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Greenhouse Gas Emission Reductions from Domestic Anaerobic Digesters Linked with Sustainable Sanitation in Rural China

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Thesis Committee Chair: Justin V. Remais, Ph.D.

An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
in partial fulfillment of the requirements for the degree of
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Abstract

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By Radhika Dhingra

Anaerobic digesters provide clean, renewable energy (biogas) by converting organic waste to methane, and are a key part of China's comprehensive rural energy plan. Here, experimental and modeling results are used to quantify the net greenhouse gas (GHG) reduction from substituting a household anaerobic digester for traditional energy sources in Sichuan, China. Tunable diode laser absorption spectroscopy and radial plume mapping were used to estimate the mass flux of fugitive methane emissions from active digesters. Using household energy budgets, the net improvement in GHG emissions associated with biogas installation was estimated using global warming commitment (GWC) as a consolidated measure of the warming effects of GHG emissions from cooking. In all scenarios biogas households had lower GWC than non-biogas households, by as much as 54%. Even biogas households with methane leakage exhibited lower GWC than non-biogas households, by as much as 48%. Based only on the averted GHG emissions over 10 years, the monetary value of a biogas installation was conservatively estimated at US$28.30 ($16.07 ton^{-1} CO_2-eq.), which is available to partly offset construction costs. The interaction of biogas installation programs with policies supporting improved stoves, renewable harvesting of biomass, and energy interventions with substantial health co-benefits, are discussed.

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Introduction

Lack of access to clean sources of energy, like biogas, gives rise to a substantial burden of disease in rural agricultural populations [1]. Strategies that improve access to clean and sustainable energy sources create the co-benefits of improved near-term health and mitigated climate change, which ultimately impacts future health outcomes[1]. Implementation of anaerobic digesters, which substitute biogas produced by decaying biomass for traditional fuels, at the rural household level create the unique opportunity to improve health outcomes while simultaneously enhancing the standard of living through improved energy sources. Benefits offered by this technology include reduction of indoor air pollution [2-5], reduction in parasite viability in fecal matter [6, 7], reduction in greenhouse gas (GHG) emissions [8, 9], and provision of an additional energy source in addition to other improvements to quality of life [8].

As combustion of biogas produces primarily carbon dioxide, replacing traditional fuels with biogas would result in substantial reduction in respiratory disease burden. Studies show a well-established relationship between indoor air quality pollutants from combustion of natural fuel (e.g. partially incinerated compounds, carbon monoxide, NOx and particulate matter) and lower respiratory infections, chronic obstructive pulmonary disease and cancers of the respiratory tract [2-5].

As residue of the digester is available for use as fertilizer, ova inactivation as result of holding time in the digester may substantively reduce exposure to fecal pathogens [7]. Proper disposal of human waste reduces disease transmission resulting from the fecal exposure. Twelve months storage has been found sufficient for inactivation of most pathogens [7]. In Sichuan province of China, where feces are commonly used as fertilizer, disruption of Schistosoma japonicum life cycle by holding human waste in a digester has resulted in reduction of viable parasite ova [6].

In addition to these immediate health benefits, several lifestyle improvements that accompany the adoption of a biogas system. Digester residue used as fertilizer may provide some financial benefit to the user, either by enhancing crop yields or by obviating purchase of market fertilizer [8, 10]. Biogas usage reduces the physical effort required of a householder to collect natural fuels such as wood from the environs or coal from the market [8]. These benefits in addition to the improved indoor environment are perceived positively by biogas system adopters [8].

As of 2002, approximately half of the world's population cooked with indoor fuels including more than 75% of China's population [5]. The global warming commitment of traditional cooking fuel combustion in rural China has been estimated an experimentally estimated range of ~25-400 g Carbon per MJ of delivered energy [11]. Using the assumptions described in the following paper, this GWC range corresponds to an upper limit of 0.3 tons Carbon per stove per year.

Rising GHG concentrations have been identified as a distal cause to changes in health outcomes, through a variety of pathways, including food yield, sea-level rise, extreme weather events, flooding and shifting ranges in vector-borne disease [reviewed in 12, 13]. Though forecasting some health risks are inherently more uncertain as a result of both methods of extrapolation into the future as well as a the uncertainty of climate projections, empirical studies have demonstrated seasonal effects of climate on enteric disease, impacts of extreme heat events and disease vector range shifts [13]. Those with cardiovascular disease or chronic respiratory disease, which are disease outcomes linked to the use of traditional indoor fuels, are particularly vulnerable to heat events. Replacing traditional fuels with biogas in the present may thus result in greater adaptive capacity in the face of extreme heat events.

GHG savings have been quantified under ideal circumstances (e.g. fully functional digester without inefficiency of leaking biogas), though such estimates vary widely [e.g. 8, 9]. Water and sanitation studies have frequently shown that interventions frequently fail, suffer from lack of maintenance and fall into disuse [14]. Thus, the assumption that technological improvements work ideally is inadequate in both the investigation of improvements in indoor air quality and the reduction of household greenhouse gas emissions. While rigorous empirical investigation of the emissions of stoves (both improved and non-improved) in combination with various fuels have been conducted [15], no such study thus far has considered the associated GHG savings. Since biogas is largely composed of methane, which has a high global warming commitment, a leaking digester may nullify GHG savings resulting from replacement of traditional fuels. In this collaborative effort, we verified that anaerobic digester implementation does indeed result in GHG savings even in the presence of operational inefficiencies.

My contributions. Members of the Remais research group collected path-integrated methane concentration data from households in three villages in the neighborhood of Chengdu in Sichuan Province, China, in the summer of 2009. I was responsible for carrying out a quantitative leakage estimation by developing a method to reconstruct plumes of methane emitted from each anaerobic digester. I imported the data from field records into Matlab (r2010a) and adapted code provided by our collaborators at the University of Washington and Taiwan University to analyze the collected data. I carried out test simulations using an ideal Guassian plume to verify the accuracy of the reconstruction method implemented in my adapted code, and then applied the method to the field-collected data. Importantly, the circumstances of field data collection in rural China are less than ideal for use of the Remote Methane Leak Detector, as detailed below. Thus, I adapted the plume reconstruction code using a Monte Carlo process described in the Methods section to produce an range of possible values to the amount of methane that might leak from an anaerobic digester. Once the reconstructions were carried out, I extrapolated an upper bound for the amount of methane that might leak in the span of a year from the upper bound of a leakage rate. I then extended the GWP model (described below) first developed by my colleague, Erick Christensen, which demonstrated the GHG savings from biogas use as compared to traditional fuels under ideal circumstances. I verified Mr. Christensen's model results and extended the model to incorporate the leakage determined from field data and investigate uncertainty resulting from the use of various values taken from improve stove literature. I then compared the resulting quantities to assess the relative and absolute GHG emissions benefit of the biogas systems, analyzing these under a number of conservative assumptions. I also briefly quantified the monetary value of the offset carbon emissions, according to present value on the carbon market. As a result of these efforts, a published manuscript [16], written primarily by myself with the help of Prof. Remais and reproduced below, resulted.

Assessing the problem. Improved access to clean fuels for cooking and heating, the most energy intensive activities among the world's poor, has been identified as crucial to attaining UN Millennium Development Goals [17]. In China, more than half the population is rural, most relying on traditional solid fuels, such as coal, wood, and crop residues for household cooking [18]. Indoor air pollution from burning these fuels is currently the largest environmental health risk factor in China, leading to an estimated 420,000 premature deaths per year [18]. Moreover, typical stoves poorly combust these fuels, emitting greenhouse gases (GHG) with broad public health consequences [19, 20]. In addressing rural energy needs, China has implemented one of the most successful improved stove dissemination programs in the world [21]. Yet while improved stoves have greater fuel efficiency, they have also been shown to have higher emissions of incomplete combustion products, with consequences for both public health and climate [22].

A move towards clean energy technologies for the rural population in China could reduce GHG emissions associated with non-renewable coal and incomplete combustion of solid fuels, while simultaneously easing the burden of disease associated with exposure to indoor air pollution [19]. A key technology which may permit a switch from solid fuels to cleaner gaseous fuels in rural China is anaerobic digestion, where organic human and animal wastes are digested under anaerobic conditions generating biogas, composed primarily of methane (CH_4), which can be sequestered and burned for cooking, heating and lighting [6]. Through multiple programs, China is rapidly investing in biogas infrastructure, with a national target of 27 million systems installed in 2010, up from 9.8 million households in 2000 [23, 24]. Because these systems also provide basic sanitation services [6], their widespread installation has the potential to simultaneously achieve multiple energy and public health goals by improving rural sanitation and respiratory health while providing a low-cost, renewable rural energy supply and mitigating GHG emissions [6].

When fuel from biogas systems directly replaces non-renewable sources such as coal, there is a clear GHG benefit of their adoption [9]. Even replacing renewably harvested biomass fuels with biogas provides a significant GHG benefit due to reduction of incomplete combustion products such as CH_4 and non-methane hydrocarbons [NMHC; 15]. Biogas is approximately 700,000 ppm CH_4 [25], a potent GHG with a global warming potential (GWP) 25 and 72 times that of CO_2 over a 100 year and 20 year time horizons, respectively [26]. Any gains made reducing GHG emissions by substituting biogas for solid fuels could be offset by CH_4 leaked from biogas systems directly into the atmosphere. Previous studies in China have addressed social, economic and climate aspects of anaerobic digesters [27], but have not quantified the net change in GHG emissions, nor the operational inefficiencies, observed in actual use [10]. Here, global warming commitment (GWC), defined as the total atmospheric warming committed by an emission of a gas mixture emitted by fuel burning, is used to quantify the net change in GHG emissions associated with biogas systems. Annual GWCs of biogas and non-biogas households are quantitatively compared by combining field measurements of CH_4 vented from biogas digesters with energy budgets for households with and without biogas systems.

Methods

Study area. About one fifth of China's biogas systems are installed in Sichuan Province [28], where the Ministry of Agriculture finances anaerobic digester construction through integrated improvement grants that fund simultaneous renovation of household kitchens, latrines and livestock sheds [6]. The systems are operated in a pressurized state that propels gas into the household via plastic tubing. This positive pressure is maintained by wax, concrete and earthen seals which prevent biogas leakage and inhibit the intrusion of oxygen into the chamber. A typical 8 m^3 digester can generate 250-300 m^3 yr^{-1} biogas in southern China, and 150-200 m^3 yr^{-1} in the colder northern areas [29]. Typical systems in Sichuan are fixed-dome, 6-10 m^3 underground tanks with ground-level input and output ports and specific design and construction parameters described elsewhere [6]. This study surveyed six agricultural villages (Figure A1) located in the Chuanbei region of Sichuan Province, People's Republic of China (E104°29' N31°06'). The villages lie on the hilly, agricultural areas surrounding the city of Deyang (or 100 km NE of Chengdu, Sichuan's capital city), a region characterized by a subtropical climate suitable for efficient methanogenesis. About 19 percent of households have and use a biogas system in their home [27].

Household survey. A convenience sample of 67 heads of household representing a total of 326 household members in six villages in Jingyang and Zhongjiang counties were selected for a detailed questionnaire about their current and past energy usage; 32 of the households had a functioning biogas system, while the remainder used traditional fuel sources. Participants were asked to disclose their household demographics, fuel sources, energy consuming activities, and animal husbandry activities. Additionally, biogas households were questioned about the performance, maintenance and use of household biogas, and their digesters were surveyed for CH_4 leakage as described below. All surveys were independently, forward and back translated, and administered with free and informed participant consent by trained personnel from the Sichuan Centers for Disease Control and Prevention. Interactions with human participants were approved by the Institutional Review Boards of the University of California at Berkeley, Emory University and the Sichuan Centers for Disease Control, Chengdu, PRC, prior to data collection.

Leak identification and quantification. In order to assess the prevalence and intensity of system failures, CH_4 leaks were characterized using a combination of path-integrated concentration measurements and radial plume mapping techniques. Thirty-two biogas systems present in surveyed households were scanned in July 2009 using a Remote Methane Leak Detector (RMLD; Health Consultants, Houston, TX) to discover fugitive CH_4 emissions in demarcated area above the underground digester. The scanning area included a zone at least 1 meter beyond the boundaries of the underground digester, as well as along seals and plastic tubing where seal failures or structural defects in the system may be found. A background CH_4 concentration was collected for each residence by taking a twenty second static reading with the RMLD pointed directly at the ground from a height of one meter and at a location at least 10 meters upwind from any known probable CH_4 source. The demarcated zone was then scanned with the RMLD by moving the laser in a sweeping zigzag pattern in 1 meter wide swathes according to the manufacturer's protocol. If a concentration above background was observed during the sweep, the scanning range and speed was reduced until a location of maximal concentration was established and marked with a survey flag for plume mapping. In addition to the ground surface above the tank, cap, dome perimeter, intake points and piping from the digester to point of use (e.g. household kitchen) were also scanned.

Gaseous flux from each identified leak was estimated following methods developed for plume mapping using multiple path-integrated concentration measurements [30]. Readings were taken across multiple vertical planes at, and downwind of, the area of interest and used to construct a concentration profile. With the RMLD mounted on a tripod, path-integrated concentration readings were taken at 25 target points arranged in a grid pattern perpendicular to the ground crossing through the area of a suspected leak (Figure 1). Additionally, two sets of five readings were taken along a vertical target aligned with the grid but placed at points closer to the RMLD. The size of the grid varied for each site, but it typically was 2m long by 1m high with rows spaced by 25cm and columns, by 50cm. Best efforts were made to position the RMLD and target grid such that the suspected source was approximately at the midpoint between the two, with the prevailing wind perpendicular to the measurement path. Four RMLD measurements (~0.3 sec/ measurement) were made at each target point, and two replicates of the entire procedure were carried out at each leak location. Wind speed, direction and temperature were recorded every three seconds using a HOBO Micro Station data logger (ONSET Computer Corporation, Bourne, MA, USA).

A Vertical Radial Plume Mapping (VRPM) approach [30-32] was used to reconstruct the concentration field in the vertical plane at each leak site. A smooth basis functions minimization (SBFM) algorithm [33] was used to fit the parameters of the bivariate Gaussian function to planar path-integrated concentration measurements as follows. From a given set of planar path-integrated concentration data, random selections of measurements (minimum 5) in the planes were drawn for fitting by SBFM to generate a set of 10,000 possible realizations of two-dimensional concentration fields. The concordance correlation factor (CCF), which compares measured path-integrated concentrations to those specified by identical paths taken through the reconstructed field, was used to assess the validity of each reconstruction [30]. Reconstructions with CCF<0.6 show poor fit to the Gaussian mathematical function, and were therefore discarded. Products of each accepted reconstructed field and associated perpendicular median wind speed at the site were calculated to obtain a range of flux estimates for each leak site. The median mass flux of all detected biogas leaks was input into the GWC model as described below.

Household energy budget. Cooking energy budgets for households with and without biogas systems were developed based on the household survey in order to calculate household GHG emission rates. Cooking fuel usage was estimated for biogas, coal, firewood, straw, and liquefied petroleum gas (LPG) fuels. For households with biogas systems (BG households) and those without biogas systems (NB households), the contribution of each cooking fuel type to the energy delivered to cooking pot was estimated as follows. First, reported annual cooking fuel expenditures were converted into mass of fuel used per day based on current market values. Daily cooking fuel usage was converted into energy delivered to cooking pot, adjusting for efficiency of stove/fuel combinations, based on an existing emissions database and standard methods [15]. The proportional contribution of each fuel type to daily household cooking energy use was then used to estimate GHG emissions and the resulting GWC of BG and NB households.

Greenhouse gas emissions and global warming commitment. Household emissions of GHG from cooking activities were estimated using a uniform daily budget (2 MJ) of energy delivered to the cooking pot of all households following standard methods [15, 34], roughly equivalent to the energy required for cooking two meals. GWCs are expressed per 2 MJ delivered to pot, and are calculated assuming that, while BG and NB households use the same quantity of energy delivered to pot, the efficiency and GHG emissions per unit of energy delivered to pot varies between BG and NB households based on the mixture of fuels used as informed by the household survey.

GWCs for wood burning stoves are calculated using ultimate emissions, which, unlike instant emissions, include unburned char and represent a more realistic combustion scenario where left over char is saved and subsequently burned alongside wood and converted to airborne carbon species at the next meal [15]. Based on previous work, GWC was estimated for BG and NB households based on the relative GHG emissions from their fuel mix, where GWC for each stove is defined as [15]:

$$GWC = \sum GHG_i \times GWP_i$$

where GHG_i is moles of the ith GHG observed, and GWP_i is defined as the total warming per mole of the ith GHG compared to CO_2 based on the most recent IPCC assessment [35, 36]. As the validity of single time horizon GWP estimates has been questioned [36], GWCs for 20, 100 and 500-year time horizons were estimated. The GHGs considered were CO_2, CO, CH_4, NO_2 and NMHC. Their GWPs for both renewable and non-renewable scenarios, described below, are listed in Table A1.

Four household models were explored in this study (Table 1). Model 1 represents NB households. Three alternative BG household models were created: a simple BG model (Model 2), a model including CH_4 leakage (Model 3), and a model accounting for modified biogas digester performance during cold months (Model 4). In Sichuan, anaerobic digesters generally produce biogas approximately 10 months out of the year, and thus a simple sinusoidal function based on seasonal temperature cycling in Sichuan was used in Model 4 to represent the decrease in biogas approaching December, transitioning back to full biogas use again in February. During cold periods with no or limited biogas production, modeled BG households were assumed to switch to the NB fuel mixture. The time-weighted average GHG emissions from the annual seasonal cycle was used to calculate GWC for Model 4. Daily biogas leakage estimated by radial plume mapping was added to the GHG emissions in Models 3 and 4 based on the gaseous composition of biogas [37], and in Model 4, leakage was also adjusted for temperature-sensitive, seasonal biogas production.

Six scenarios in this study stem from different GWC accounting methods associated with two renewable energy scenarios and three different stove distribution scenarios (Table 1). The GWCs of the four models were evaluated under each of the six GWC accounting scenarios for three time horizons. In renewable energy scenarios, biomass (wood, agriculture waste and animal dung) is assumed to be renewably harvested, meaning that CO_2 emissions are completely returned to a vegetative sink yielding no net increase in GWC from CO_2 [22, 35]. Completely efficient combustion of renewably harvested biomass fuels would result in zero GWC. However most stoves (including biogas and traditional stoves) generate products of incomplete combustion such as CO, CH_4 and NMHC, which are eventually converted into CO_2 in the atmosphere but have a significant impact on climate forcing before conversion. Thus, renewable energy scenarios account for renewably harvested fuels by adjusting the GWP of each gas emitted (subtracting 1.0 from the GWP for CO_2, CO, CH_4, and NMHC), resulting in a smaller net addition to GWC (Table A1). In contrast, non-renewable scenarios treat straw and biogas fuels as renewable and coal and firewood as non-renewable.

To address variation in the distribution of improved stoves among households, and the potential impact of an improved stove program, models were subjected to three alternative stove distributions: (1) improved stoves in all households, (2) no improved stoves in any household, and (3) all stove types uniformly distributed among households, for each respective fuel type [15]. Descriptions of stoves used in the models are shown in Table A2. Since limited data are available regarding the distribution of stove types used in China [11], in scenario variant 3, equal use of all stove models (both improved and non-improved) is assumed for each fuel type in the Chinese stove emissions database [15].

Uncertainty and sensitivity analysis. Variation in stove upkeep, stove usage and other behavioral sources of uncertainty were not quantified in this analysis. However, substantial uncertainty in emissions factors reported in the Chinese stove emissions database [15] was propagated through the GWC estimation procedure to obtain a range of GWCs representing the influence of a single source of uncertainty associated with each particular fuel/stove combination. Application of emissions factors assumes that stoves are in an operable condition equivalent to the standardized conditions used to construct the stove emissions database. Scenario-based sensitivity analysis was conducted to investigate the influence of temperature, stove distribution and renewable harvesting on GWC of leaking biogas households (See Appendix A1).

Results

Household survey. The average annual income of all surveyed households was 14,220 RMB (range: 550 – 100,000 RMB; USD 1 =~ 7 RMB), and no statistical difference was detected between BG and NB households (p=0.16). More than 80% of respondents identified as farmers. All 32 BG households reported their digesters were constructed within the past 5 years (average age 2.4 years) following standard concrete and brick design with 10cm digester walls. The average reported cost of digester construction was approximately 1,900 RMB, with more than 90% of families having received government subsidies averaging about 400 RMB. Plastic piping was used in all BG households to channel gas to point of use. Wood and crop residues dominated solid cooking fuels in BG and NB households, with a small amount of coal use. Biogas was exclusively used for cooking and heating water. Daily cooking energy usage from solid fuels of NB households and BG households before biogas was installed are comparable (Table A3). In order to minimize modeled differences between BG and NB households, a conservative assumption was made that BG households used total cooking energy equal to that reported by NB households; therefore, the BG household deficit in energy usage (Table A3) was assumed to be biogas.

Leak measurements and flux estimation. The mean background CH_4 path-integrated concentration was 9.80 ppm-m (SD=11.8; range 0-105; *n*=126). Because households were well-ventilated, background measurements did not significantly differ between indoor and outdoor (p=0.63). Small CH_4 leaks were detected at 3 BG households, suggesting that most systems were well-maintained with minimal fugitive emissions. Where leakage was detected, consistent measurements at the source were typically 100-200 ppm-m CH_4 (Figure A2). A simulated leak from an intentionally opened system valve resulted in measurements on the order of 1.0×10^3 ppm-m CH_4 (data not shown). Figure 2 illustrates a reconstructed plume for one set of BG household measurements after background subtraction. Median CH_4 mass flux estimated from the product of plume reconstructions with CCF>0.6 and associated perpendicular median wind speed at each leak site was 0.067 g hr^{-1} (mean absolute deviation: 0.97).

Global warming commitment. In all scenarios, BG households showed reduced GWC as compared to NB households. Table 2 and Figure A3 give GWCs for households with and without biogas based on 20-yr, 100-yr and 500-yr GWPs. In NB households, modeled GWCs (as g-CO_2-eq. per 2 MJ) range from 986 to 2350 over the 20 year horizon, from 359 to 1631 over the 100 year horizon and from 128 to 1308 over the 500 year horizon; uncertainty in GWC estimates associated with variation in emissions factors is shown for the 100 year horizon in Table A4. BG households show 23% to 55% reductions in GWC as compared with NB households. Introducing leakage to a modeled BG household using renewable fuel sourcing adds 17% to 40% (temperature-sensitive and total leakage, respectively) to the GWC expected without leakage when evaluated over a 20 year horizon. For non-renewable scenarios, leakage adds 34% to 73% (temperature-sensitive and total) to the GWC expected without leakage over the same horizon (Appendix A1). Thus, about a sixth to three fourths of GHG benefits of biogas can be negated by a poorly maintained system under short time-horizons. Compared to leakage and renewable fuel sourcing, stove distribution had a more modest effect on the reduction in GWC in BG households (see Appendix A1 and Table A5), yet stove distribution had a large impact on NB households as would be expected (Table 2).

Discussion

Using both field measurements of CH_4 leakage from anaerobic digesters and household energy budgets, the GWC of BG and NB households were modeled under several GHG accounting scenarios, accounting for temperature dependence of digester performance, varying distribution of stoves and renewable sources of energy. Because of the relatively high GWP of CH_4, any GHG emission reductions made by replacing traditional cooking fuels with biogas digesters could easily be negated by a moderate CH_4 leak. Determining the prevalence and intensity of CH_4 leaks from biogas digester systems clarified the extent to which biogas interventions offer GHG benefits. In our study, all scenarios in which NB were compared to BG households, including scenarios taking into account system leakage, BG households had lower GWC than their NB counterparts. Moreover, models incorporating leaks (Models 3 and 4) made the highly conservative assumption that all BG systems leak, whereas only ~10 percent of surveyed systems showed detectable leaks.

Based only on the benefits of reduced GHG emissions, the monetary value of a biogas installation can be estimated on the current carbon market. Observed reductions in GWC among BG households range from 24.5 to 5.1 mol-CO_2 equivalents per 2 MJ. To calculate the value of averted emissions to a household replacing 2 MJ of cooking fuel per day with biogas over 10 years, the Certified Emissions Reduction rate as of June 2010 of \$16.07 per ton of offset CO_2-eq and a discount rate of 3% were used [38, 39]. Based on the modeled change in emissions observed in Sichuan province, averted carbon over 10 years of household use was conservatively valued at \$28.30, which, in addition to the savings associated with averted fuel use, can contribute to digester's construction cost.

Among stoves sharing the same fuel type, there is a wide variation in GWC depending on stove technology (Figure A4; [15]). For instance, among stoves that use coal there is a nine-fold difference between the lowest and highest GWC. Interestingly, GWC of the biogas stove is one sixth of the GWC of the lowest emitting traditional fuel source, the straw burning stove, and half the GWC of coal burning stoves. Thus data describing the specific distribution of stoves in the population would raise confidence in the GWC estimated for a particular community subset.

Using an ultimate emission assumption, improved wood stoves had lower GWC than non-improved stoves. If only instant emissions are considered, however, improved wood-burning stoves may have a larger GWC contribution because of variation in combustion efficiencies associated with using char as a fuel source. Improved stoves have greater heat transfer efficiency at the cost of reduced combustion efficiency [15]. Reduced combustion efficiency led to greater emissions of products of incomplete combustion (e.g. NO_2, CO, NMHC, CH_4), which in turn lead to higher GWC of improved stoves using an assumption of instant emissions [15]. Products of incomplete combustion accounted for the increase in GWC seen in the 100% improved stove distribution scenarios as compared to the 0% improved stove scenarios.

The GWC reductions in BG households examined in this study were more sensitive to renewable harvesting than stove distribution or temperature-sensitive leakage (See Appendix A1 and Table A5). The greatest proportional increases in GWC from leakage are observed in renewable energy models, which, because they have fewer GHG emissions overall, result in leakage assuming a greater proportion of GWC. As expected, the increase in GWC associated with CH_4 leakage is reduced when the effect of temperature on CH_4 production is accounted for.

Differences between renewable and non-renewable models in Table 2 result from CO_2 being recycled back into the environment. The choice between renewable/non-renewable biomass harvesting showed a greater impact on a household's GWC than the choice between biogas/non-biogas. It should be noted, however, that the effect of renewable harvesting was accentuated by defining the scenario as 100 percent renewable biomass sourcing, a very ambitious target. GWC of uniform stove distributions for the 20-yr model was 80% higher in the non-renewable energy model as compared to renewable energy model. This was due to large contributions of CO_2 from wood burning stoves, and highlights the significant impact that renewable harvesting can have on limiting carbon emissions from household energy use. In order to assess the validity of the renewable energy model, data on the fraction of fuels being nonrenewably harvested in the area are needed, including information on regional woodfuel resources, harvesting practices and use [40, 41]. In the absence of these data, our models represent the range of outcomes associated with conservative (miminal renewable havesting) and optimistic (extensive renewable havesting) assumptions.

This analysis assumed that BG and NB households consume the same quantity of energy delivered to each pot. This assumption may inflate BG household GWC by overestimating the amount of biogas required to accomplish the same tasks in a NB household. Deriving biogas energy from waste material may free up capital to increase and/or diversify energy purchases. With respect to cooking, however, the data suggested that cooking activities of NB households and BG households before biogas adoption consume approximately the same amount of energy to pot. Furthermore, total energy usage in biogas households might decrease because biogas gives highly resolved control over energy use in ways solid fuel combustion does not. Biogas stoves can be turned on and off quickly and easily, whereas solid fuel fires smolder and are difficult to restart after extinguishing and thus households may keep solid fuel fires burning throughout more of the day.

This limited investigation of uncertainty resulting from variance of emission factors for each of these scenarios was generally larger for NB households than for BG households (Table A4) as a result of the particular variety of fuels and stoves used by NB households. Compared to other populations in Sichuan, the region studied here relied more on wood and crop residues for cooking fuel, and less on coal [6, 42]. Similar analyses conducted in a coal-dependent community would likely reveal a greater carbon benefit and, accordingly, a greater value to the global carbon market than shown here.

Conclusion

Biogas digesters provide a renewable source of energy that reduces household GWC compared to NB households, even when accounting for system failures. In the face of major environmental challenges facing rural China, and the increasing importance of mitigating global climate change, policies that integrate rural energy needs, public health goals and GHG emissions reduction are increasingly urgent [18]. Thus policy incentives to establish anaerobic digesters, as well as other energy interventions with substantial health co-benefits (e.g. improved stoves), along with renewable harvesting policies, are essential.

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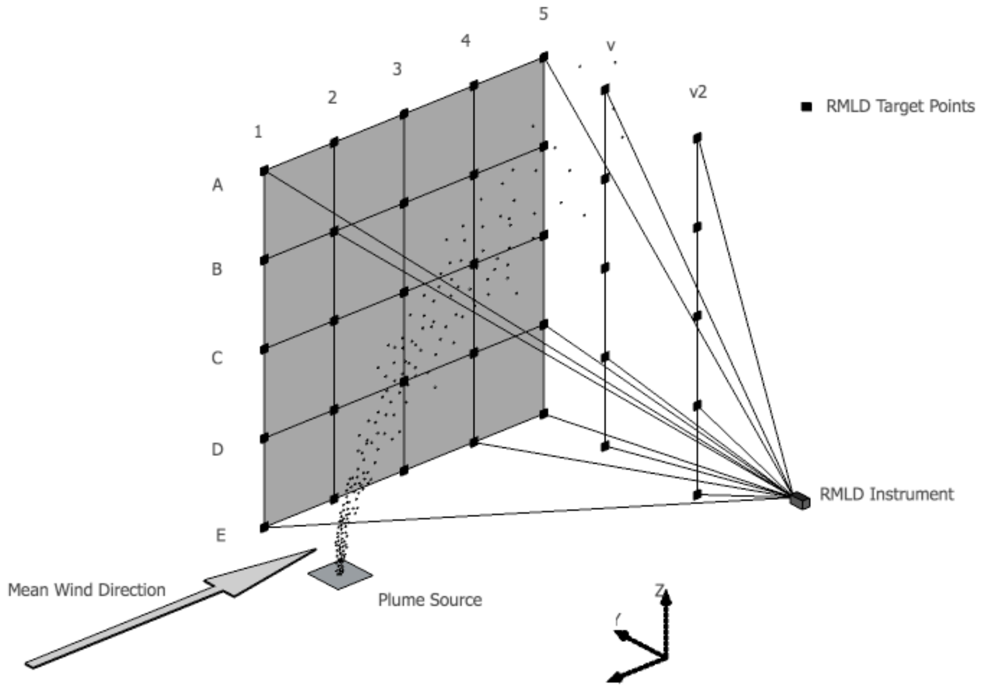

Figure 1. Experimental setup for plume mapping using multiple path-integrated concentration measurements taken along paths targeting 35 grid points. Only selected paths for path-integrated concentration measurements are shown for clarity.

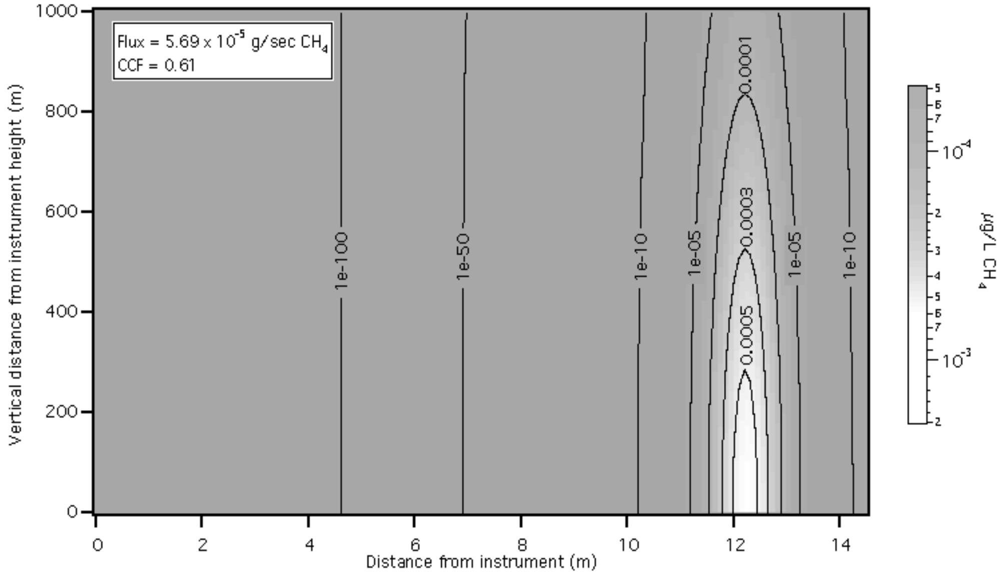

Figure 2. Methane concentration profile reconstructed using radial plume mapping of one set of ppm-m measurements collected at a leaking biogas location in Gaohuai village.

Table 1. GWC models for households with and without biogas systems, renewable energy and stove scenarios, and time horizons explored in this analysis.

Model 1: Households without biogas digesters **Model 2**: Households with biogas digesters without biogas leakage **Model 3**: Households with biogas digesters including biogas leakage **Model 4**: Households with biogas digesters including biogas leakage adjusted for temperature sensitive production	**Scenario 1**: Renewable biomass energy sourcing and 100% improved stove distribution **Scenario 2**: Renewable biomass energy sourcing and uniform stove distribution **Scenario 3**: Renewable biomass energy sourcing and 0% improved stove distribution **Scenario 4**: Non-renewable biomass energy sourcing and 100% improved stove distribution **Scenario 5**: Non-renewable biomass energy sourcing and uniform stove distribution **Scenario 6**: Non-renewable biomass energy sourcing and 0% improved stove distribution	**Horizon 1**: 20 years **Horizon 2**: 100 years **Horizon 3**: 500 years

Table 2. GWC as g-CO_2 per 2 MJ for all modeled households over 20, 100 and 500 year time horizons. Percent reduction in GWC (compared to households without biogas digesters) is shown in parentheses for households with digesters using alternative stove distributions, renewable and non-renewable fuel sourcing, and accounting for leakage.

20-year Time Horizon

Stove distribution	Harvesting model	Household GWC (% reduction in GWC)			
		Non-biogas†	Biogas total[1]	Biogas TSL[2]	Biogas without leak
0% improved	Non-renewable	2350	1483 (37%)	1366 (42%)	1164 (50%)
	Renewable	1239	919 (26%)	801 (35%)	599 (52%)
Uniform	Non-renewable	2089	1329 (36%)	1212 (42%)	1010 (52%)
	Renewable	1155	855 (26%)	738 (36%)	536 (54%)
100% improved	Non-renewable	1702	1125 (34%)	1007 (41%)	805 (53%)
	Renewable	986	761 (23%)	644 (35%)	441 (55%)

100-year Time Horizon

Stove distribution	Harvesting model	Household GWC (% reduction in GWC)			
		Non-biogas†	Biogas total[1]	Biogas TSL[2]	Biogas without leak
0% improved	Non-renewable	1631	921 (44%)	881 (46%)	810 (50%)
	Renewable	520	357 (31%)	316 (39%)	246 (53%)
Uniform	Non-renewable	1388	796 (43%)	755 (46%)	685 (51%)
	Renewable	454	322 (29%)	281 (38%)	211 (54%)
100% improved	Non-renewable	1075	638 (41%)	598 (44%)	527 (51%)
	Renewable	359	275 (23%)	234 (35%)	164 (54%)

500-year Time Horizon

Stove distribution	Harvesting model	Household GWC (% reduction in GWC)			
		Non-biogas†	Biogas total[1]	Biogas TSL[2]	Biogas without leak
0% improved	Non-renewable	1308	690 (47%)	677 (48%)	656 (50%)
	Renewable	197	125 (37%)	113 (43%)	91 (54%)
Uniform	Non-renewable	1100	585 (47%)	573 (48%)	551 (50%)
	Renewable	167	111 (34%)	98 (41%)	77 (54%)
100% improved	Non-renewable	844	456 (46%)	444 (47%)	422 (50%)
	Renewable	128	92 (28%)	80 (38%)	59 (54%)

† Reference group for % reduction in GWC

[1] Biogas total: GWC from biogas households including non-adjusted CH_4 leakage data;

[2] Biogas TSL (temperature-sensitive leak): GWC from biogas households including CH_4 leakage adjusted for seasonal ambient temperature change.

Appendix

Table A1. Global warming potentials (GWP) relative to CO_2 for selected greenhouse gases for 20, 100 and 500-year time horizons [13].

GHG	Renewable GWP			Non-renewable GWP		
	20 years	100 years	500 years	20 years	100 years	500 years
CO_2	1	1	1	0	0	0
CO	4.5	1.9	1.9	3.5	0.9	0.9
CH_4	72	25	7.6	71	24	6.6
NMHC	12	4.1	2.3	11	3.1	1.3
NO_2	289	298	153	288	297	152

Table A2. Stove/fuel pairings used in the present analysis based on previous work [11].

Fuel Type		ID	Stove Description
Coal	Unprocessed coal – unwashed	1.	Metal stove with flue
		2.	Metal stove without flue
		3.	Brick stove with flue
	Unprocessed coal – washed	4.	Metal stove with flue
	Processed coal – honeycomb briquettes	5.	Metal stove with flue
		6.	Metal stove without flue
		7.	Improved metal stove with flue
	Processed coal – briquettes	8.	Metal stove with flue
		9.	Metal stove without flue
Agricultural waste	Maize	10.	Brick stove with flue
		11.	Improved metal stove with flue
	Wheat	12.	Brick stove with flue
		13.	Improved metal stove with flue
Wood	Fuel wood	14.	Brick stove with flue
		15.	Improved metal stove with flue
		16.	Metal stove without flue *
Biogas	Biogas	17.	Metal stove with flue *

* From India

Table A3. Reported daily energy usage from solid fuels for cooking in 32 surveyed BG and 35 surveyed NB households.

	Wood		Coal		Crop residues		
	Kg (SE)	MJ	kg (SE)	MJ	kg (SE)	MJ	**Total MJ**
BG	4.46 (0.39)	12.15	0	0	0.65 (0.13)	1.34	15.45
NB	8.78 (0.68)	23.93	0.04 (0.003)	0.02	2.61 (0.31)	5.42	29.37
BG before†	6.63 (0.58)	18.06	0	0	5.73 (1.37)	11.90	29.96

† BG households reporting on energy usage before their biogas system was installed

Table A4. GWC per 2 MJ to pot for non-renewable model using 100-yr GWP, with (±SD) associated with the uncertainty in emissions factors reported in the stove emissions database [11].

Stove Distribution	Household GWC			
	Non-biogas	Biogas total[1]	Biogas TSL[2]	Biogas without leak
0% Improved	1631 (52, 3210)	921 (125, 1717)	881 (86, 1676)	810 (14, 1606)
Uniform	1388 (195, 2581)	796 (205, 1387)	755 (164, 1346)	685 (94, 1276)
100% Improved	1075 (421, 1729)	638 (324, 952)	598 (284, 912)	527 (212, 842)

[1] Biogas total: GWC from biogas households including non-adjusted CH_4 leakage data;

[2] Biogas TSL (temperature-sensitive leak): GWC from biogas households including CH_4 leakage adjusted for seasonal ambient temperature change.

A1. Scenario-Based Sensitivity Analysis

To better understand the relative influence of temperature-sensitive methane leakage, renewable/non-renewable resource use and improved stove distribution on GWC of leaking biogas digesters, a scenario-based sensitivity analysis was carried out over the 20 year time horizon. The referent categories were 'Biogas Total' (temperature-independent leakage), 0% improved stoves and non-renewable sourcing of fuel. GWC in leaking BG households was most sensitive to the renewable/non- renewable sourcing status of fuels, which resulted in the largest reductions (32% to 42%) in GWC compared to the reference category (Table S5B). The addition of temperature sensitive leakage produced reductions in GWC of 8 to 15% as compared to Biogas Total (Table S5A). Finally, distribution of 100% improved stoves produced reductions of 17% to 26%; whereas, uniformly distributed improved stoves produced more modest GWC reductions of 7% to 11% (Table S5C). For discussion of these sensitivity results, see the Discussion section of the main manuscript.

Table A5. Scenario-based sensitivity analyses of leaking BG models under a 20 year time horizon.

A. SENSITIVITY TO TEMPERATURE-SENSITIVE LEAKAGE

Stove dist.	Harvesting	Leakage	Household GWC (% reduction in GWC)
0% improved	**Non-renewable**	**Biogas Total†**	1483
		Biogas TSL	1366 (-8%)
	Renewable	**Biogas Total†**	919
		Biogas TSL	801 (-12%)
Uniform	**Non-renewable**	**Biogas Total†**	1329
		Biogas TSL	1212 (-9%)
	Renewable	**Biogas Total†**	855
		Biogas TSL	738 (-13%)
100% improved	**Non-renewable**	**Biogas Total†**	1125
		Biogas TSL	1007 (-10%)
	Renewable	**Biogas Total†**	761
		Biogas TSL	644 (-15%)

B. SENSITIVITY TO RENEWABLE/NON-RENEWABLE RESOURCES

Stove dist.	Leakage	Harvesting	Household GWC (% reduction in GWC)
0% improved	**Biogas Total**	**Non-renewable†**	1483
		Renewable	919 (-38%)
	Biogas TSL	**Non-renewable†**	1366
		Renewable	801 (-41%)
Uniform	**Biogas Total**	**Non-renewable†**	1329
		Renewable	855 (-36%)
	Biogas TSL	**Non-renewable†**	1212
		Renewable	738 (-39%)
100% improved	**Biogas Total**	**Non-renewable†**	1125
		Renewable	761 (-32%)
	Biogas TSL	**Non-renewable†**	1007
		Renewable	644 (-36%)

C. SENSITIVITY TO STOVE DISTRIBUTION

Leakage	Harvesting	Stove dist.	Household GWC (% reduction in GWC)
Biogas Total	**Non-renewable**	**0% improved†**	1483
		Uniform	1329 (-10%)
		100% improved	1125 (-24%)
	Renewable	**0% improved†**	919
		Uniform	855 (-7%)
		100% improved	761 (-17%)
Biogas TSL	**Non-renewable**	**0% improved†**	1366
		Uniform	1212 (-11%)
		100% improved	1007 (-26%)
	Renewable	**0% improved†**	801
		Uniform	738 (-8%)
		100% improved	644 (-20%)

† Reference group for % reduction in GWC calculation

TSL: Temperature-Sensitive Leakage

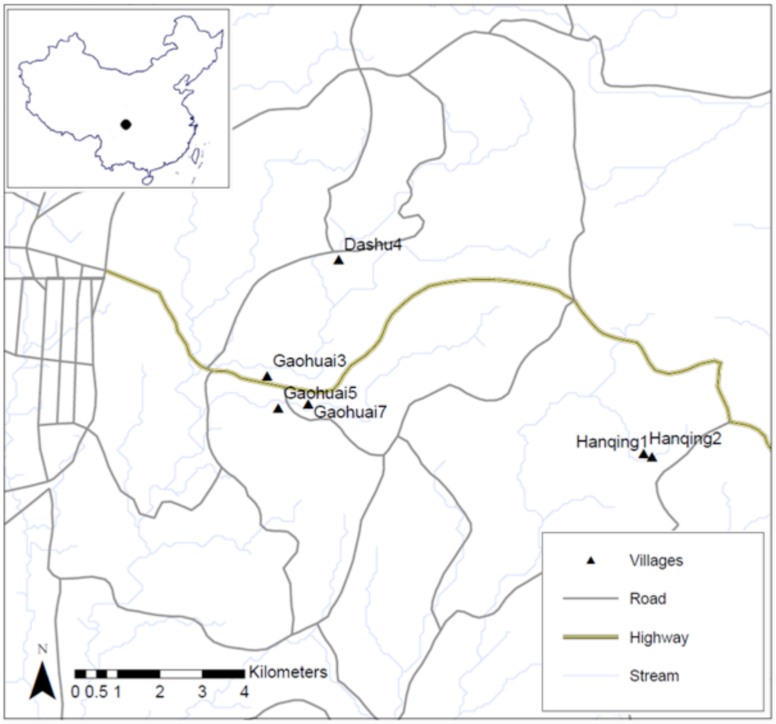

Figure A1. Map of study villages located within China's southwestern province, Sichuan.

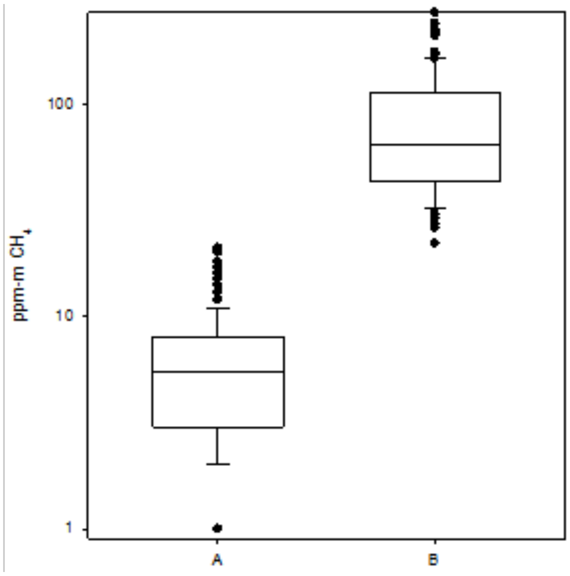

Figure A2. Distribution of RMLD background readings (n=180) taken over 120 seconds in a well-ventilated storage barn (A) and at a leak location indoors in a well-ventilated BG household (B).

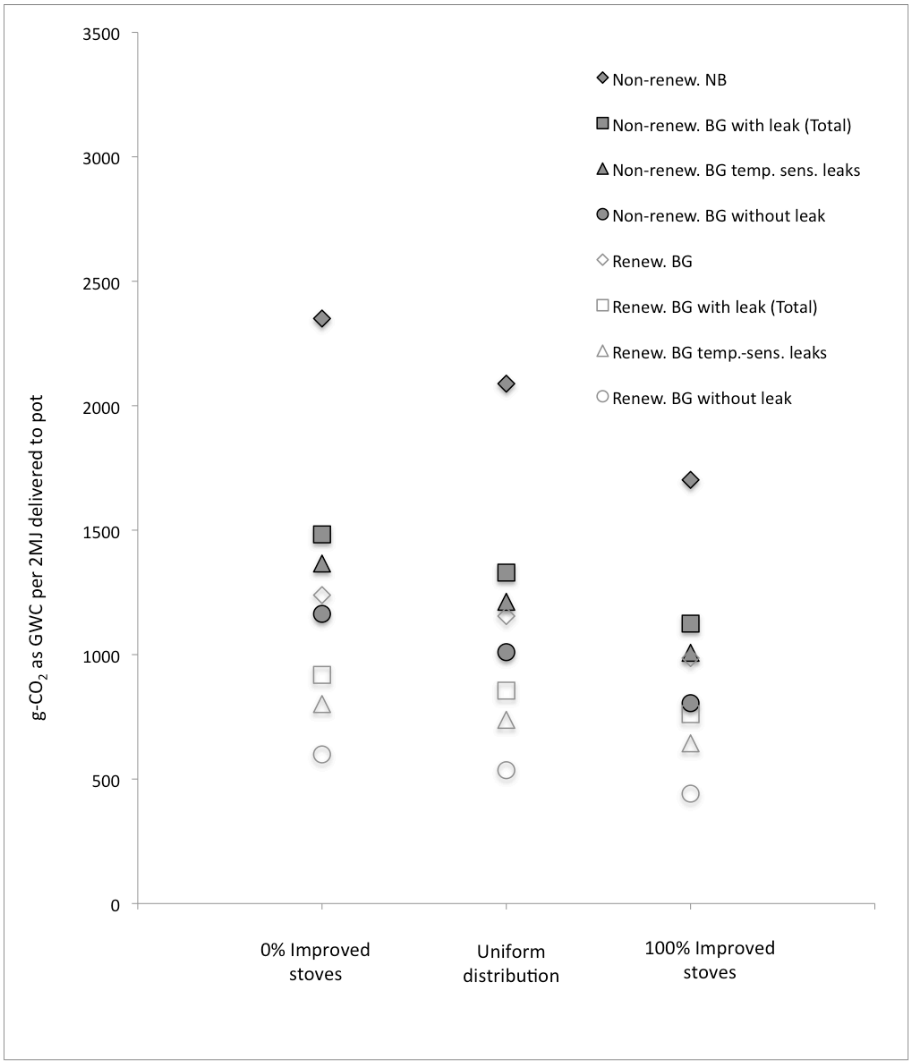

Figure A3. **GWC of renewable and non-renewable energy model using 20-year GWP estimates for biogas households (BG) and non-biogas households (NB).**

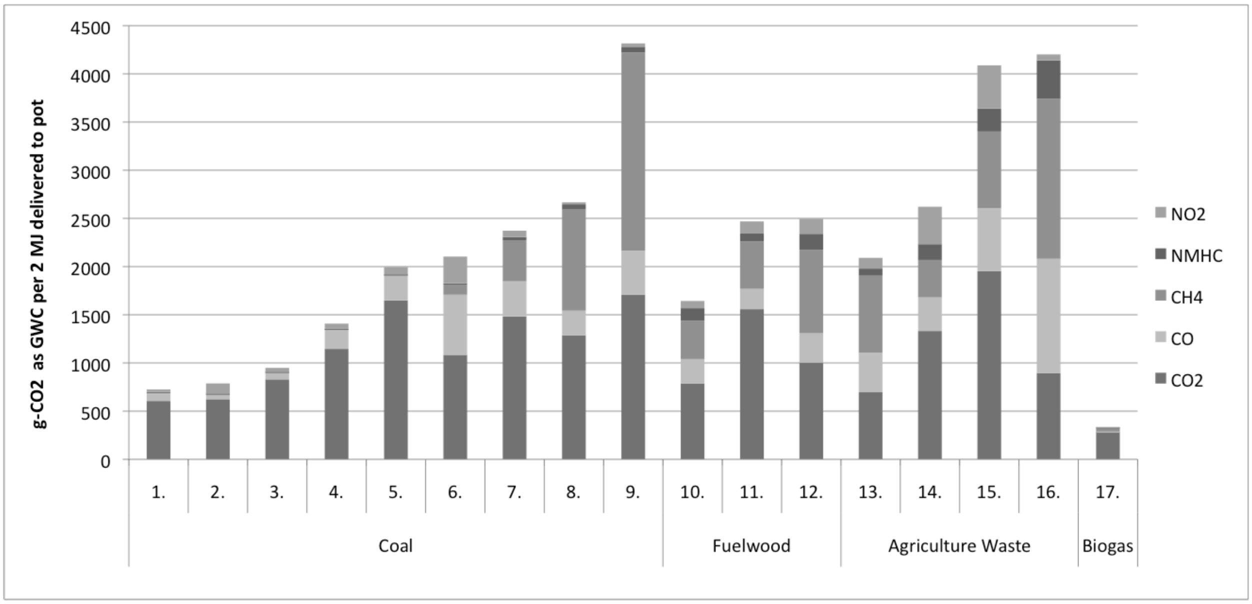

Figure A4. Individual GWC of stoves delivering 2 MJ to pot using non-renewable energy GWP. Stoves are identified by number as described in Table S2.