WPS7349

Policy Research Working Paper 7349

# Biogas: Clean Energy Access with Low-Cost Mitigation of Climate Change

*E. Somanathan*
*Randall Bluffstone*

WORLD BANK GROUP
Development Research Group
Environment and Energy Team
June 2015

Policy Research Working Paper 7349

## Abstract

With data from the nearly 6,000 households in the Nepal Living Standards Survey of 2010–11, this paper finds that the mean reduction in household firewood collection associated with use of a biogas plant for cooking is about 1,100 kilograms per year from a mean of about 2,400 kilograms per year. This estimate is derived by comparing only households with and without biogas in the same village, thus effectively removing the influence of many potential confounders. Further controls for important determinants of firewood collection, such as household size, per capita consumption expenditure, cattle ownership, and unemployment are used to identify the effect of biogas adoption on firewood collection. Bounds on omitted variable bias are derived with the proportional selection assumption. The central estimate is much smaller than those in the previous literature, but is still large enough for the cost of adopting biogas to be significantly reduced via carbon offsets at a modest carbon price of $10 per ton of CO2e when using central estimates of emission factors and global warming potentials of pollutants taken from the scientific literature.

This paper is a product of the Environment and Energy Team, Development Research Group. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The lead author may be contacted at som@isid.ac.in.

# Biogas: Clean Energy Access with Low-Cost Mitigation of Climate Change

E. Somanathan[1] and Randall Bluffstone[2]

Keywords: climate change. fuelwood. biogas. carbon credits.

JEL Classifications: *D12, O13, Q41, Q54, Q56*

[1] Economics and Planning Unit, Indian Statistical Institute, 7 SJS Sansanwal Marg, New Delhi 110016, India. E-mail: som@isid.ac.in

[2] Department of Economics, Portland State University, Portland OR, USA.

**Biogas: Clean Energy Access with Low-Cost Mitigation of Climate Change**[1]

## 1. Introduction

Household air pollution from solid fuels is estimated to have killed 3.5 million people in 2010. It constitutes the fourth largest risk factor for the global burden of disease, and the largest risk factor for the disease burden in South Asia (Lim et al. 2012). Pollutants from wood-burning stoves commonly used for cooking in low- and middle-income countries also contribute to global warming via the release of carbon dioxide from non-sustainably harvested wood, *and* via the release of other pollutants, principally black carbon, carbon monoxide, and methane, even if the wood is sustainably harvested (Grieshop, Marshall, and Kandlikar 2011).

Although energy access varies widely across developing countries around the world, it is much lower in low-income developing countries than middle-income developing countries (UNDP and WHO, 2009). It is well documented that improving access to low-polluting and reliable forms of energy services is essential to reduce poverty and promote economic growth (Leach, 1992; UNDP, 2005; WHO, 2006; UNDP and WHO, 2009; UNIDO, 2009; Barnes et al., 2011; Ekouevi and Tuntivate, 2012).

As of 2010, about 1.3 billion people did not have access to electricity and 2.6 billion people relied on traditional biomass for cooking, mainly in rural areas of developing countries (MacCarty, 2008; Jeuland and Pattanayak, 2012). Most of the biomass used is firewood and most is harvested from common rather than private forests (Cooke, Kohlin, and Hyde 2008); Bluffstone et al., 2013).

Concurrently with this heavy reliance on fuelwood for cooking and other household needs in developing countries, climate change has emerged as a major environmental threat. The UN Collaborative Programme on Reducing Emissions from Deforestation and Degradation in Developing (REDD+) is a still-evolving

[1] Financial support for this research was provided by the World Bank through the Knowledge for Change Program. We thank Mike Toman and seminar participants at the REDD workshops in Dhulikhel and Kathmandu for comments, Animesh Kumar for research assistance, and Milind Kandlikar and Chandra Venkataraman for pointers to the scientific literature.

program envisioned to provide incentives to non-Annex 1 countries like Nepal to reduce deforestation and forest degradation. The associated reductions in greenhouse gas emissions represent potentially important climate change contributions, because deforestation and forest degradation account for between 12% and 20% of annual GHG emissions (Saatchi et al., 2011; van der Werf, 2009). UNEP (2012) estimates a smaller, though still significant, share at 11%. In the 1990s, largely from the developing world, forests released about 5.8 Gt per year, which was more than all forms of transport combined (Saatchi et al., 2011).

Because monitoring and verification of carbon sequestration can be a real challenge anywhere, but particularly in developing countries, there is interest in input-based compliance measures for which GHG impacts can be reliably estimated. Such a strategy can be an attractive way to credit offsets, because it may not involve measuring and monitoring actual carbon sequestration in forests. Promoting adoption of more sustainable fuels like biogas to replace harmful and unsustainable biomass fuels could be one part of an input-based climate change mitigation policy. If it is known, for example, that a particular technology reduces fuelwood use, all that has to be monitored is whether the subsidy to biogas from carbon finance actually reaches households and if biogas plants are installed and used.

REDD+ may be one policy mechanism to incentivize such shifts if adoption of biogas indeed results in less fuelwood use that is creditable in international carbon markets. The purpose of this paper is to examine the potential for financing a switch from wood and other solid fuels to biogas using carbon offset markets. This could open up a much larger source of finance than the limited resources currently flowing into this sector from aid programs. The major contribution of this paper is to use a nationally representative survey of households in Nepal to estimate the reduction in firewood use that can be expected when a household acquires a biogas plant and draw conclusions regarding financing and climate change mitigation.

## 2. Literature Estimating the Effects of Fuel Switching on Biomass Fuel Use

The conversion of fuel into cooking energy depends on the cookstove used. These different types of cookstoves are typically associated with specific types of energy. For example, three stone traditional, unimproved enclosed stove, simple non-traditional (e.g., clay pot-style or simple ceramic liners), chimney, rocket, charcoal and gasifier stoves all use solid fuels that are common in rural areas of developing countries. In recent years, biogas cookstoves are also gaining popularity in rural areas of developing countries.

The conversion efficiency[2] of household cookstoves varies widely by energy source and depends on a variety of site-specific circumstances. Cooking fuels also differ in their energy densities. Modern fuels have high energy content per kg of fuel, while traditional biomass fuels have low energy content. The use of biomass energy in inefficient or open stoves is considered a traditional way of cooking. Biogas stoves, particularly from a greenhouse gas perspective, are some of the most climate-friendly cooking technologies available (Smith et al., 2000).[3]

Reductions in fuelwood use due to adoption of new energy technologies and fuels have been quantified in two ways in previous studies. One approach that has been used is to estimate annual firewood use (AFU) as AFU = AEC/(thermal efficiency) x (energy content of a kg of firewood), where AEC denotes annual energy consumption in millions of Joules, and thermal efficiency is the fraction of energy in the fuel that is actually delivered to the pot and so goes into the cooking of food (Grieshop et al., 2011; (Johnson et al. 2008); Zhang et al., 2000). Such methods can usefully synthesize a large amount of information from the literature (e.g. Jeuland and Pattanayak, 2012).

To infer the reduction in firewood use that would accrue from a switch to an alternative fuel and technology like biogas, it is sometimes assumed that the entire consumption of firewood for cooking is replaced by biogas. However, it is well

---

[2] Meaning the percentage of energy in the fuel that is transferred to the food being cooked. See below.
[3] Such conclusions generally do not consider the animal raising decision. Households are typically assumed to have the same number of large dung-producing animals with or without adopting biogas. Biogas plants then allow the dung from those animals to be used.

known that rural households in low- and middle-income countries that cook with biogas or other non-biomass fuels often also continue to use firewood (Arnold et al., 2006; Cooke et al, 2008).[4] Thus, this method is sure to over-estimate the actual reduction in firewood use from adoption of an alternative fuel/cooking technology package.

The second method used in the literature is direct, relying on surveys of households that have started to use a technology and asking them how much they reduced their firewood consumption (Katuwal and Bohara (2009); Masera et al., 2007; Thakuri, 2009). A particularly relevant paper is Christiansen and Heltberg (2014), who evaluate a large biogas program in China using survey data. Though the results are not fully conclusive due to the nature of their data, they find strong indications that users are satisfied with the technology and that biogas adoption reduces firewood use and collection time. We use a different direct method in Section 3 of this paper, relying on comparisons between adopter and non-adopter households, which do not rely on respondents' ability to recall past use.

In Section 4, we go on to calculate the greenhouse gas implications of those reductions using emission factors for various pollutants emitted from traditional wood stoves and 100-year Global Warming Potentials from the scientific literature. This allows us to map firewood reductions into carbon market offsets to which households adopting biogas might be entitled. With this information and the offset price of $CO_2e$ emissions reductions, we can evaluate to what extent carbon offsets could subsidize biogas in Nepal and similarly situated countries.

## 3. The Effect of Biogas Adoption on Firewood Consumption

To estimate the effect of biogas adoption on firewood use, we use data from the third round of the Nepal Living Standards Survey (NLSS-III), which is managed by the Central Bureau of Statistics of the Government of Nepal (GON) and sponsored by the World Bank and GON. NLSS-III is a nationally representative survey of 5,988

[4] For empirical support of such "fuel stacking" behavior, see Heltberg, 2004; 2005; Leach (1992), Davis (1998) and Campbell et al. (2003).

households in 499 wards conducted in 2010. About two-thirds of the households sampled are rural. The data show that in 2010-11 only 3% of households in Nepal used biogas as their primary cooking fuel (see Table 1). However, cow dung is the principal feedstock for biogas plants and 50% of all Nepali households own at least two cows or buffaloes, so the potential reach of biogas is large.

Table 1: Primary Cooking Fuel in Nepal in 2010-11

| Main cooking fuel | Percent of households |
|---|---:|
| Firewood | 62 |
| Cylinder gas | 23 |
| Dung | 8 |
| Biogas | 3 |
| Leaves, straw, etc | 3 |
| Kerosene | 1 |
| Other | 1 |

Note: Percentages do not add to 100 due to rounding. Survey weights used to obtain population fractions.

We follow other studies (Baland et al. 2010)(Nepal, Nepal, and Grimsrud 2011) in using firewood collection, not consumption, as the dependent variable. This is because firewood consumption, although reported by some households, is mostly missing. Furthermore, sales of firewood are rarely reported, so collection is a good proxy for consumption. The NLSS-III data set reports firewood collection in loads of firewood (*bharis* in Nepali).[5] We then convert *bharis* to kilograms as follows. Households were asked how many kilograms a *bhari* of wood contained, but not all firewood-collecting households answered this question. We used the conversion factor reported by households when it was available. This was the case for 3,389 households. We imputed the conversion factor for the remaining 631

[5] A bhari is a load of firewood, the amount one person usually carries on one trip. Very few households collected firewood using carts and the appropriate conversion factor was used in those cases.

households that reported an amount for firewood collection (in *bharis*), by using the average conversion factor reported by other households in that ward. Where even this was missing, we used the average conversion factor in the district. The overall average was 33 kilograms per *bhari*. This conversion factor is important, because it can scale our estimates up or down. Since it is directly reported by 84% of households, it is much more reliable than using an arbitrary estimate.

Before beginning our analysis, we transparently remove outliers by dropping the top 1% of households in terms of firewood collection. The maximum annual firewood collection reported in the sample is 200,000 kg, which falls to 9,000 kg after dropping outliers. Our identification strategy to estimate the effect of biogas adoption on firewood collection relies on a comparison between biogas-using and non-biogas-using households in the *same* ward via the use of ward fixed effects. Thus, differences in the propensity to consume firewood arising out of geographic differences are all but eliminated. These differences are important determinants of collection – for example, villages in the Terai (the lowlands) that are close to extensive forests often have much easier access to firewood, although their firewood demand for purposes of heating is also likely to be lower.

We also control for household-specific characteristics that are likely to influence firewood consumption of households living in the same village. These include household size and its square, annual per capita consumption expenditure in Nepali rupees[6] and its square, hectares of land owned and its square, levels of education of the household head, dummies for ownership of one, two, three, and four or more cows or buffaloes, and the time taken to collect a unit of firewood and its square. Cattle ownership influences firewood consumption, because it is common in Nepal and adjoining parts of India to partially cook grains that are fed to cattle. These activities increase the demand for firewood. Cattle ownership may, however, lower the opportunity cost of firewood collection, because firewood collection can be done while cattle are being grazed in forests. Descriptive statistics are reported in the Appendix.

[6] The exchange rate was approximately 100 Nepali rupees per US dollar at the time of this writing.

Table 2 below reports regressions of firewood collection on dummies for main cooking fuels including biogas and controls. The omitted category for the main cooking fuel is firewood.

Table 2: OLS Models of Reported Annual Firewood Collection (kilograms) in 2010-11, with Ward Fixed Effects

| VARIABLES | Model_1<br>firewd_coll | Model_2<br>firewd_coll | Model_3<br>firewd_coll |
|---|---|---|---|
| Main cooking fuel- Bio-gas | -1,165*** | -1,161*** | -1,062*** |
| | (108.7) | (108.0) | (119.7) |
| Main cooking fuel- dung | -763.3*** | -756.2*** | -449.2*** |
| | (131.3) | (132.3) | (154.8) |
| Main cooking fuel- leaves/straw | -471.6*** | -470.5*** | 270.6 |
| | (168.6) | (168.3) | (234.3) |
| Main cooking fuel- LPG | -1,125*** | -1,111*** | -856.0*** |
| | (108.1) | (107.9) | (159.5) |
| Main cooking fuel- Kerosene | -982.0*** | -989.0*** | 986.2*** |
| | (134.0) | (132.9) | (183.6) |
| Main cooking fuel- other | -818.3*** | -850.3*** | -216.5 |
| | (188.3) | (185.0) | (458.0) |
| Household size | 151.6*** | 155.9*** | 241.3*** |
| | (28.39) | (28.37) | (38.86) |
| Hh size squared | -2.916 | -2.788 | -5.344* |
| | (2.300) | (2.260) | (2.872) |
| Annual per capita household consumption | 0.00306*** | 0.00307*** | 0.0108*** |
| | (0.00112) | (0.00113) | (0.00319) |
| Per capita consumption squared | -5.85e-09** | -5.84e-09** | -2.66e-08* |
| | (2.62e-09) | (2.64e-09) | (1.60e-08) |
| Household head less than 5 yrs education | 49.49 | 46.67 | 36.96 |
| | (55.38) | (55.58) | (68.30) |
| Household head completed 5-7 yrs education | 46.39 | 43.23 | 39.15 |
| | (63.19) | (63.10) | (79.66) |
| Household head completed 8-10 yrs education | 68.65 | 70.92 | 93.69 |
| | (70.00) | (69.95) | (104.0) |
| Household head completed 11+ yrs education | 8.237 | 7.897 | -53.69 |
| | (52.40) | (52.29) | (96.86) |
| Total area of land owned (ha) | 76.51* | 76.40* | 109.7* |
| | (44.76) | (44.83) | (61.77) |
| Land owned squared | -5.112** | -4.755** | -11.48*** |
| | (2.275) | (2.281) | (3.507) |
| Household with one cow/buffalo | 89.28 | 80.98 | -9.687 |

| | | | |
|---|---|---|---|
| | (70.14) | (70.15) | (76.40) |
| Household with two cows/buffaloes | 218.6*** | 208.5*** | 126.4 |
| | (71.25) | (71.43) | (77.51) |
| Household with three cows/buffaloes | 270.8*** | 257.6*** | 166.4* |
| | (83.94) | (83.95) | (90.42) |
| Household with four or more cows/buffaloes | 472.0*** | 457.8*** | 307.7*** |
| | (80.64) | (80.54) | (87.85) |
| Number of unemployed men (15-60 yrs) in a household | | -1.119 | 61.70 |
| | | (54.58) | (118.0) |
| Number of unemployed women (15-60 yrs) in a household | | -134.4*** | -75.91 |
| | | (36.07) | (101.8) |
| Minutes taken to collect a kg of firewood | | | 767.4*** |
| | | | (187.7) |
| Minutes to collect a kg of firewd squared | | | -531.3*** |
| | | | (130.0) |
| Constant | 994.6*** | 997.0*** | 760.5*** |
| | (98.77) | (97.88) | (160.9) |
| Observations | 4,750 | 4,750 | 3,329 |
| R-squared | 0.115 | 0.117 | 0.112 |
| Number of wards | 497 | 497 | 404 |

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

Table 2 shows the results of regressions of annual firewood collections in kilograms by households on the independent variables mentioned above. We find that households whose main cooking fuel is reported to be biogas on average collect about 1,060 to 1,160 fewer kilograms of firewood annually than households that use firewood as their main fuel, a reduction of somewhat less than 50%.[7] We emphasize, therefore, that biogas does not eliminate firewood collection, but it does reduce it substantially.[8]

However, this reduction may be an over-estimate of the impact of biogas adoption. Households who have a high opportunity cost of firewood collection (after

[7] Mean firewood collection for households whose primary source of cooking fuel is firewood is about 2400 kg/year.

[8] We performed a similar exercise using the second round of the NLSS from 2003-04. At that time, about 1.7% of Nepali households used biogas as their main source of cooking fuel. Only about one-sixth of the households are common to the samples in the second and third rounds, so they are largely independent samples. The estimated reduction in firewood use associated with biogas is between 1240 and 1290 kg/year in 2003.

removing the influence of the controls) are likely to adjust their firewood consumption downwards, and are also likely to have adopted biogas more frequently than other households. We have controlled for some correlates of these opportunity costs using measures of education, unemployment, and firewood collection time, but these may be inadequate.

On the other hand, it is also the case that high demand for firewood arising from shocks to household utility functions would result in high firewood collection,[9] more labor allocated to this purpose, and, therefore, a high demand for and greater adoption of biogas to relieve the pressure on household labor supply. This would lead to our regressions under-estimating the reduction of firewood collection due to biogas.

We use the method proposed by (Altonji, Elder, and Taber 2005), (Krauth 2011), and (Oster 2013) to bound the bias in our estimate of the impact of biogas on firewood consumption. The idea is the following. Suppose $v$ is an omitted variable in our regression model that is correlated with biogas adoption, is orthogonal to all the controls (the other right-hand-side variables), and whose marginal effect on firewood collection is 1. The latter two assumptions may be made without loss of generality by simply defining $v$ and choosing its units appropriately. The operational assumption that we now make is that the magnitude of the correlation of $v$ with biogas does not exceed the magnitude of the correlation of $xb$ with biogas, where $x$ is the vector of controls in our regression above and $b$ the associated coefficient parameter vector (Krauth 2011).

We note that if $v$ is uncorrelated with biogas, then the bias will be zero, and as the magnitude of the correlation of $v$ with biogas increases, so does the magnitude of the bias. Our assumption that the correlation of $v$ with biogas is no more than the correlation of $xb$ with biogas allows us to bound the bias. Using Oster's (2013) Stata code, we find that the bound on the bias ranges from 375 kg/year in Model 1 to 412 kg/year in Model 3. This gives us a lower bound for the reduction of firewood due to biogas of 650 kg/year.

[9] For example, the presence of a sick person who needs more firewood for heating.

We note that the true estimate is unlikely to be close to this bound for two reasons. First, the set of controls that include village fixed effects is quite comprehensive so that omitted variables are unlikely to be just as well correlated with biogas as the controls. Second, the bound is reached under the assumption that *all* the variance in firewood collection is explained by the explanatory variables once $v$ is included (Oster 2013). This is also very unlikely. We conclude that the true effect is likely to be closer to the estimate than to either the upper or lower bound.

We therefore proceed to the next stage of the analysis by using a reduction of 1,000 kg/year as a best guess of the true effect of biogas adoption.[10] Since all subsequent calculations are linear in this quantity, it is easy to examine how they will change under alternative estimates. Before proceeding to the next stage we report a comparison with the existing literature.

Our estimates are much lower than the estimate of 3,000 kg/household/year obtained from a survey of 461 biogas users in 15 of the 75 districts in Nepal in 2007-2008. The survey was conducted by a consulting firm for the Alternative Energy Promotion Center of the Government of Nepal and this result is reported in Katuwal and Bohara (2009). The AEPC survey also gave estimates for consumption of firewood both before and after biogas adoption that are roughly twice the estimates we obtain from the much larger nationally representative NLSS-III.

The reasons for these differences are not clear, but could be in part due to the assumption of Katuwal and Bohara (2009) of a larger conversion factor of 40 kg/bhari than the average in the NLSS of 33 kg/bhari. However, to reconcile the estimates, it would have to be true that the correct conversion factor in the AEPC survey would be as low as 20 kg/bhari, which seems very low and highly unlikely.[11] It appears that the survey may not have been representative of Nepal.

---

[10] We discuss in the next section the adjustments to our estimate that would be necessary when we take into account the possibilities that (a) some biogas users would substitute biogas for cylinder gas rather than firewood, and (b) some new adopters of biogas may be induced to hold more cattle than they would have done if there were no increase in the biogas subsidy.

[11] Baland et al (2010) use a conversion factor of 35 kg/bhari for the 2003 round of the NLSS.

## 4. The Effect of Firewood Consumption Reduction on CO2-Equivalent Emissions

To make the link between estimated firewood collection reductions and reduced $CO_2e$ emissions, we use emission factors for each pollutant emitted from traditional wood-fired cookstoves taken from the scientific literature collated by (Pandey et al. 2014) per kg of firewood burned. These are then multiplied by the 100-year Global Warming Potentials (GWPs) for each pollutant to arrive at tonnes of carbon-dioxide equivalent emissions per Kg of wood burned. The results are presented in Table 3 below.

The GWP for CO2 is, by definition equal to 1. However, the CO2 saving from not burning a kg of wood depends on whether the wood is harvested unsustainably (in which case the saving is 100% of the GWP) or sustainably (in which case the saving is zero).[12] While the extent of unsustainable harvesting is unknown, in Nepal, where many forests are still recovering from over-harvesting during the 40 years or so following nationalization in the 1950s, it is plausible that reduction of harvesting of branches for firewood would result in carbon sequestration in increased branch volume. Accordingly, we assume that 50% of the wood is harvested unsustainably and adjust the GWP of CO2 down to 0.5.

Using the best estimate of the reduction in wood consumption per biogas plant of 1,000 kg/year, we arrive at the figures in the fifth column of Table 3. We note that about three-quarters of the annual savings of 1.6 tonnes of CO2e per biogas plant come from the saving from unsustainable harvested wood and reduced emissions of black carbon (BC).

Our estimate of the total saving of CO2e per year is about one-half of that assumed by aid agencies that support Nepal's biogas subsidy program.[13]

[12] Firewood used for cooking is in principle carbon neutral if equivalent trees are replanted or allowed to grow. This is how the term "sustainable" is used in this context.
[13] See http://www.ashden.org/files/BSP%20case%20study%20full.pdf. Accessed January 29, 2015.

Table 3: Emission Factors, 100-Year Global Warming Potentials, and biogas plant values at a carbon price of $10/tCO2e.

| Pollutant | Emission Factor (g of Pollutant/Kg of wood) | 100-year Global Warming Potential (tCO2e) | Tonnes of CO2e saved per Kg of wood | Annual tCO2e saved per biogas plant | Annual value of CO2e/biogas plant (USD) | Discounted value of savings at 2% discount rate over 15-year life in USD. |
|---|---|---|---|---|---|---|
| CO2 | 1358 | 0.5 | 0.000679 | 0.679 | 6.79 | 87.24649917 |
| BC | 0.7 | 900 | 0.00063 | 0.63 | 6.3 | 80.95036005 |
| OC | 1.9 | -46 | -0.0000874 | -0.0874 | -0.874 | -11.2302563 --- |
| SO2 | 0.1 | -76 | -0.0000076 | -0.0076 | -0.076 | 0.976544026 |
| CO | 76 | 1.8 | 0.0001368 | 0.1368 | 1.368 | 17.57779247 |
| NMVOC | 6.9 | 8.8 | 0.00006072 | 0.06072 | 0.6072 | 7.802072798 |
| CH4 | 4.9 | 28 | 0.0001372 | 0.1372 | 1.372 | 17.62918952 |
| N2O | 0.1 | 265 | 0.0000265 | 0.0265 | 0.265 | 3.405054828 |
| **TOTAL** | | | **0.00157522** | **1.57522** | **15.7522** | **202.4041685** |

Sources: Emission factors: (Pandey et al. 2014), Table SI3. Global Warming Potentials: IPCC (2013), Appendix 8.A, except for SO2 which is from Grieshop et al. (2011).
Notes: The GWP for CO2 is adjusted to account for partly sustainable harvesting of wood. Annual wood saving per plant is assumed to be 1000 kg in the 5th column and the carbon price assumed for the 6th column is $10/tCO2e.

Using a carbon price of $10/tCO2e, we get the annual value of savings in USD per biogas plant to be about $16. This carbon price is about 20% lower than the average of $12 per ton $CO_2$e price during 2014 in California. Since the price floor in the quarterly auctions in California in 2014 was $11.34 and is set to rise at 5% plus the inflation rate annually, our assumed $10 price is quite conservative.[14]

A 6-cubic-meter plant (the most commonly installed size) costs about $400 to install and has an expected life of 15-20 years. Assuming a long-term social discount rate of 2% per year, the carbon value of a biogas plant is found in the last column of Table 3 to be $200. Thus, a subsidy greater than 50% could be financed

[14] See http://calcarbondash.org/ and http://www.edf.org/california-cap-and-trade-updates. Accessed January 29, 2015.

from developed country carbon markets with a carbon price greater than \$10/tCO2e that permitted such offsets.

We note that there is considerable scientific uncertainty in all three stages of this calculation. First, of course, the estimate of firewood reduction of 1,000 kg/year may have an error bound of 30-40% when we account for omitted variable bias and sampling error. Second, the rate of unsustainable harvesting is unknown and may be higher or lower than 50%. So also is the emission factor for black carbon, which we assumed was 0.7. The interval estimate is 0.3 to 1.4 (Pandey et al. 2014). Third, the GWP for black carbon is also highly uncertain and the reported interval around the central estimate of 900 is 100-1,700 (Bond et al. 2013).[15] If we use the lower ends of the ranges of emission factors and GWPs and assume all firewood is sustainably harvested, then the value of the carbon saving per biogas plant shrinks to about \$14 (still using our estimate of a 1,000 kg annual reduction in firewood burnt per biogas plant). If we make the opposite assumptions, the value rises to \$615 per plant.

We next consider the possibility that biogas adopters may come not from those whose primary cooking fuel is firewood, but from those whose primary cooking fuel is in one of the other categories. Since not many households rely on other solid fuels (as seen in Table 1), and in any case, the emissions from these are likely to be broadly similar to those from firewood, it is hardly necessary to adjust our estimate to take them into account.

Twenty-three percent of households use cylinder gas (liquefied petroleum gas or LPG), and some of these may switch to biogas if the available subsidy increases. However, nearly one-half of households whose primary cooking fuel is LPG are in urban Kathmandu, which has no biogas adopters at all. Of the remaining LPG users, about 60% are from other urban areas while fewer than 30% of all biogas adopters are from these areas. Thus, it is unlikely that of all new biogas adopters even 10% would otherwise have used LPG. Since biogas and LPG have a very similar energy content and efficiency in cooking, the emissions displaced by biogas when it substitute for LPG are given by the CO2 emissions of LPG. These are

[15] The uncertainty arises largely from uncertainty in aerosol-cloud interactions.

about three times the weight of LPG and consumption of the latter is about 170 kg/year. So emissions saved from a switch to biogas from LPG are about 0.5 tCO2e as compared to 1.6 tCO2e when the switch is from firewood. With fewer than 10% of biogas adopters coming from LPG-using households it follows that our estimate will need to adjusted downward by at most 0.1 tCO2e to 1.5 tCO2e. This is not large enough to make a material difference to our conclusions.

We should also take into account the fact that a few households may be induced to increase their livestock holdings (or to retain livestock they would otherwise have stopped keeping) if the subsidy to biogas were to increase. However, most households that adopt biogas are likely to be those for whom this decision would not affect their livestock holdings. Since the effect of additional livestock on firewood consumption is not very high (Table 2), once again this effect, while reducing the value of emission reductions from biogas plants will not be large enough to make a material difference to our conclusions above.

Since any offset program for biogas stoves will be very small relative to global emissions, we may suppose that its effect will be linear with respect to climate change. Hence, expected utility maximization would suggest that the expected value of the saving should be used. Despite the remaining uncertainty, there is, therefore, a strong case for using the central estimates and designing offset programs to link existing carbon markets with capital subsidies to biogas in Nepal and similarly situated countries.

In sum, we conclude that an offset program for biogas can be a very attractive option for low-cost mitigation of climate change from the point of view of the designers of carbon markets. It can be equally, if not more attractive, for the governments of Nepal and other similarly placed countries as a means of finance for tackling the issues of energy access, pollution, health, and forest degradation.

## 5. Conclusions

In this paper we demonstrate the important positive external effects private adoption of biogas can have in developing countries. International carbon markets and programs like REDD+ can potentially credit the carbon portion of these external effects if adoption reduces emissions of greenhouse gases.

We find that biogas adoption reduces greenhouse gas emissions in rural Nepal. Using a nationally representative household sample, we estimate that adopting biogas reduces household firewood collections, which are primarily used for cooking, by about 1.1 metric tons per year. We use central values from the latest literature on the greenhouse gas content of fuelwood burned in traditional biomass cookstoves in developing countries and find that biogas plants reduce $CO_2e$ emissions on average by 1.6 tons per household per year compared with what would have been emitted had biogas not been adopted. This is considerably lower than the figures being used by the limited existing aid programs for biogas. However, it is still significant. Using a modest carbon price, we conclude that the carbon savings from adoption of a biogas plant are high enough for current international carbon markets to be able to serve as an important source of finance for Nepali villagers who would like to adopt biogas, but do not have the resources.

## References


Altonji, Joseph G., Todd E. Elder, and Christopher R. Taber. 2005. "Selection on Observed and Unobserved Variables: Assessing the Effectiveness of Catholic Schools." *Journal of Political Economy* 113 (1): 151.

Arnold, M., G. Kohlin, R. Presson, and G. Shepherd. 2003. *Fuelwood Revisited: What has changed in the last decade?* Jakarta, Indonesia: Center for International Forestry Research (CIFOR).

Baland, Jean-Marie, Pranab Bardhan, Sanghamitra Das, Dilip Mookherjee, and Rinki Sarkar. 2010. "The Environmental Impact of Poverty: Evidence from Firewood Collection in Rural Nepal." *Economic Development and Cultural Change* 59 (1): 23–61.

Barnes, D. F, S. R. Khandker, and H. A. Samad. 2011. "Energy poverty in rural Bangladesh." *Energy Policy* 39 (2):894-904.

Bluffstone, R., E. Robinson and P. Guthiga. 2013. "REDD+ and community-controlled forests in low-income countries: any hope for a Linkage, *Ecological Economics*. Vol. 87: 43-52.

Bond, Tami C., Sarah J. Doherty, D. W. Fahey, P. M. Forster, T. Berntsen, B. J. DeAngelo, M. G. Flanner, et al. 2013. "Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment." *Journal of Geophysical Research: Atmospheres* 118 (11): 5380–5552.

Campbell, B. M., S. J. Vermeulen, J. J. Mangono, and R. Mabugu. 2003. "The energy transition in action: urban domestic fuel choices in a changing Zimbabwe." *Energy Policy* 31 (6):553-562.

Christiansen, L. and R. Heltberg (2014). "Greening China's rural energy: new insights on the potential of smallholder biogas." *Environment and Development Economics*, 19, pp 8-29. doi:10.1017/S1355770X13000375.

Cooke, Priscilla, Gunnar Kohlin, and William F. Hyde. 2008. "Fuelwood, Forests and Community Management-Evidence from Household Studies." *Environment and Development Economics* 13 (1): 103.

Davis, M. 1998. "Rural household energy consumption: The effects of access to electricity—evidence from South Africa." *Energy Policy* Vol. 26 (3):207-217.

Ekouevi, K., and V. Tuntivate. 2012. *Household Energy Access for Cooking and Heating: Lessons Learned and the Way Forward*, *World Bank Studies*. Washington, D.C.: The World Bank.

Grieshop, Andrew P., Julian D. Marshall, and Milind Kandlikar. 2011. "Health and Climate Benefits of Cookstove Replacement Options." *Energy Policy* 39 (12): 7530–42.

Heltberg, R. 2005. "Factors determining household fuel choice in Guatemala." *Environment and Development Economics* Vol. 10 (3):337-361.

Heltberg, R. 2004. "Fuel switching: evidence from eight developing countries." *Energy Economics* Vol. 26 (5):869-887.

IPCC. 2013. *Climate Change 2013: The Physical Basis Summary for Policymakers*, Working Group 1 Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva

IPCC. 2006. *Good Practice Guidelines for National Greenhouse Gas Inventories.* Switzerland: Intergovernmental panel on climate change.

Jeuland, M.A. and S.K. Pattanayak. 2012. "Benefits and costs of improved cookstoves: Assessing the implications of variability in health, forest and climate impacts." *Plos ONE* 7(2): 1-15.

Johnson, Michael, Rufus Edwards, Claudio Alatorre Frenk, and Omar Masera. 2008. "In-Field Greenhouse Gas Emissions from Cookstoves in Rural Mexican Households." *Atmospheric Environment* 42 (6): 1206–22.

Krauth, Brian. 2011. "Bounding a Linear Causal Effect Using Relative Correlation Restrictions." Simon Fraser University. http://summit.sfu.ca/item/10925.

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

Lim, Stephen S, Theo Vos, Abraham D Flaxman, Goodarz Danaei, Kenji Shibuya, Heather Adair-Rohani, Mohammad A AlMazroa, et al. 2012. "A Comparative

Risk Assessment of Burden of Disease and Injury Attributable to 67 Risk Factors and Risk Factor Clusters in 21 Regions, 1990–2010: A Systematic Analysis for the Global Burden of Disease Study 2010." *The Lancet* 380 (9859): 2224–60. doi:10.1016/S0140-6736(12)61766-8.

MacCarty, N, D. Ogle, D. Still, T. Bond, C. Roden. 2008. "A laboratory Comparison of the global Warming Impact of Five Major Types of Biomass Cooking Stoves," *Energy for Sustainable Development,* Vol. 12: 5-14.

Masera, O., Edwards, R., Arnez, C.A., Berrueta, V., Johnson, M., Bracho, L.R., Riojas-RodrÌguez, H., Smith, K.R. 2007. "Impact of Patsari improved cookstoves on indoor air quality in Michoac·n, Mexico." *Energy for Sustainable Development* Vol. 11: 45 - 56.

Nepal, Mani, Apsara Nepal, and Kristine Grimsrud. 2011. "Unbelievable but Improved Cookstoves Are Not Helpful in Reducing Firewood Demand in Nepal." *Environment and Development Economics* 16 (01): 1–23. doi:10.1017/S1355770X10000409.

Oster, Emily. 2013. *Unobservable Selection and Coefficient Stability: Theory and Validation*. National Bureau of Economic Research. http://www.nber.org/papers/w19054.

Pandey, Apoorva, Pankaj Sadavarte, Anand B. Rao, and Chandra Venkataraman. 2014. "Trends in Multi-Pollutant Emissions from a Technology-Linked Inventory for India: II. Residential, Agricultural and Informal Industry Sectors." *Atmospheric Environment* 99: 341–52.

Saatchi, S, M. Harris, S. Brown, M. Lefsky, E. Mitchard, W. Salas, B. Zutta, W. Buermann, S. Lewis, S. Hagen, S. Petrova, L. White, M. Silman, A. Morel. 2011. "Benchmark Map of Carbon Forest Carbon Stocks in Tropical Regions across Three Continents," *Proceedings of the National Academy of Sciences* vol. 108 (24): 9899-9904.

Smith, K. R., Uma, R., Kishore, V.V.N., Zhang, J., Joshi, V. and Khalil, M.A.K.2000 "Greenhouse Implications of Household Stoves: An Analysis for India." *Annual Review of Energy and the Environment*, 25: 741–63

Thakuri, M. B. M. 2009. "Revising the Need of Improved Stoves: Estimating Health, Time and Carbon Benefits," SANDEE Working Paper No. 44-09. Kathmandu.

UNDP. 2005. *Energizing the Millennium Development Goals: A Guide to Energy's Role in Reducing Poverty*. New York: UNDP.

UNDP and WHO. 2009. *The Energy Access Situation in Developing Countries: A Review Focusing on the Least Developed Countries and Sub-Saharan Africa*. New York: UNDP.

UNEP and WMO. 2011. *Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers*. Nairobi: UNEP and WMO.

UNIDO. 2009. *Scaling up Renewable Energy in Africa*.12th Ordinary Session of Heads of State and Governments of the African Union, Addis Ababa, Ethiopia. Vienna: United Nations Industrial Development Organisation (UNIDO).

van der Werf, G. R.; D. C. Morton; R. S. DeFries; J. G. J. Olivier; P. S. Kasibhatla; R. B. Jackson; G. J. Collatz; and J. T. Randerson. 2009. "$CO_2$ emissions from Forest Loss," *Nature Geoscience* 2: 737 – 738.

WHO. 2006. *Fuel for Life: Household Energy and Health*. Geneva: WHO.

Zhang, J., K. R. Smith, Y. Ma, S. Ye, F. Jiang, W. Qi, P. Liu, M. A. K. Khalil, R. A. Rasmussen, and S. A. Thorneloe. 2000. "Greenhouse Gases and other Airborne Pollutants from Household Stoves in China: a Database for Emission Factors." *Atmospheric Environment* 34 (26):4537-4549.

## Appendix

Table A1: Summary Statistics of NLSS-III household sample

| Variable | Mean | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|
| Annual firewood collection | 1684.051 | 1727.468 | 0 | 8400 |
| Main cooking fuel- Bio-gas | 0.030488 | 0.1719257 | 0 | 1 |
| Main cooking fuel- dung | 0.0789694 | 0.269691 | 0 | 1 |
| Main cooking fuel- leaves/straw | 0.0271572 | 0.1625415 | 0 | 1 |
| Main cooking fuel- LPG | 0.2321461 | 0.4222018 | 0 | 1 |
| Main cooking fuel- Kerosene | 0.0070707 | 0.0837899 | 0 | 1 |
| Main cooking fuel- other | 0.0070228 | 0.0835075 | 0 | 1 |
| Household size | 4.786714 | 2.320337 | 1 | 20 |
| Annual per capita household consumption | 43380.99 | 40352.93 | 4541.014 | 510733.1 |
| Household head less than 5 yrs. education | 0.1409919 | 0.3480132 | 0 | 1 |
| Household head completed 5-7 yrs. education | 0.1254381 | 0.331215 | 0 | 1 |
| Household head completed 8-10 yrs. education | 0.1132296 | 0.3168732 | 0 | 1 |
| Household head completed 11+ yrs. education | 0.1606089 | 0.3671699 | 0 | 1 |
| Land owned in hectares | 0.4865621 | 0.9106142 | 0 | 24.40285 |
| Household with one cow/buffalo | 0.0849691 | 0.2788357 | 0 | 1 |
| Household with two cows/buffaloes | 0.1722511 | 0.3775986 | 0 | 1 |
| Household with three cows/buffaloes | 0.0985999 | 0.2981241 | 0 | 1 |
| Household with four or more cows/buffaloes | 0.224974 | 0.4175652 | 0 | 1 |
| No. of unemployed men | .0711161 | .2797065 | 0 | 3 |
| No. of unemployed women | .1819654 | .4576618 | 0 | 4 |
| Time taken to collect a kg of firewood (minutes) | .1474427 | .3671236 | 0 | 3 |

Note: The 1% of observations with the largest values of firewood collection were dropped. Sampling weights were used to reflect population characteristics.