusted at the household after connecting to the grid, as in equations B11 and B12 in Table 3. These quantities are monetized by applying the social cost of carbon, which is considered a function of the social discount rate (Interagency Working Group on Social Cost of Carbon 2015).

Other environmental benefits to society include the avoided cost of tree replacement in the case of sustainable biomass harvest. This value is estimated as a function of the reduction in household fuelwood consumption, the share of biomass that is sustainably harvested in Bhutan, and the cost of tree replacement. This analysis does not include the value of ecosystem services that are preserved via reductions in fuelwood consumption, given the absence of estimates of the ecosystem services lost per kilogram of fuelwood harvested.[18]

At the private, household level, benefits are realized in the form of fuel savings (Equation B12) and returns to education (Equation B13). Fuel savings come from changes in both kerosene and fuelwood use. Rural households in Bhutan get their fuelwood almost exclusively from collection rather than purchase, so reductions in fuelwood consumption lead to time savings (PA Consulting Group 2011). These savings are monetized using the market wage for unskilled labor in Bhutan, to which an estimate

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[18] See footnote 29.

of the shadow value of time is applied. Monetary savings from reductions in kerosene use are estimated based on the magnitude of the reduction as well as the price households pay (full price minus the government subsidy) for kerosene (Khamudkhanov and Nunez 2008; Rauniyar et al. 2010). Finally, returns to education are estimated based on the increases in schooling that result from electrification. These returns are monetized based on a global review of the returns to education by Montenegro and Patrinos (2014). The return to education is not estimated for Bhutan, so we instead rely on the returns in other South Asian countries. We consider this increase in education to be an increase in primary education, given that, in rural Bhutan, the majority of the population has not completed primary school (NSB and ADB 2013). We apply these returns to the current level of rural income in Bhutan, which is expected to grow at the rate of GDP growth over the 50-year time span.

After calculating the present value of each category of costs and benefits over the 50-year time span considered, we then calculate the net present value (NPV). The NPV is calculated by summing the present value of the full set of benefits and subtracting the present value of the costs. The equations presented below, for the private ($p$) and social ($s$) analysis, reference the equations in Table 3:

$$NPV_p = (fuel_{hh} + educ_{ben} + emp) - (elec + app_1 + app_2 + educ_{cost}) \qquad (B7)$$

$$\begin{aligned} NPV_s = \big(&fuel_g + carb_w + carb_k + env + fuel_{hh} + educ_{ben} + emp\big) \\ &- (grid + gen + land + elec + app_1 + app_2 + educ_{cost}) \qquad (B8) \end{aligned}$$

## Table B1. CBA Parameter Definitions and Units

| Parameter | Description | Unit | Data Source |
|---|---|---|---|
| $Ge$ | Grid extension & connection cost | USD/household | ADB |
| $Om$ | Grid operation and maintenance cost | % of per household grid expansion & connection cost | ADB |
| $om_l$ | Share of O&M cost that is labor | % | UNDP/WB ESMAP |
| $\delta_s$ | Social discount rate | None | |
| $\delta_p$ | Private discount rate | None | |
| $E$ | Electricity consumption | KWh/hh-year | ADB, BPC |
| $e_g$ | Annual growth rate of electricity consumption | % | ADB, BPC |
| $c_g$ | Economic cost of generation | BTN/KWh | ADB |
| $Tar$ | Electricity tariff | BTN/KWh | BEA, BPC |
| $c_t$ | Cost of tree replacement | US/kg | Jeuland et al. 2017 |
| $B$ | Biomass density | kg/Ha | Monga Bay |
| $Flc$ | Forest land conversion from grid expansion | Ha/household | Bhutan NEC |
| $\Lambda$ | Percent of biomass consumption that is non-renewable | % | Drigo et al., 2014 |
| $X$ | Exchange rate (July, 2012) | BTN/USD | |
| $ex_l$ | Expenditure on lightbulbs | BTN/room/year | BLSS 2012 |
| $R$ | Number of rooms | Room(s)/household | ADB |
| $ex_c$ | Purchase cost of rice cooker, curry cooker and/or water boiler | BTN | BLSS 2012 |
| $m_c$ | Maintenance cost of rice cooker, curry cooker and/or water boiler | BTN/year | BLSS 2012 |
| $n_b$ | Number of school-age boys | boys/household | BLSS 2003, 2007, 2012 |
| $n_g$ | Number of school-age girls | girls/household | BLSS 2003, 2007, 2012 |
| $ex_b$ | Annual school expenditure, boys | BTN/year | BLSS 2007 |
| $ex_g$ | Annual school expenditure, girls | BTN/year | BLSS 2007 |
| $ed_b$ | Increased years of education from grid connection, boys | years of school | Authors' analysis |
| $ed_g$ | Increased years of education from grid connection, girls | years of school | Authors' analysis |
| $Inc$ | Per capita income, rural | BTN/year | BLSS 2012 |
| $\omega_b$ | Returns to schooling, boys | % | Montenegro & Patrinos, 2014 |
| $\omega_g$ | Returns to schooling, girls | % | Montenegro & Patrinos, 2014 |
| $M$ | GDP growth | % | Projected using World Bank GDP data |
| $k_l$ | Reduction in kerosene consumption | liters/household-month | Authors' analysis |
| $k_p$ | Kerosene price | BTN/liter | ADB |
| $k_s$ | Government subsidy of kerosene | BTN/liter | ADB |
| $f_l$ | Reduction in firewood consumption | kg/household-month | Authors' analysis |
| $f_b$ | Wood per backload | kg/backload | Thinley, 2016 |
| $Colt$ | Firewood collection time | hours/backload | BLSS 2003, 2007, 2012 |
| $W$ | Market wage for unskilled labor | BTN/day | Bhutan Ministry of Labor and Human Resources |
| $\kappa_t$ | Shadow value of time | fraction | Jeuland et al. 2017 |
| $c_c$ | Social cost of carbon | $/ton | EPA, 2007 |

## Table B1. Continued. CBA Parameter Definitions and Units

| Parameter | Description | Unit | Data Source |
|---|---|---|---|
| $\boldsymbol{\varepsilon_{CO2,w}}$ | $CO_2$ in trad (wood) | g/MJ fuel | Smith et al. 2000; MacCarty et al. 2010; Bond et al. 2013[19] |
| $\boldsymbol{\varepsilon_{CH4,w}}$ | $CH_4$ in trad (wood) | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{N2O,w}}$ | $N_2O$ in trad (wood) | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{CO,w}}$ | CO in trad (wood) | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{BC,w}}$ | BC in trad (wood) | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{OC,w}}$ | OC in trad (wood) | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{CO2,k}}$ | $CO_2$ in kerosene | g/MJ fuel | Lam et al. 2012; Fan and Zhang 2001; Smith et al. 2000; MacCarty et al. 2010; Jeuland et al. 2017 |
| $\boldsymbol{\varepsilon_{CH4,k}}$ | $CH_4$ in kerosene | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{N2O,k}}$ | $N_2O$ in kerosene | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{CO,k}}$ | CO in kerosene | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{BC,k}}$ | BC in kerosene | g/MJ fuel | |
| $\boldsymbol{\varepsilon_{OC,k}}$ | OC in kerosene | g/MJ fuel | |
| $GWP_{CH4}$ | Global Warming Potential of $CH_4$ | CO2e/g | Shindell 2015 |
| $GWP_{N2O}$ | Global Warming Potential of $N_2O$ | CO2e/g | |
| $GWP_{CO}$ | Global Warming Potential of CO | CO2e/g | |
| $GWP_{BC}$ | Global Warming Potential of BC | CO2e/g | |
| $GWP_{CO2}$ | Global Warming Potential of $CO_2$ | CO2e/g | |
| $GWP_{OC}$ | Global Warming Potential of OC | CO2e/g | |
| $\alpha_w$ | Fuel efficiency of traditional woodstoves | MJ useful energy/MJ heat | Smith et al 2000[20] |
| $\alpha_k$ | Fuel efficiency of kerosene appliances | MJ useful energy/MJ heat | Jeuland et al. 2017 |
| $\beta_w$ | Energy conversion factor of wood | MJ/kg | IOR Energy |
| $\beta_k$ | Energy conversion factor of kerosene | MJ/kg | IOR Energy |
| $TV$ | Terminal value, resale value of grid asset | % of per hh connection cost | Authors' assumption |
| $a_f$ | Number of working-age females | females/hh | BLSS 2003, 2007 & 2012 |
| $a_m$ | Number of working-age males | males/hh | BLSS 2003, 2007 & 2012 |
| $Em$ | Effect of electrification on non-subsistence employment | | Authors' analysis |
| $Na$ | Share of rural income that is non-agricultural | % | BLSS 2012 |

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[19] As cited in Jeuland et al. (2017).

[20] As cited in Jeuland et al. (2017).

## Table B2. Equations to Determine Costs and Benefits

| Equations | | Eq. No. |
|---|---|---|
| Social Costs | | |
| Grid connection, O&M | $grid = ge - \frac{TV * ge}{(1+\delta)^{50}} + \sum_{t=1}^{50} \frac{ge * om * (1 - om_l) + ge * om * om_l * (1+\mu)^t}{(1+\delta)^t}$ | C1 |
| Generation | $gen = \sum_{t=1}^{44} \frac{e * \left(1 + e_g\right)^{(t-1)} * (c_g - tar)}{(1+\delta)^t * \chi}$ | C2 |
| Land conversion | $land = c_t * b * flc * (1 - \lambda)$ | C3 |
| Household costs | | |
| Electricity costs | $elec = \sum_{t=1}^{50} \frac{e * \left(1 + e_g\right)^{(t-1)} * tar}{(1+\delta)^t * \chi}$ | C4 |
| Appliance costs | $app_1 = \sum_{t=1}^{50} \frac{(ex_l * r) + ex_c}{(1+\delta)^t * \chi}, t \in [1,6,11,16,\ldots,46]$ | C5 |
| | $app_2 = \sum_{t=1}^{50} \frac{(ex_l * r) + m_c}{(1+\delta)^t * \chi}, t \in [2,3,4,5,7,8,9,10,\ldots,47,48,49,50]$ | C6 |
| Education costs | $educ_{cost} = \frac{(n_b * ex_b * ed_b) + (n_g * ex_g * ed_g)}{(1+\delta)^t * \chi}, t = 1$ | C7 |
| Social Benefits | | |
| Fuel savings | $fuel_g = \sum_{t=1}^{50} \frac{k_l * k_s * 12}{(1+\delta)^t * \chi}$ | B8 |
| GHG emission reduction | $carb_w = \sum_{t=1}^{50} \frac{\frac{c_c}{1000000} * GWP_w * (f_l * 12) * \alpha_w * \beta_w}{(1+\delta)^t}$ | B9 |
| | $carb_k = \sum_{t=1}^{50} \frac{\frac{c_c}{1000000} * GWP_k * (k_l * 12) * \alpha_k * \beta_k}{(1+\delta)^t}$ | B10 |
| Other environmental benefits | $env = \sum_{t=1}^{50} \frac{(1-\lambda) * c_t * f_l * 12}{(1+\delta)^t}$ | B11 |
| Private benefits | | |
| Fuel savings | $fuel_{hh} = \sum_{t=1}^{50} \frac{(k_l * 12 * \left(k_p - k_s\right)) + (\frac{f_l * 12}{f_b} * collt * \frac{W + (1+\mu)^t}{8} * \kappa_t)}{(1+\delta)^t * \chi}$ | B12 |
| Returns to education | $educ_{ben} = \sum_{t=1}^{50} \frac{inc * (1+\mu)^t * ((\omega_b * ed_b * n_b) + (\omega_g * ed_g * n_g))}{(1+\delta)^t * \chi}$ | B13 |
| Increased earnings | $emp = \sum_{t=1}^{T} \frac{inc * na * (1+\mu)^t * em * (a_f + a_m)}{(1+\delta)^t * \chi}$ | B14 |

### Table B3. CBA Parameter Ranges and Distributional Assumptions

| Parameter | Unit | Low | Base value | High | Distributional Assumption | Correlations |
|---|---|---|---|---|---|---|
| Grid extension & connection cost | USD/household | 1747.03 | 2414.70 | 3101.68 | Uniform | |
| Grid operation and maintenance cost | % of per household grid expansion & connection cost | 1.0% | 2.5% | 10.0% | Uniform | |
| Share of O&M cost that is labor | $ | 5% | 15% | 40% | Uniform | |
| Social discount rate | None | 1.0% | 3.5% | 6.0% | Uniform | |
| Private discount rate | | 5% | 10% | 15% | Uniform | |
| Electricity consumption | KWh/hh-year | 600 | 780 | 1680 | Uniform | |
| Annual growth rate of electricity consumption | % | 0% | 1% | 3% | Uniform | |
| Economic cost of generation | BTN/KWh | 3.88 | 7.75 | 11.63 | Uniform | |
| Electricity tariff for < 100 KWh/month | BTN/KWh | 0 | 0 | 0.85 | Uniform | |
| Electricity tariff for > 100 KWh/month | BTN/KWh | 0 | 1.82 | 3 | Uniform | |
| Duration of lifeline block | Years | 5 | 15 | 50 | Uniform | GDP growth (-0.5) |
| Cost of tree replacement | US/kg | 0.002 | 0.01 | 0.02 | Uniform | |
| Biomass density | kg/Ha | 79 | 157 | 236 | Uniform | |
| Forest land conversion from grid expansion | Ha/household | 0.212 | 0.240 | 0.288 | Uniform | |
| Percent of biomass consumption that is non-renewable | % | 40% | 56% | 72% | Uniform | |
| Exchange rate (July, 2012) | BTN/USD | | 55.84 | | Fixed | |
| Expenditure on lightbulbs | BTN/room/year | 18 | 36 | 55 | Uniform | Electricity consumption (0.7) |
| Number of rooms | Room(s)/household | 1 | 3 | 4 | Uniform | |
| Purchase cost of rice cooker, curry cooker and/or water boiler | BTN | 1000 | 2000 | 3000 | Uniform | |
| Maintenance cost of rice cooker, curry cooker and/or water boiler | BTN/year | 0 | 234 | 351 | Uniform | |
| Number of school-age boys | boys/household | 0.00 | 0.66 | 2.00 | Uniform | -0.8 |
| Number of school-age girls | girls/household | 0.00 | 0.66 | 2.00 | Uniform | |

## Table B3. Continued. CBA Parameter Ranges and Distributional Assumptions

| Parameter | Unit | Low | Base value | High | Dist. Assump. | Correlations |
|---|---|---|---|---|---|---|
| Annual school expenditure, boys | BTN/year | 1461 | 2922 | 4383 | Uniform | 0.8 |
| Annual school expenditure, girls | BTN/year | 1315 | 2630 | 3945 | Uniform | |
| Increased years of education from grid connection, boys | years of school | 0.27 | 0.60 | 0.93 | Uniform | 0.7 |
| Increased years of education from grid connection, girls | years of school | 0.54 | 0.91 | 1.28 | Uniform | |
| Per capita income, rural | BTN/year | | 27824 | | Fixed | |
| Returns to schooling, boys | | 2.8% | 4.7% | 9.6% | Uniform | 0.7 |
| Returns to schooling, girls | | 1.8% | 4.8% | 6.4% | Uniform | |
| GDP growth | | 0% | 5% | 10% | Uniform | |
| Reduction in kerosene consumption | liters/household-month | 4.90 | 7.02 | 9.14 | Uniform | Elec consump. (0.8) |
| Kerosene price | BTN/liter | | 53 | | Fixed | |
| Government subsidy of kerosene | BTN/liter | | 41 | | Fixed | |
| Reduction in firewood consumption | kg/household-month | 80 | 120 | 170 | Uniform | Elec consump. (0.8) |
| Wood per backload | kg/backload | 20 | 30 | 40 | Uniform | |
| Firewood collection time | hours/backload | 0.50 | 1.25 | 6.00 | Uniform | |
| Market wage for unskilled labor | BTN/day | | 111 | | Fixed | |
| Shadow value of time | fraction | 0.08 | 0.30 | 0.62 | Uniform | |
| Social cost of carbon | USD/ton | $106.14*e^{(-97.75*\delta s)}$ | $202.36*e^{(-68.06*\delta s)}$ | $939.92*e^{(-62.6*\delta s)}$ | Triangular | |
| $CO_2$ in trad (wood) | g/MJ fuel | 450 | 510 | 570 | Uniform | |
| $CH_4$ in trad (wood) | g/MJ fuel | 0.6 | 2.05 | 3.5 | Uniform | |
| $N_2O$ in trad (wood) | g/MJ fuel | 0.03 | 0.315 | 0.6 | Uniform | |
| CO in trad (wood) | g/MJ fuel | 13 | 25 | 37 | Uniform | |
| BC in trad (wood) | g/MJ fuel | 0.28 | 0.3 | 0.32 | Uniform | |
| OC in trad (wood) | g/MJ fuel | 0.25 | 0.675 | 1.1 | Uniform | |
| $CO_2$ in kerosene | g/MJ fuel | 140 | 151 | 162 | Uniform | |
| $CH_4$ in kerosene | g/MJ fuel | 0.001 | 0.027 | 0.053 | Uniform | |
| $N_2O$ in kerosene | g/MJ fuel | 0.032 | 0.055 | 0.078 | Uniform | |
| CO in kerosene | g/MJ fuel | 0.38 | 1.74 | 3.1 | Uniform | |
| BC in kerosene | g/MJ fuel | 0.007 | 0.0115 | 0.016 | Uniform | |

## Table B3. Continued. CBA Parameter Ranges and Distributional Assumptions

| Parameter | Unit | Low | Base value | High | Distributional Assumption | Correlations |
|---|---|---|---|---|---|---|
| OC in kerosene | g/MJ fuel | 0.003 | 0.006 | 0.009 | Uniform | |
| Global Warming Potential of $CH_4$ | CO2e/g | | 66.6 | | Varies with social discount rate | |
| Global Warming Potential of $N_2O$ | CO2e/g | | 266.3 | | | |
| Global Warming Potential of CO | CO2e/g | | 19.26 | | | |
| Global Warming Potential of BC | CO2e/g | | 2225.9 | | | |
| Global Warming Potential of $CO_2$ | CO2e/g | | 1.00 | | | |
| Global Warming Potential of OC | CO2e/g | | -306.9 | | | |
| Fuel efficiency of traditional woodstoves | MJ useful energy/MJ heat | 7% | 14% | 21% | Uniform | |
| Fuel efficiency of kerosene appliances | MJ useful energy/MJ heat | 44% | 47% | 50% | Uniform | |
| Energy conversion factor of wood | MJ/kg | | 16 | | Fixed | |
| Energy conversion factor of kerosene | MJ/kg | | 30 | | Fixed | |
| Terminal value, resale value of grid asset | % of per hh connection cost | 0.3 | 0.6 | 0.9 | Uniform | |
| Working-age women per household | women/hh | 0 | 1.6 | 3 | Uniform | -0.8 |
| Working-age men per household | men/hh | 0 | 1.5 | 3 | Uniform | |
| Effect of electricity on non-subsistence employment status | | 0 | 0.03 | 0.05 | Uniform | |
| Share of rural income that is non-agricultural | % | 50% | 76% | 100% | Uniform | |

## Appendix C: Impact Assessment Methods

This Appendix provides a more detailed discussion of our two impact estimation methods: regression and propensity score matching. We first assess the non-randomness of grid roll out and household connection by analyzing the determinants of grid connection status. We then use these identified determinants to conduct our impact analyses.

*Determinants of Grid Electrification*

In the first stage of the impact analysis, we assess the non-randomness of grid connection status by identifying the community and household-level drivers of grid extension. We estimate the following equation (also equation 1 in the main text):

$$E_{hj} = \beta^{e}{}_{0} + \beta^{e}{}_{1}X_{hj} + \beta^{e}{}_{2}Z_{j} + \gamma^{e}{}_{t} + \delta^{e}{}_{d} + \gamma^{e}{}_{t}\delta^{e}{}_{d} + \varepsilon^{e}{}_{hj} \qquad \text{(C1)}$$

The results of this estimation confirm what is illustrated in Table A3. Table C1 presents the results of estimating equation C1. We find that many of the differences between grid and non-grid connected households are drivers of grid electrification. At the community-level, cost is a major driver of electrification. Communities closer to an existing road and closer to a district headquarters, assumed to be more densely populated, have a lower cost of grid electrification per household, both in terms of infrastructure construction and transmission of power (Barnes 2007). Wealth is also a major driver of electrification, as households whose dwellings are constructed from brick and whose head is employed in a personal business or wage-earning activity are more likely to connect to the grid.[21] Households that already have adopted environmental health and infrastructure technology, such as improved water sources, are also more likely to connect.

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[21] "The use of cement-bonded bricks…for exterior walls increases with per capita household consumption quintile" (NSB and ADB 2013, 50).

## Table C1. Determinants of Household Grid Connection Status

| | Grid connection (1=yes) | | |
|---|---|---|---|
| | (1) | (2) | (3) |
| Improved water source (1=yes) | 0.090*** | 0.090*** | 0.138*** |
| | (0.011) | (0.019) | (0.021) |
| Household head can read & write in Dzongkha (1=yes) | 0.055*** | 0.055*** | 0.078*** |
| | (0.008) | (0.011) | (0.013) |
| Employment status of household head (1=employed outside of subsistence ag) | 0.039*** | 0.039*** | 0.066*** |
| | (0.008) | (0.010) | (0.009) |
| Gender of household head (1=male; 2=female) | 0.027*** | 0.027** | 0.059*** |
| | (0.008) | (0.012) | (0.015) |
| Age of household head | 0.000* | 0.000 | 0.001*** |
| | (0.000) | (0.000) | (0.000) |
| Marital status of household head (1=married) | 0.016* | 0.016 | 0.027** |
| | (0.008) | (0.010) | (0.018) |
| Own chickens (1=yes) | -0.040*** | -0.040*** | -0.063*** |
| | (0.007) | (0.014) | (0.018) |
| Brick is main household construction material (1=yes) | 0.064*** | 0.064*** | 0.081*** |
| | (0.007) | (0.013) | (0.014) |
| Log travel time to Dzongkhag HQ, in hours[22] | -0.110*** | -0.110*** | |
| | (0.006) | (0.028) | |
| Log travel time to nearest tarred road, in hours | -0.056*** | -0.056*** | |
| | (0.004) | (0.019) | |
| Time trend | 0.019*** | 0.019*** | 0.014*** |
| | (0.004) | (0.001) | (0.014) |
| District indicators | Yes | Yes | Yes |
| District/time interaction terms | Yes | Yes | Yes |
| Constant | -0.607*** | -0.607 | -0.693*** |
| | (0.003) | - | (0.000) |
| Observations | 12,877 | 12,877 | 11,285 |
| Pseudo R-squared | 0.416 | 0.416 | 0.235 |

Values reported are average partial effects.

Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1.

Standard errors in columns 2 and 3 clustered at the district level.

The findings are similar to other studies that have identified drivers of household energy transitions. A recent systematic review of the drivers of improved cookstove adoption finds that adoption is positively related to education and income (Lewis and Pattanayak 2012). A study of grid electrification in Bangladesh similarly finds that

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[22] Community characteristics were tested at the household level, as data is not available regarding the communities to which the grid has been extended. These variables were defined at the gewog-year level, of which there were 474 (86 from 2003, 200 from 2007 and 188 from 2012). Gewog, or village block, is the second largest administrative district in Bhutan, below Dzongkhag. There are around 200 gewogs in the country.

houses made of brick are more likely to be electrified (Khandker et al. 2012). A study of electrification in Vietnam finds that, while the most densely populated and economically developed communities were targeted for grid connection, household-level characteristics played little role in grid connection status. Only the education level of the adult male in the household is a significant determinant. This is due to the fact that, once a community is targeted for grid electrification, all households are likely to connect (Khandker et al. 2009a).

*Regression Analysis*

After identifying the drivers of grid electrification, two methods are used to estimate the impacts on the four outcomes identified above. The first comprises linear and non-linear regression methodologies, controlling for the household- and community-level drivers identified. The outcomes of interest are modeled as a function of grid electrification as well as the drivers identified above, district and year characteristics, and, in the case of individual-level outcomes, individual characteristics. The following equation is estimated (it is also equation 2 in the main text):

$$y_{ihj} = \beta_0 + \beta_1 E_{hj} + \beta_2 X_{hj} + \beta_3 Z_j + \beta_4 V_{ijh} + \gamma_t + \delta_d + \gamma_t \delta_d + \varepsilon_{ihj} \qquad \text{(C2)}$$

*Propensity Score Matching*

As an additional estimate as well as a robustness check, we apply propensity score matching techniques, which is an increasingly popular approach in practical evaluations of development and environment outcomes (Pattanayak 2009). In applying this technique, we first calculate a household's probability of treatment, i.e., connection to the grid, conditional on a set of household and community characteristics. The propensity score for each household is the probability of treatment estimated from equation C1. The covariate balance of the matched sample, post-nearest neighboring matching, is presented in Table C2.

Grid connected households are then matched with non-connected households based on this propensity score, using either the nearest neighbor with replacement or kernel density matching[23] techniques to reduce the difference in propensity score between matched treatment and control households (Rosenbaum and Rubin 1985).[24] In applying nearest neighbor matching, we match each treated unit to the nearest control unit; we match only one unit to minimize bias. This matched subsample generates treatment and control groups that are similar on characteristics known to be driving grid electrification. Propensity score matching techniques are beneficial in that they do not restrict the relationship between outcomes and covariates to a pre-defined functional form. Additionally, matching based on the propensity score reduces the parameters in the final estimation equation, increasing the efficiency of the estimates. We then use this matched sample to estimate the effect of electrification, controlling for characteristics such as age and gender in the case of individual-level outcomes.

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[23] In applying kernel density matching, we rely on the epanechnikov kernel (the default in Stata's -psmatch2- program), setting the bin width to 0.1 (Leuven and Sianesi 2003; Heckman, Ichimura, Smith, and Todd 1998a; Heckman, Ichimura, and Todd 1998b).

[24] Matching based on the propensity score distance, as opposed to the Mahalanobis distance, was found to perform better in cases when more than 5 covariates are considered (Gu and Rosenbaum 1993; Rubin and Thomas 2000).

## Table C2. Post-nearest Neighbor Matching Covariate Balance

| Variable | Mean |  | Difference | % reduction in bias from unmatched sample |
|---|---|---|---|---|
|  | Treatment | Control |  |  |
| Household characteristics |  |  |  |  |
| Household size | 5.018 | 5.170 | -0.152*** | 57.6% |
| Gender of household head (1=male; 2=female) | 1.366 | 1.399 | -0.033*** | 51.3% |
| Age of household head | 48.95 | 49.06 | -0.590 | 82.4% |
| Marital status of household head (1=married) | 0.786 | 0.775 | 0.011 | -94.5% |
| Household head can read & write in Dzongkha (1=yes) | 0.294 | 0.227 | 0.067*** | 41.6% |
| Acres of land owned | 2.769 | 2.440 | 0.329*** | 30.2% |
| Brick is main household construction material (1=yes) | 0.686 | 0.684 | 0.002 | 97.5% |
| Improved water source (1=yes) | 0.945 | 0.933 | 0.012** | 91.1% |
| Own chickens (1=yes) | 0.448 | 0.477 | -0.029*** | 86.2% |
| Community Characteristics |  |  |  |  |
| Travel time to Dzongkhag HQ, in hours | 3.198 | 3.114 | 0.084 | 98.4% |
| Travel time to nearest tarred road, in hours | 1.784 | 1.415 | 0.369*** | 92.4% |

Stars indicate significance level of t-test of difference in means; *** p<0.01, ** p<0.05, * p<0.1.