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Sizing an Anaerobic Digester in a Rural Developing World Community:

Does Household Fuel Demand Match Greenhouse Gas Production?

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
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Dedication

Por los soldados en la lucha.

Acknowledgments

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Abstract

Anaerobic digestion is the process by which organic carbon is converted into biogas in the form of carbon dioxide (CO_2) and methane (CH_4). Both of these products are greenhouse gases that contribute to global warming. Therefore if anaerobic reactors are improperly maintained and biogas is leaked or intentionally released into the atmosphere because biogas production exceeds household demand, these reactors may become generators of greenhouse gas emissions instead of sustainable energy producers. The objective of this research was to develop a framework to assess if the demand for biogas by a rural adopter of an anaerobic digester matched with the associated local gas production. A literature review of the energy required to prepare commonly consumed food of rice and beans was conducted to establish required household biogas volumes. This review determined that 0.06 m^3 of methane was required to prepare a half a kg of rice (on a dry weight basis) and 0.06 m^3 of methane was required to prepare a half a kg of beans (on a dry weight basis). Furthermore an analysis of occupants of a rural Panamanian town was performed along with a design model for rural anaerobic reactor gas production to determine if an overproduction of biogas would occur if anaerobic reactors were built for families who owned swine. It was determined using this approach that all of the fifteen household would experience an overproduction of biogas based on household demand of methane and therefore would risk the release of greenhouse gases. Household size ranged from one to seven occupants and swine ownership ranged from one to fifteen per household. The differences of biogas supply with respect to demand from these fifteen situations ranged from 0.09 to 0.35 m^3 of a biogas with 40% methane and 0.27 to 6.17 m^3 of excess biogas with a methane content of 70% per household per day. An average of 0.45 m^3 of a biogas with 40% methane per household per day was calculated and 0.87m^3 for 70% methane for all fifteen households, excluding one outlier. However, because this research uses

a model based on plug flow reactor mechanics, results may produce varied results from other studies concerning small scale anaerobic digestion.

Chapter 1: Introduction

1.1 Problem Statement

Technologies that produce a resource(s) from a waste product are essential in the efforts towards engineering a cleaner and healthier environment (REN21, 2005). Anaerobic digestion is the process by which organic wastes such as those from livestock management can be converted into renewable resources as soil amendments, fertilizers, and biogas. This process can provide a cleaner energy source from onsite agricultural wastes and is increasingly being implemented by governments and development organizations around the world as a benefit for rural communities (REN21, 2014). Methanogenesis is the primary biological process that anaerobic digestion utilizes to reduce organic carbon found in anthropogenic wastes such as municipal wastewater sludge, municipal solid waste, and agricultural waste into methane, carbon's most reduced oxidation state (Rittmann and McCarty, 2001). Furthermore because anaerobic digestion has an increased production of methane gas in warmer climates its application is being embraced by many countries in tropical locations to address energy needs of underdeveloped rural populations (Rittmann and McCarty, 2001) and achieve Goal 7 of the United Nation's Sustainable Development Goals: to ensure access to affordable, reliable, sustainable, and modern energy for all (UN, 2015).

Two examples of countries leading the effort to promote the use of waste to biogas are China and India which are currently global leaders in constructing small-scale biodigesters (e.g., 2-10 m^3). For example, in 2013 they built nearly 2 million reactors bringing their combined total to 48.2 million (Brunn et al., 2013; REN21, 2014). However, despite the increase in the number of rural anaerobic biodigesters constructed as one solution to the many environmental and economic struggles faced by rural households in lower-income countries, the neglect of small-scale digesters has been suggested as a potentially serious and escalating problem for the environment (REN21, 2014). This is because biogas that contains the greenhouse forcing gas of methane can be lost due to leaks in the gas line or voluntary bleeding of the system by operators. Therefore, no matter the upside of this technology, the technology must be maintained and monitored to ensure its contribution to environmental sustainability; otherwise, digesters may increase the global risk associated with emissions of an important greenhouse gas.

As mentioned previously, the United Nations has named access to affordable, reliable, sustainable and modern energy for all as Goal 7 for their Sustainable Development Goals. The objective of Goal 7 is to provide people with access to modern amenities such as lighting, telephone, and Internet in order to empower populations to compete in the global workplace. It is estimated that 1.7 billion people between 1990 and 2010 have gained access to electricity (UNDP, 2015). While this statistic is encouraging, and is expected to increase as further progress is made to provide people with electricity, the method of providing this energy through fossil fuels and the associated greenhouse gas emissions is resulting in detrimental changes to the Earth's climate and exacerbate serious problems around the world (UNDP, 2015). Therefore technologies such as anaerobic digestion that provide sustainable energy without burning fossil fuels and do not contribute to the increased presence of greenhouse gasses in the atmosphere are essential in the realization of Sustainable Development Goal 7.

Anaerobic digesters provide households with a renewable energy source by their ability to convert locally generated waste materials into a biogas that can be used for cooking, heating water, and in more developed situations production of electricity. Anaerobic digestion can provide several benefits to households and communities by improving indoor air quality, combating deforestation, and providing a nutrient-laden supernatant that may be useful as a substitute for crop fertilizers. While these benefits can be important towards improving the standard of living for households, the ability of anaerobic digesters to mitigate or contribute greenhouse gas emissions such as methane and carbon dioxide into the atmosphere is the point of focus in this research.

Problems with small-scale anaerobic digesters may arise when biogas is lost because of holes in the gas line or gas loss due to voluntary bleeding of the system by an operator. This is an environmental problem because the composition of the biogas is primarily made up of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) (Bruun et al., 2014). Methane is more prevalent in the makeup of biogas than carbon dioxide and is also 25 times more harmful to the environment as a greenhouse gas than carbon dioxide on a per equivalent basis (IPCC, 2007; Mihelcic et al., 2014). Importantly, it is estimated by Bruun et al. (2014) that global fugitive methane emissions from small-scale rural digesters could be contributing anywhere from 4.5–11 Tg CH_4 (112.5-275 Tg CO_2eq) each year, or approximately 1% of all methane emissions worldwide. This estimate is based on total annual global CH_4 emissions of 550 Tg CH_4 $(13{,}750\ CO_2eq)$ taken from an International Panel for Climate Change (IPCC) study which states that from 1997 to 2006 total global methane emissions have ranged from 503–610 Tg each year (Dlugokencky et al., 2011). Furthermore, the percent contribution of small-scale digesters to total methane global emissions may increase as the technology is continually promoted and embraced in rural communities. However, despite the projected 4.5-11 Tg CH_4 by Brunn et al. (2014) from rural anaerobic reactors around the world, anthropogenic methane emissions from the United States and China contributed an estimated 21.44 Tg CH_4 and 53.12 Tg CH_4 in 2006 (14 % of the total non-anthropogenic emissions 550 Tg CH_4 estimated by the IPCC) (World Bank, 2013).

1.2 Advantages and Disadvantages of Anaerobic Digestion

Anaerobic processes offers many solutions for stabilizing industrial and municipal wastes and are an increasingly essential tool as the threats of climate change and rising energy costs continue. Table 1-1 provides a list of advantages and disadvantages that anaerobic processes possess and why they should be considered in the design of a wastewater treatment plant.

In aerobic processes up to half of the energy conversion from substrate contributes to cell growth while in anaerobic environments only 5–15% of the energy conversion yields cell growth (Rittmann and McCarty, 2001). In the wastewater industry, the slow production of organisms in anaerobic digestion thus provides a preferable sludge management option by decreasing disposal logistics and costs for a wastewater operator. In addition, slow growing anaerobic organisms further aid plant managers in decreasing necessary and costly nitrogen and phosphorus supplements which is required when aerobic digestion is used for dilute industrial waste streams. This is because to ensure proper reactor function aerobic reactors demand higher nutrient additions than anaerobic reactors and thus must maintain higher operational costs when industrial waste streams are dilute in rate limiting nutrients such as nitrogen and phosphorus. The production of a fuel source in the form of methane is also an advantage of an anaerobic reactor when compared to an aerobic reactor. In contrast, some aerobic reactors require large inputs of mechanical energy to provide the oxygen requirements for the aerobic oxidation of organic carbon and other pollutants. The production of biogas provided by anaerobic reactors can not only supply a significant energy to cover a plant's local demands, but in the future treatment plants also may become net providers of energy by augmenting the already established electrical grid (Energy Trust of Oregon, 2014). Finally anaerobic reactors are able to sustain larger organic loadings per reactor volume when compared to aerobic reactors which also require large transfer of oxygen to wastewater (Rittmann and McCarty, 2001).

In addition to the advantages of anaerobic digestion for large scale municipal and industrial levels, anaerobic digestion also can provide benefits for small scale rural developing households. Through the use of biogas the consumption of biomass can be mitigated on the household level and help combat the unsustainable harvesting of wood that results in deforestation as well as decrease

Table 1-1 Advantages and disadvantages of anaerobic treatment (adapted from Rittmann and McCarty, 2001).

Advantages	Disadvantages
Low sludge production	Slow growing microorganisms
Low nutrient requirements	Odorous emissions
Methane production	Requires buffers for pH control
Can be a net energy producer	Trouble with treating dilute wastes
Able to sustain high organic loadings	

respiratory diseases caused by the inhalation of smoke from cooking with charcoal and dried dung. Nutrient recovery and access to natural fertilizers from the supernatant of the anaerobic digestion process are further advantages relevant to rural households in the developing world (Kinyua et al., 2015)

Many of the disadvantages associated with anaerobic digestion are associated with the same characteristics considered advantages. For example because the rate limiting methanogens reproduce at a slower rate, anaerobic reactors have longer seeding periods and are unable to quickly recover if the system is upset from neglect or sudden toxic shocks. To address this possibility of the reactor turning sour (i.e., where the pH drops below the functional threshold), expensive buffers must be purchased to protect the reactor from experiencing sudden pH drops or spikes. Corrosion from reduced sulfur compounds that can be present in the biogas are also issues when wastewaters contain sulfur-containing proteins. In this case, operators must be cognizant of this situation and work to treat corrosive gases or prevent the formation of hydrogen sulfide which, beyond the corrosion of downstream mechanical or piping components, may lower methane production by diverting electron equivalents from the methanogens to form sulfides. Finally, in treating relatively dilute wastewaters with chemical oxygen demand (COD) concentrations of 1,000 mg/l or less, anaerobic digestion is particularly inefficient and should be followed with an aerobic reactor to produce effluent COD levels required in the developed world (Rittmann and McCarty, 2001).

1.3 Focus of Research

Anaerobic digestion has the potential to not only meet some energy needs of rural populations but also be the source of greenhouse gas emissions via leaks and uncovered areas or conscious bleeding due to production of excess biogas (Khoiyangbam, 2003; Khoiyangbam, 2004; Nazir, 1990; Thu et al., 2012). If this technology is to realize its potential as a source of inexpensive and renewable energy, investigation into the worst case scenarios where the digesters potentially serve as a source of greenhouse gas emissions is required. While there are other forms of manure management available to rural farmers such as direct crop application and aerobic composting, the objective of this research is to develop a framework to address an oversight in the design process of small-scale anaerobic digesters that is related to their potential for overproduction of biogas by better assessing if the demand for biogas by a rural household adopter of this technology matches with the associated local gas production. This will be accomplished through developing an understanding of rural household energy demand in a developing world community and linking it with a modified existing model that estimates biogas production for small-scale applications that was previously created for a developing world setting by Rowse (2011). Provided with the knowledge of general energy usage required for cooking, heating and lighting, an improved understanding of gas usage in rural households should lead to more informed decision making regarding the design of biodigesters in rural communities of the developing world.

Chapter 2: Literature Review

2.1 The State of Rural Energy Consumption

Biogas production from anaerobic digestion is stated to provide a cleaner burning fuel than common woody biomass options and is able to replace solid fuel sources such as coal and animal dung. Inefficient cooking fuels derived from biomass are estimated by the International Energy Agency (IEA) to make up 90% of household energy consumption for 3.0 billion people living in the developing world (WHO, 2015 (a)). These sources of energy used in cooking, heating water, and providing illumination are known to damage the environment through deforestation and annually contribute to the premature death of 1.3 million people from respiratory diseases (IEA, 2006). These respiratory diseases caused by the use of solid fuels include acute lower respiratory infections in children and chronic obstructive pulmonary disease, lung cancer, ischemic heart disease and stroke in adults (Mihelcic et al., 2009; WHO, 2015 (b)). Consideri90%ng the poor quality of these solid fuels and their low position on the "Energy Ladder" (Figure 2-1) it is clear why technologies such as anaerobic digestion are being promoted as one energy solution for households without access to clean energy infrastructures like electrical grids or a liquefied petroleum gas distribution network.

2.2 Microbiology of Anaerobic Digestion

The inner workings of a well-run and stable anaerobic reactor is a multifaceted balance between many groups of bacteria and archaea prokaryotes, of which the most important and fragile are the methanogens. These slow growing anaerobic Archaea produce the methane used to generate electricity on large scale operations and for household cooking and heating purposes on smaller decentralized scales.

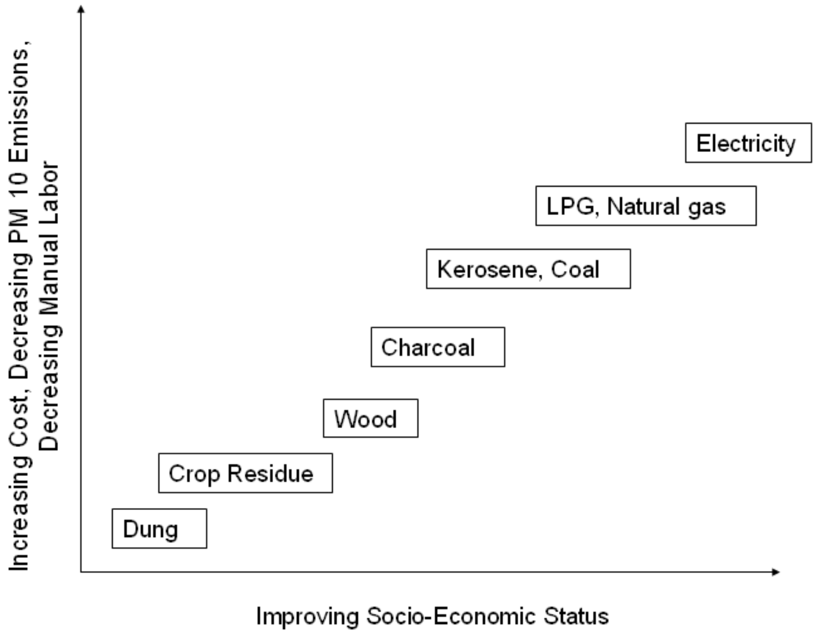

Figure 2-1 The energy ladder, showing how fuel type can change as a household's social and economic status increases (adapted from Smith et al. 1994; Source: Artwork by Linda Phillips. Reproduced from Mihelcic et al. (2009); with permission from ASCE).

There are two types of methanogens present in all anaerobic processes: 1) acetate fermenters, which use acetate as their electron donors and are slow growing, and 2) hydrogen oxidizers which use both formate and hydrogen as their electron donors.

Figure 2-2 shows the process of anaerobic digestion and how carbon from organic substrate is reduced to methane, carbon's most reduced oxidation state, -4. The process of anaerobic digestion begins with the introduction of an organic substrate (e.g. animal or human feces, compost, agricultural waste, etc.) containing proteins, carbohydrates, and fats. As shown in Figure 2-2, this substrate undergoes hydrolysis to form simple carbohydrates, amino acids, and fatty acids. Next, fermenting bacteria produce organic acids and hydrogen from these simple carbohydrates, amino acids and fatty acids in a process called acidogenesis. This step is very important in the anaerobic process because organic acids such as acetic, propionic, and butyric acid are the most prominent products in the reactor and if not monitored closely can sour the reactor by lowering the pH level below the functional range.

After the fermentation of the hydrolysis products, these intermediate organic acids are reduced again by acetogenic bacteria to form both acetic acid and hydrogen, the two main inputs for the methanogens who complete the anaerobic process by producing methane.

As expressed in Figure 2-2 the result of this complex symbiosis of bacteria is methane production. However, anaerobic digestion is commonly simplified into two steps where hydrolysis and fermentation combine to form the hydrogen and organic acids consumed in methanogenesis. This simplification focuses on the formation of the organic acids because it provides a pulse with which operators can measure the condition of the reactor using either sophisticated equipment involving chromatography or simple acid/base titration methods to monitor organic acid concentrations.

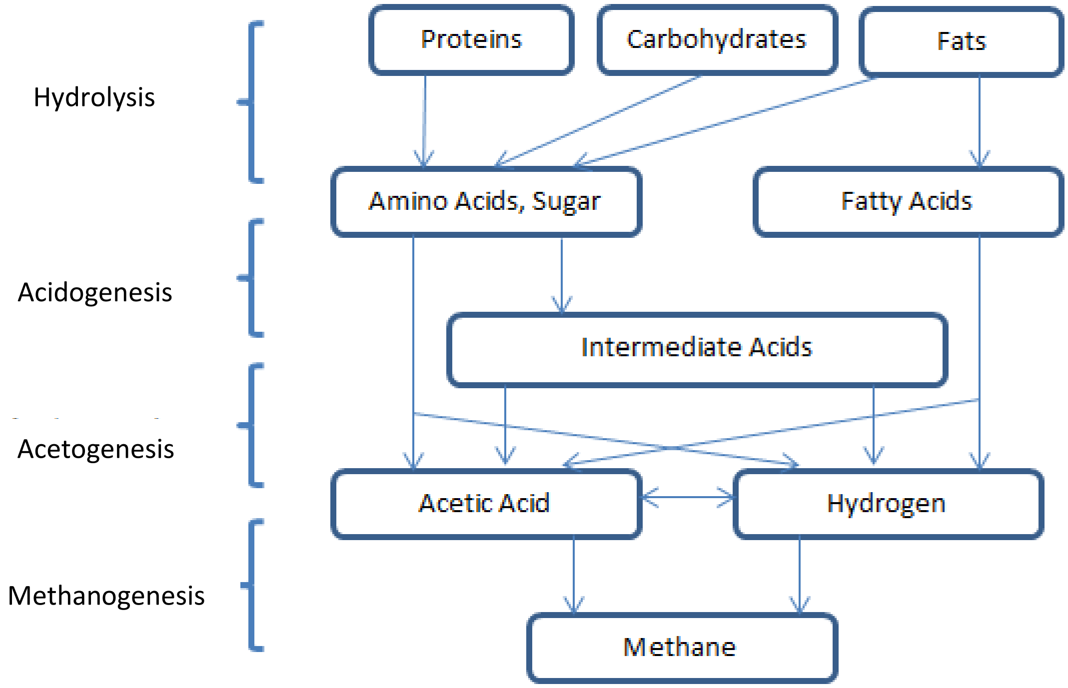

Figure 2-2 Anaerobic digestion process flow chart.

2.3 Parameters and Process Optimization of a Well Performing Anaerobic Digester

Many parameters guarantee the proper performance of an anaerobic digester. Due to the complex makeup of digesters and the multitude of organisms working together in a symbiotic manner, the failure to stay within appropriate ranges for these parameters may result in the failure of the entire system. The following parameters are important to successful performance and will be covered in greater detail in the following pages (GTZ, 1999):

- Substrate temperature
- Available nutrients
- pH level
- Nitrogen inhibition and carbon-to-nitrogen (C/N) ratio
- Substrate solid content and agitation
- Inhibitory factors
- Solids retention time (SRT)

2.3.1 Substrate Temperature

The working range of an anaerobic digester falls within three distinct groupings: 1) psychrophilic 3 –20 degrees Celsius, 2) mesophilic 20 – 40 degrees Celsius, and 3) thermophilic 40 degrees Celsius and above. As temperature increases in the reactor's environment so does the production of biogas. The optimal temperature for mesophilic organisms is around 35 degrees Celsius while thermophilic organisms operate best between 55 and 60 degrees Celsius. In fact within the mesophilic range, biogas production doubles every 10 degrees Celsius. Therefore when considering biogas production and cell growth, temperature is a very important parameter to monitor (Rittmann and McCarty, 2001). Within these temperature ranges the methanogens distinguish themselves as either psychrophilic, mesophilic or thermophilic in nature. Temperature is also important in an anaerobic digester because it will influence the fate of pathogens that are found in such systems (Manser, 2015; Manser et al., 2015).

2.3.2 Available Nutrients

All biological processes require nutrients such as oxygen, hydrogen, carbon, nitrogen, sulfur, phosphorus, potassium, calcium and magnesium to function and anaerobic digesters are no exception. As a rural technology the substrates used to feed digesters such as feces and urine from cattle, swine and poultry provide sufficient nutrients to support all the biological functions present in an anaerobic reactor (GTZ, 1999).

2.3.3 pH Level

The operational pH range of an anaerobic digester is 6.6 to 7.6 (Rittmann and McCarty, 2001). pH levels outside of this range can create an inhabitable environment for the methanogenic organisms that are cultivated to create biogas. As discussed previously, an overproduction of organic acid during the acidogenic phase is the primary factor in pH imbalance, and therefore should be closely monitored to avoid the reactor turning sour.

2.3.4 Nitrogen Inhibition and C/N Ratio

Methanogens are able to adapt to nitrogen levels as high as 5,000-7,000 mg/l as NH_4-N with optimal carbon-to-nitrogen (C/N) ratios of 8-20. The prime concern is that ammonia concentrations are typically maintained below 200-300 mg/l as NH_3-N to avoid the destruction of the methanogen population. This propagation of ammonia is highly dependent upon the pH levels and the temperature in the slurry and therefore should be closely monitored (GTZ, 1999).

2.3.5 Substrate Solids Content and Agitation

To provide increased substrate consumption, the slurry in a digester should be agitated to improve the substrate accessibility for the microorganisms by ensuring solids reduction. This reduction in solids increases the surface area of the substrate and leads to greater biogas production through increased contact. In addition, the agitation of the substrate will provide: 1) removal of metabolites produced by the methanogens (gas), 2) mixing of fresh substrate and bacterial population (inoculation),

3) preclusion of scum formation and sedimentation, 4) voidance of pronounced temperature gradients within the digester, 5) provision of a uniform bacterial population density, and, 6) prevention of the formation of dead spaces that would reduce the effective digester volume (GTZ, 1999). However, although the aforementioned points are beneficial to the anaerobic process, for many small scale digesters the ability to mix or agitate the slurry is impractical due to limitations in access to energy or mechanical machines and tools.

2.3.6 Inhibitory Factors

With the introduction of harmful chemicals, reactor performance may suffer and result in either a decrease in gas production or an overall system failure. Table 2-1 lists several inhibitory substances that are commonly found in anaerobic digesters.

Table 2-1 Inhibitory chemicals commonly found in anaerobic digesters and the concentration that may result in inhibition (GTZ, 1999).

Substance	[mg/l]
Copper	10-250
Calcium	8,000
Sodium	8,000
Magnesium	3,000
Nickel	100-1,000
Zinc	350-1,000
Chromium	200-2,000
Sulfide (as Sulfur)	200
Cyanide	2

2.3.7 Solids Retention Time

The solids retention time (SRT) is arguably the master parameter in the design and operation of anaerobic digesters because it incorporates other parameters such as temperature and substrate composition in determining the ideal balance between initial reactor costs and final gas production. SRT is defined as the amount of active biomass in the reactor in relation to the biomass' production rate. Because temperature and substrate composition determine the production of the microbial populations, these parameters are used to design the most economical reactor volume which would ensure maximum gas production and volatile solids reduction while avoiding microbial washout. Furthermore, longer SRTs provide increased contact time with pathogens that can be found in wastes which derive from human discharges or animal husbandry. However studies have shown that there is no significant differences in inactivation of *Ascaris suum* ova (a microbial parasite that is resistant to destruction and found in the tropics) in mesophilic digesters operated at different SRTs (Manser et al., 2015).

2.4 Rural Anaerobic Digesters

Despite the many previously discussed benefits associated with anaerobic digestion, their ability to decrease greenhouse gas emissions associated with the use of fossil fuels is one which is widely promoted. Furthermore by replacing traditional low quality solid fuels such as firewood, coal, and animal dung, use of biogas can decrease deforestation and further mitigate greenhouse gas emissions by providing a more thermally efficient fuel source for cooking (Bruun et al., 2014). However, as explained previously, with the production of methane gas, anaerobic digesters can potentially pollute the environment by discharging a potent greenhouse gas into the atmosphere through improper design, maintenance, and operation. Thus, in this scenario where an anaerobic digester releases CH_4 into the atmosphere, it would then negate any positive environmental impact and instead become effectively a greenhouse gas producing reactor.

The study by Bruun et al. (2014) investigated this possibility of small-scale anaerobic digesters (2–10 m^3) that may give rise to global warming by comparing fugitive methane gas emissions to those of low grade fuels such as firewood, animal dung and coal. In Table 2-2, Bruun et al. (2014) considered six scenarios in determining the break-even global warming potentials in which the percentage of methane lost in a reactor due to fugitive gas emissions would translate into the same global warming potential of 1) liquefied petroleum gas (LPG), 2) coal, 3) wood that was considered carbon neutral, 4) wood that was not considered carbon neutral, and 5) dung that was considered carbon neutral. Examination of this figure provides an understanding of biogas' ability to decrease greenhouse gas emissions by defining the amount of fugitive biogas needed to match the negative impact of traditional low grade sources of fuel. As seen in Table 2-2, the largest impact biogas provides in decreasing global warming potential is when it replaces the energy sources which make up the lowest rungs of the Energy Ladder; i.e., wood, coal, and dung. The burning of wood and dung may be considered carbon neutral because the carbon dioxide released during their combustion was either fixed before the wood or feed was harvested and therefore do not introduce new sources of carbon into the atmosphere. This outlook is not applicable argues Bruun et al. (2014) because these sources are less thermally efficient than biogas and in comparison will release more carbon dioxide into the environment. Furthermore in much of the world wood is typically harvested unsustainably and the carbon dioxide released will not be reintroduced into the environment by photosynthesis.

Table 2-2 Break-even points for each biofuel considered by Bruun et al. (2014) in which the percentage of methane lost in a reactor due to fugitive gas emission would translate into the same global warming potential.

LPG	Coal	Wood Neutral	Wood Not Neutral	Dung Neutral
16	51	3	44	28

Considering Bruun et al.'s (2014) conclusion that rural anaerobic reactors could be contributing up to 1% of all methane emissions globally, it is critical to define the quantity of fugitive biogas being released by the estimated 48.2 million plus digesters that are estimated to currently exist in the developing world (Wang, 2009; Thu, 2011;REN21, 2014).

2.5 Evaluation of Biodigester Operation and Maintenance

Anaerobic digestion has shown itself able to address many problems rural households throughout the developing world currently face and its increased implementation can be viewed as an encouraging step towards advancing sustainable development (German Agency for Technical Cooperation, 1999; Thu, 2011; REN21, 2014). However the ability to develop a network of skilled and knowledgeable installers and local operators able to support the escalation of decentralized small-scale anaerobic digesters is not known and may directly contribute towards their neglect and misuse (Zhang, 2009). Because of the makeup of biogas that contains at least two harmful greenhouse gases, a lack of capacity building may create a scenario in which this potentially positive technology could instead become a global liability.

In India it was reported that 30% of anaerobic reactor failures were due to a lack of maintenance and access to parts required to address damages (Dutta et al., 1997). In contrast, in China, the coverage provided by management service systems was reported to be 18.9% in rural areas and 85.9% in urban areas, instead of a desired 70% and 100%, respectively (Zhang, 2009). Furthermore, in 2007 it was estimated that of the 26.5 million household anaerobic reactors installed in China, approximately 60% were in operation (references provided in Bruun et al., 2014). This inability to monitor and support small-scale digesters has also been identified as an issue in countries in Sub-Saharan Africa and other locations in the world (Surendra, 2009; Rupf, 2015).

The abandonment and failures of development projects are unfortunately a reality in the developing world and one reason is the lack of capacity building that has neglected training of technicians as well as other support systems (Schweitzer and Mihelcic, 2012). For example, China, despite the increase in their educated population, still lacks the ability to manage and monitor their large number of rural biodigester projects (Zhang et al., 2007; Chen et al. 2010; Jiang, 2011). This would seem like a standard case of failed investment in infrastructure if these projects didn’t possess the added potential of damaging the environment through release of greenhouse gases. Furthermore, in research conducted by Khoiyangbam et al. (2003), fugitive methane emissions from small-scale fix domed digesters (3-9 m^3) located in India were associated with the design of the reactor. This design was found to have exposed orifices that allowed for the escape of biogas through its inlets and outlets where the manure waste that was being processed enters and exits the digester. It was also found that depending on whether they were constructed in warm or cold climates, anywhere from 53.2 kg to 22.3 kg of methane were released annually from each digester (Khoiyangbam et al., 2003; Bruun et al., 2014).

There is also evidence that poor construction and material deterioration leads to fugitive biogas emissions. For example, issues such as dome leakages, damaged digester caps, and loose gas valves have all been identified to contribute to average biogas losses of up to 10% of total gas production (Thu, 2012; Nazir, 1990; Bruun et al., 2014).

Undoubtedly methane produced from an anaerobic digester should be prevented from escaping into the atmosphere via unaddressed damages and faulty valves, as well as from openings due to physical construction and layout. However, the most detrimental cause of fugitive methane may be associated with the intentional release of biogas due to overproduction. For example, after interviewing 135 swine farms with biogas plants in Vietnam the majority of operators admitted to releasing unused biogas into the atmosphere (Thu, 2012). In a separate unpublished survey of 216 Vietnamese biodigesters it was found that 140 owners (64.8%) generated more biogas than they could use (Vu and Dihn, 2011). In addition, 48.6% of the 140 surveyed digester owners admitted to releasing excess biogas directly into the atmosphere (Vu and Dihn, 2011). Extrapolating from these numbers Bruun et al. (2014) estimated that these digesters could be purposefully releasing upwards of 57% of their biogas yield because of an inability to match gas use with gas production. Furthermore, a study in Thailand reported that 15% of biogas produced in small-scale digesters is either released into the atmosphere or flared because of over production (Prapaspongsa et al., 2009).

Because most rural digesters are primarily constructed to supplement fuel use for cooking (REN21, 2014; Thu, 2012), a review of how the design of a small-scale anaerobic digester could be better managed to meet household demand is necessary in order to prevent an unconsciously detrimental use of the technology.

Chapter 3: Methods

Preventing fugitive gas emissions from either overproduction or underutilization of biogas can be addressed by a design framework that connects gas production with household demand. In designing an anaerobic reactor, there currently appears to exist the motivation to size the reactor with respect to optimal gas production. However, in light of the potential environmental damage caused by extraneous biogas production a more conservative approach should be to design reactors based on user demand. Using energy demands derived from rural households and an existing model able to estimate gas production from small-scale anaerobic reactors, a method was developed to improve the criteria for sizing a more environmentally friendly anaerobic digester.

3.1 Study Location

Rural Panamá was selected as the location for this study to serve as an example for estimating household energy requirements because of the author's experience living and working there as a Peace Corps volunteer for fifteen months as part of the Master's International Program (Mihelcic, et al., 2006; Mihelcic, 2010; Manser, et al. 2015). The author was located in the Darien Provence of Panamá in a town named Rio Pavo, shown in Figure 3-1. Rio Pavo is a small community of 150 inhabitants located along the Rio Congo and is centered on a logging road used to transport cattle and lumber. Ranching and logging are the two most profitable economic pursuits in this region but most households are supported by subsistence farming and day labor. Raising swine is another common investment made by rural Panamanian households who sell swine locally to be butchered. During the author's service he observed some construction of small-scale digesters in the area and he gained knowledge of local eating

Figure 3-1 Location of town where the author served 15 months as a Peace Corps Volunteer. Obtained from the Central Intelligence Agency Web site The World Factbook. <https://www.cia.gov/library/publications/the-world-factbook/geos/pm.html>.

and cooking customs. This knowledge paired with dietary census data allowed for a more accurate approach in developing sound representations of household biogas demands.

3.2 Estimating Biogas Production

The model developed by Rowse (2011) is a design tool using Microsoft Excel that is intended to size rural anaerobic digesters constructed in the developing world. To adrress the purpose of this research a modified version of Rowse's mathamatical model was used to estimate only biogas production. Rowse constructed this model based on her experience working in rural Dominican Republic as a water/sanitation engineer Peace Corps volunteer as part of the Master's International program (Mihelcic et al., 2006; Mihelcic, 2010; Manser et al., 2015). Complied data from the literature is matched with user inputs that are selected and inserted into internal model calculations which generate the final design outputs. Figure 3-2 demonstrates the user inputs, calculation pathways and final outputs for the Rowse (2011) model. Figure 3-2 shows that model inputs include: 1) type and combination of animal manure, 2) number of animals and livestock arrangments, 3) mean temperatures in warm and cold seasons, and 4) type of digester design. Model inputs are then processed through a series of calculations derived from the principles of mass balance and reaction rate kinetics which result in the final digester dimensions, recommended daily water additions, and biogas production.

The quantity of manure and its characterization is the primary input defined in Figure 3-2. Therefore, the number of animals supplying the digester and their species are selected from five animals commonly raised in rural households. These include swine gestating sow (referred to as swine in this study), swine boar, poultry, and both beef and dairy cattle. Next, based on the selected animal species and their number, the chemical formula of the waste stream and the amount of manure it contains is determined. Therefore, different animals will yield different biogas volumes based on the manure's chemical composition from their diet, and the amount of manure provided to the digester by each

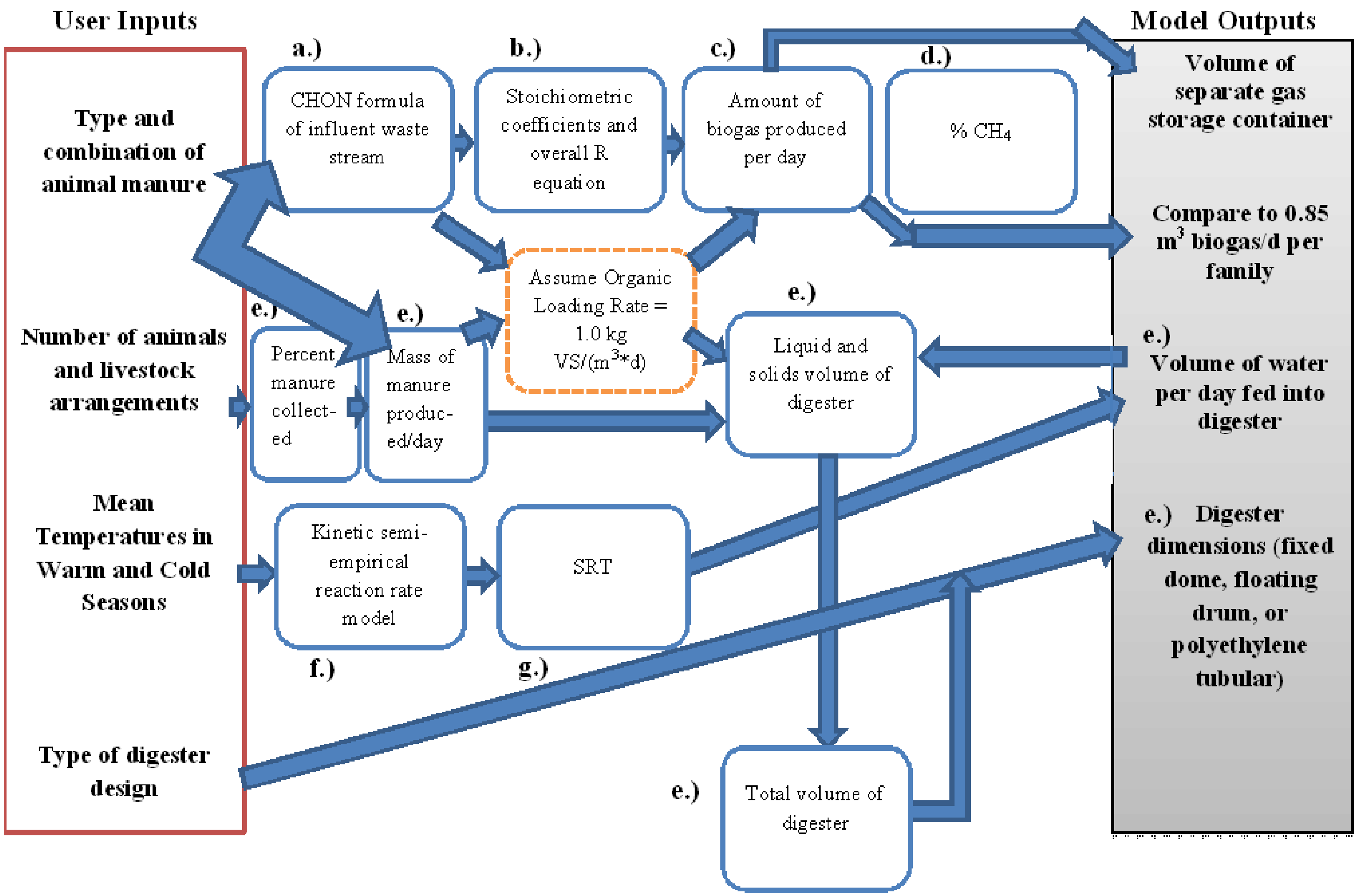

Figure 3-2 Anaerobic digester design tool flowchart used to estimate gas production. (Reproduced with permission from Rowse, 2011). [1]

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[1] For a deeper explanation of Rowse's model please consult the work (Rowse, Laurel Erika, "Design of Small Scale Anaerobic Digesters for Application in Rural Developing Countries") at http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=4519&context=etd.

animal. From the defined chemical composition of the waste stream and daily supply of manure, defined by default manure yields per species found in literature and imputed manure collection method, the stoichiometric half reaction coefficients and organic loading rates built into the model are used to calculate gas production of the digester. The input reactor types a user can design for are 1) fixed-dome digesters, 2) floating-drum digesters, and 3) polyethylene tubular digesters. Furthermore, the mean temperatures of the coldest and warmest seasonal periods of the region and reactor type are paired with the assumed organic loading and gas production rates to calculate the final digester volume and dimensions.

3.3 Estimating Household Biogas Demand

The energy demand for rural households is comprised of lighting, power generation and cooking (GTZ, 1999). Cooking is estimated to make up 90% of all household energy consumption in the developing world (IEA, 2006). Therefore, with a better understanding of what is being cooked in a typical household and how much energy is required to prepare meals, an accurate value for the energy demand can be established in designing an anaerobic digester appropriately sized to meet household demand. Measuring the energy habits of a rural household can be approached in several ways (GTZ, 1999):

1. Determining biogas demand on the basis of present energy consumption.
2. Using reference data obtained from literature.
3. Estimating biogas demand by way of appliance consumption data and assumed periods of use.

The first approach listed above develops household energy consumption data based on measurements obtained from first-hand accounts and observations. It is therefore the most accurate source of information, but is the most difficult information to obtain. The second approach uses data sourced from literature concerning energy use, food consumption, and diet census data. This form of data collation varies by source and location and can yield a broad range of values. Finally, in the third approach, household biogas demand can be obtained through estimating appliance usage and back calculating the energy required to support specific appliances.

Approaching rural household energy consumption by estimating appliance usage was not used in this study because rural decentralized households disconnected from electrical grids do not often own or operate kitchen appliances and therefore household appliance data is unavailable and usage cannot be determined or estimated in advance. Furthermore the ability to generate electricity to operate appliances requires increased capital demand. Therefore, this research was developed around the current statues of rural developing households and providing energy to cover the most immediate and demanding energy requirement, cooking. To do this reference data from literature concerning energy requirements to cook foods and the consumption quantities of those foods was researched and collected. Direct measurement of user consumption is ideal in developing a strategy to estimate household energy demand because it accounts for individual nuances and patterns that may distinguish one household form its neighbors. However, this approach is not always available when digesters are being designed. Therefore in many cases decisions must be based on measurements obtained from experiments or calculations derived from physical phenomenon.

Table 3-1 provides a summary of the various reported energy requirements to cook rice and beans. The energy requirement to cook rice and beans was quantified as m^3 of methane instead of $m^3\ of$ biogas in an attempt to standardize the energy output from biogas which varies based on methane content variations and volume fluctuations due to environmental conditions. Rice and beans were selected because they are dietary staples commonly prepared in many rural kitchens around the world and demand large energy quantities because of their long preparation periods. A mass of 0.5 kg (on a dry weight basis) for rice and beans was selected to conform to the precedent established in literature as a way to express energy and biogas quantities in relation to food quantities. From the information provided in this table, a reader can see the wide range of available data which must be chosen from to accurately estimate daily gas allowances for preparation of common foods and the inherent errors that can arise by choosing one data set over another. Assumptions made in compiling this data included: similar cooking methods by each study, cooking is performed at normal temperature and pressure for each study, and the caloric value for biogas is 22 MJ/ m^3 (GTZ, 1999) and for methane is 50 MJ/ m^3 (Engineering Toolbox (a.)).

Table 3-1 Literature reported values of biogas required to cook 0.5 kg of rice and 0.5 kg of beans on a dry basis.

Source	m^3 CH4/ 0.5 kg rice	m^3 CH4/ 0.5 kg beans
GTZ, 1999	0.09	0.12
Kumar De et al., 2014	0.01	0.01
Amarasekara, 1994	0.04	-
Anoopa et al.	0.03	-
Nijaguna, 2002	0.09	-
Itodo, 2007	0.09	-
Itodo, 2007	172.31	588.22
Obada, 2014	8.47	-
Average	0.06	0.06
Theoretical Calculation	0.04	0.21

The data reported by Itodo (2007) and Obada (2014) were excluded from the calculated averages of 0.06 m^3 of methane per 0.5 kg of rice and 0.06 m^3 of methane per 0.5 kg of beans, respectively, because the results were deemed unreasonable by comparison with the results from the other studies. Also, because of disagreement in values presented in Table 3-1 (which stems from a lack of standardization in the literature) the need for further research in better defining the capacity in which biogas can be used to cook staple dietary options such as rice and beans is made apparent.

Therefore, in an attempt to provide these values with more context, theoretical values were calculated based upon the energy required to cook 0.5 kg of rice and 0.5 kg of beans on a dry basis. This data, provided in the bottom row in Table 3-1 (referred to as Theoretical Calculation), provides a benchmark upon which realistic values can be better understood and determined.

Appendix A provides detailed calculations which describe the total heat required to heat a steel pot of 4.7 liters (20 cm diameter and 15 cm height) and its contents to the boiling point of water and then maintain a simmer for the preparation periods of both rice (half an hour) and beans (three hours). Because further energy input is required to maintain a simmer in the pot due to heat losses, it was assumed that the heat lost due to convection, evaporation of water, and radiation would represent the energy needed to maintain a simmer in the pot after boiling point was reached and until the food was cooked. Once the heat required to cook both a pot full of rice and a pot full of beans was determined, the necessary amount of methane to provide this energy was calculated and converted to represent each food quantity on a 0.5 kg basis. This second calculation is shown in detail in Appendix B with an assumed stove efficiency of 55% and a caloric value of 50 MJ/ kg for methane (Engineering Toolbox (a.)).

The volume of methane necessary to cook 0.5 kg of rice was calculated to be 0.04 m^3 which is higher than the value found by Kumar De et al. (2014) at 0.01 m^3 of methane but smaller than the highest value measured by GTZ (1999) at 0.09 m^3 of methane. Concerning beans, the theoretical value of 0.21 m^3 of methane needed to cook 0.5 kg beans determined in the study was above the range found in literature at 0.12 – 0.01 m^3 of methane for 0.5 kg of beans measured by GTZ (1999) and Kumar De et al. (2014). These differences in findings suggest a discord in either food preparation, cooking methods, stove efficiencies and/or other omitted variables.

Table 3-2 contains the results of a nutrition survey conducted by the government of Panamá in 1992. This survey summarizes the daily intake of principle food groups by both rural and urban Panamanians. Data from the survey was used to estimate biogas demand per household by calculating the energy required to prepare meals of rice and beans based on the daily consumption of staple food groups. Because 1992 was the most recent data concerning Panamanian diets, it is important to note that the rural poverty headcount ratio at national poverty line (% of rural population) in Panamá (a statistic that represents the percentage of rural Panamanians who live below the poverty line in Panamá) has decreased from 35% in 1996 to 28% in 2012, an increase in living standards could correlate with an increase in consumption of more expensive foods such as meat (Trading Economics, 2015).

Table 3-2 Daily intake of principle food groups for Panamanians in 1992 adapted from the Food and Agricultural Organization of the United Nations (1999).

Demographic	Cereals	Tubers	Legumes	Fruits/ Vegetables	Oils/Fats	Meat	Fish
Rural	78.1	18.0	8.0	31.0	12.7	36.8	12.7
Urban	69.7	25.1	6.5	50.0	14.2	61.2	6.5

In determining the fuel required to provide a Panamanian household with sufficient energy to prepare food, the intake of cereals and legumes were the two items considered. This was assumed because in rural Panamá over 50% of all daily energy comes from cereal consumption, of which rice is the most common (FAO, 1999). In addition to rice, beans were added based on the author's experience working with swine farmers in Panamá and their tendency to use biogas from anaerobic digesters as a LPG substitute specifically when cooking beans.

Meats and fish were excluded from the calculations in this research because in Panamá meats and fish are typically fried in a pan and are not cooked for more than five or ten minutes. Therefore they were assumed to require a negligible fraction of biogas in comparison to rice and beans, the more abundant and cooking time intensive staples to prepare. Furthermore, cooking of tubers was not included in this research because the author observed they are customarily boiled outside in large pots over a three-stone fire and consumed on a mass scale for special occasions in soups.

During the author's time working in Panamá, he performed a population and livestock census involving 51 households in the community where he worked. Table 3-3 contains results of the fifteen (29%) households which owned swine at the time of the census and omits those that did not. None of the houses included in the survey owned or operated anaerobic digesters and manure was washed out from pens with water and left on the surrounding ground. This is important because if the manure were otherwise feed into an anaerobic reactor there would be an increased production of methane and an increased risk of introducing more methane into the environment from mismanagement. Households that owned swine were selected because real world examples of biogas supply and demand could be developed and further used to estimate the appropriate amount of animals to size of household and excess biogas generation if anaerobic digesters were constructed.

Table 3-3 Census data from a rural town in the Darien Provence of Panamá of households which owned swine. Data was collected by the author in June of 2015 during his service as a Peace Corps volunteer.

House	Number of People	Number of Swine
A	2.00	2.00
B	3.00	5.00
C	1.00	2.00
D	3.00	1.00
E	2.00	3.00
F	2.00	3.00
G	3.00	5.00
H	4.00	1.00
I	3.00	2.00
J	4.00	1.00
K	2.00	1.00
L	7.00	2.00
M	4.00	1.00
N	4.00	4.00
O	3.00	15.00

In Table 3-3 family sizes for households that owned swine in this community ranged from one to seven people and the number of swine owned by families ranges from one to fifteen.

The quantity of methane required to prepare the daily intake of food for an individual can be determined as:

$$\text{PMGR} = \Sigma\ [C_{food} * m_{consumed} * C_{0.5\ kg}] * C_{day} \qquad (3.1)$$

where PMGR is the personal daily methane requirement [m^3/person], C_{food} is the methane required to cook 0.5 kg of food from Table 3-1 [m^3/ 0.5 kg of food], $m_{consumed}$ is the individual mass of food consumed annually from Table 3-2 [kg/person-year], $C_{0.5\ kg}$ is the half kg converter [0.5 kg of food/kg of food], and C_{day} is the year to day converter [year/day].

The following equation uses Equation 3.1 to calculate the appropriate amount of animals for a household.

$$P = \frac{PMGR*FS}{BG*MC} \tag{3.2}$$

where P is the appropriate amount of animals based on family size [animals/family (#)], PMGR is the personal daily methane requirement [m^3/person], FS is the family size [# of people/family (#)], BG is the daily animal biogas production [m^3/animal], and MC is methane content [%].

By comparing the supply of biogas from the outputs of the Rowse (2011) model (see Appendix C for examples of model inputs and outputs), the personal daily methane requirement from Equation 3.1, and the size of household from Table 3-3, rural anaerobic reactors can be accurately sized based on household methane gas demand rather than risk biogas surpluses due to sizing based on maximum biogas or methane yields.

Chapter 4: Results and Discussion

4.1 Methane Demand

From the information provided in Table 3-1, Table 3-2, and Equation 3.1 it was determined that a Panamanian living in rural Panamá would require 0.03 m^3 of methane with a calorific value of 50 MJ/kg and a stove efficiency of 55% to provide enough energy to cook their daily supply of rice and beans (i.e. cereals and legumes). This calculation assumes a daily consumption of rice and beans and therefore 0.03 m^3 represents the daily individual methane demand per Panamanian. A sample calculation provided in Appendix D demonstrates the method developed to determine the personal daily methane requirements (PMGR) for a Panamanian diet in the location of this study.

4.2 Biogas Supply and Methane Content

Using Rowse's (2011) model, manure from a single swine provides 0.6 m^3 of biogas a day. In addition to swine, dairy cows are a common means of income for rural Panamanian households and because they are typically contained in a central location, their excrement can be fed into an anaerobic digester and converted into biogas. Using Rowse's (2011) model it was calculated that 5.2 m^3 of biogas could be generated daily per dairy cow. These calculations were based on the study region's maximum mean local temperature of 26 degrees Celsius (The Encyclopedia of Earth, 2008). Because methane is the combustible substance of biogas used in cooking it was calculated by further defining the biogas supply in terms of its methane content. This calculation is to better understand the ability of biogas to provide energy to households by comparing the amount of methane required to supply a family with sufficient energy to cook.

4.3 Biogas Production

The daily production of biogas from a dairy cow is 8.7 times the volume of biogas produced by a single swine (Rowse, 2011). From Figure 3-1, the amount of biogas produced per day is dependent upon two factors: 1) the organic loading rate of the waste stream and 2) the stoichiometric coefficients and overall reaction equation (i.e. overall R equation). The combination of these two factors allows for the estimation of biogas production from various livestock scenarios by defining the quantity and composition of the volatile solids in the waste stream. The organic loading rate of the waste stream defines the quantity of volatile solids in the manure by describing the weight of volatile solids per day where the stoichiometric coefficients and overall R equation define the composition of the waste stream by characterizing the molecular weight of the volatile solids. Therefore the increased production of biogas from dairy cow manure versus swine manure can be understood when larger values for both the loading rate and molecular weight of the volatile solids from dairy cow manure are introduced into Equation 4.1.

Equation 4.1 calculates the number of moles of the organic molecule by normalizing the bulk generation of volatile solids (mass VS) with respect to the organic molecule's molecular weight (MW) of a specific waste stream.

Number of moles for the organic molecule $C_nH_aO_bN_c$/d (Rowse, 2011 Equation 3.2.9) (4.1)

mol $C_nH_aO_bN_c$/d = 1,000*$\frac{mass\ VS}{MW}$

In Equation 4.1, mol $C_nH_aO_bN_c$/d is the number of moles of the organic molecule per day [$mol_{C_nH_aO_bN_c/\mathrm{d}}$ /day], 1,000 is the unit conversion for the number of grams in a kilogram[g/kg], mass VS is the mass of volatile solids added per day [kg VS/day], and MW is the molecular weight of $C_nH_aO_bN_c$/d [g/mol].

Because the molecular mass (77.43 g/mol) and the volatile solid mass per day (7.5 kg VS/day) associated with dairy cows are greater than the molecular mass (54.16 g/mol) and the volatile solid mass per day of swine (1 kg VS/day), the waste stream of dairy cows is shown to yield 96.86 mol/day compared to the 18.46 mol/day waste stream of swine (Rowse, 2011). Next, the quantity of biogas is calculated based on the number of moles of the organic molecule in the waste stream.

However, because the model used in this study is based on plug flow reactor mechanics, results could vary from those of other studies concerning small scale anaerobic digestion. For example the production of biogas from a plug flow model may be a conservative estimate when compared to other models based on up flow anaerobic sludge blanket digestion mechanics which have been found to produce more biogas and to be more accurate representations of small scale tubular anaerobic digesters (Kinyua et al., 2016).

4.4 Appropriate Number of Animals for Household Demand

Using the known personal daily methane requirements for one rural Panamanian (0.03 m^3) determined in Section 4.1, the normal range of methane for biogas of 40-70% (GTZ, 1999), and the volume of biogas supplied by a single swine (0.6 m^3/day) or dairy cow (5.2 m^3/day) located in the Darien Provence of Panamá, the appropriate number of swine and dairy cows needed to provide sufficient biogas to cook the daily intake of rice and beans for each of the fifteen surveyed households was calculated using Equation 3.1 and Equation 3.2. Results for a biogas with methane content of 40% are presented in Table 4-1 while Table 4-2 presents the results for a biogas with a methane content of 70%.

Table 4-1 shows that House C (with the lowest number of occupants at one) would require 0.11 swine or 0.01 dairy cows at a 40% methane content to supply the household with sufficient biogas for cooking where House L (with the highest number of occupants at seven) would require 0.79 swine or 0.09 dairy cows at a 40% methane content. The average household size of 3.13 people would require 0.35 swine or 0.04 dairy cows at 40% methane to be supplied with sufficient methane to cook.

Table 4-1 Number of swine or dairy cows each household would need to cover cooking energy demands with a biogas of 40% methane.

House	Number of People	Appropriate Number of Swine (40% Methane)	Appropriate Number of Dairy Cow (40% Methane)
A	2.00	0.23	0.03
B	3.00	0.34	0.04
C	1.00	0.11	0.01
D	3.00	0.34	0.04
E	2.00	0.23	0.03
F	2.00	0.23	0.03
G	3.00	0.34	0.04
H	4.00	0.45	0.05
I	3.00	0.34	0.04
J	4.00	0.45	0.05
K	2.00	0.23	0.03
L	7.00	0.79	0.09
M	4.00	0.45	0.05
N	4.00	0.45	0.05
O	3.00	0.34	0.04
Average	3.13	0.35	0.04

Table 4-2 Number of swine or dairy cows each household would need to cover cooking energy demands with a biogas of 70% methane.

House	Number of People	Appropriate Number of Swine (70% Methane)	Appropriate Number of Dairy Cow (70% Methane)
A	2.00	0.13	0.01
B	3.00	0.19	0.02
C	1.00	0.06	0.01
D	3.00	0.19	0.02
E	2.00	0.13	0.01
F	2.00	0.13	0.01
G	3.00	0.19	0.02
H	4.00	0.26	0.03
I	3.00	0.19	0.02
J	4.00	0.26	0.03
K	2.00	0.13	0.01
L	7.00	0.45	0.05
M	4.00	0.26	0.03
N	4.00	0.26	0.03
O	3.00	0.19	0.02
Average	3.13	0.20	0.02

Table 4-2 shows that House C (with the lowest number of occupants at one) would require 0.06 swine or 0.01 dairy cows at a 70% methane content to supply the household with sufficient biogas for cooking where House L (with the highest number of occupants at seven) would require 0.45 swine or 0.05 dairy cows at a 70% methane to supply the household with sufficient fuel for cooking. The average household size of 3.13 people would require 0.2 swine or 0.02 dairy cows at a 70% methane to be supplied with sufficient methane to cook.

According to the results of Table 4-1 and Table 4-2 not one of the fifteen households included in this study would require more than one entire swine or dairy cow to be supplied with sufficient methane to cook rice and beans for everyone in the household. Furthermore, because the 2010 Panamanian census reported a 3.15 people per household average that matches closely with the average household in this survey, these results may be able to be extended nationwide (Radio Panamá, 2010).

4.5 Assessment of Biogas Supply and Household Demand

Table 4-3 and Table 4-4 provide information on the possibility of each household in the community to produce excessive biogas by comparing the household demand of methane with the potential supply of methane if an anaerobic reactor were built and the full production of swine manure was collected for each household included in the survey. Based on these values each household was assessed as to whether or not gas production exceeded household demand and therefore would potentially contribute to atmospheric greenhouse emissions.

In order to determine the supply volume of methane for each household's situation, the number of swine was multiplied by the daily yield of biogas as determined by Rowse's (2011) model and its corresponding methane content defined by GTZ (1999) of 40-70%. From the methane volume required to prepare 0.5 kg of rice and beans provided in Table 3-1 and the annual food consumption of Panamanians in Table 3-2, personal methane per Panamanian was calculated using Equation 3.1.

Appendix D provides a sample calculation for this estimation of personal methane demand. After the personal daily methane demand was established (0.03 $\boldsymbol{m^3}$) it was multiplied by the number of occupants of each household to determine household methane demand. Thus, with both the supply and demand of methane for each household determined, a comparison was made as to whether or not supply would exceed demand.

Of the fifteen households in the survey shown in Table 4-3, where biogas with a methane content of 40% was considered, all were found to experience an over production of methane that would exceed the household demand for cooking rice and beans. The highest ratio of people to swine was seen in Houses M, J, and H with four people to one swine where the production of methane exceeded the demand by 0.09 m^3. Inversely the lowest ratio of people to swine was seen in House O with fifteen swine to three people and the overproduction of biogas was calculated to be 3.47 m^3 of methane. Because of the large amount of swine to family size for House O, there would be a supply of methane nearly 32 times the demand if an anaerobic reactor was built.

Of the fifteen households in the survey shown in Table 4-4, where biogas with a methane content of 70% was considered, all were found to experience an over production of methane that would exceed the household demand for cooking rice and beans. The highest ratio of people to swine was seen in Houses M, J, and H with four people to one swine where the production of methane exceed the demand by 0.27 m^3. Inversely the lowest ratio of people to swine was seen in House O with fifteen swine and three people and the overproduction of biogas was calculated to be 6.17 m^3 of methane. An over production of methane that is 56 fold the demand for methane.

Therefore, due to House O's large overproduction of methane, it was excluded from the average of excess methane production in both Table 4-3 and Table 4-4 but included in the total production of methane for the fifteen households. It was calculated from the survey that the average household of 3.13 people and the average swine ownership of 2.36 would produce 0.45 m^3 of excess methane from

Table 4-3 Swine ownership, methane supply, and methane demand emissions for a biogas with a methane of 40%.

House	Number of People	Number of Swine	Methane Supply (40%) m^3/day	Methane Demand m^3/day	Difference in Supply and Demand (40%) m^3/day	Does Supply Exceed Demand?
A	2.00	2.00	0.48	0.08	0.40	yes
B	3.00	5.00	1.20	0.11	1.08	yes
C	1.00	2.00	0.48	0.04	0.44	yes
D	3.00	1.00	0.24	0.11	0.13	yes
E	2.00	3.00	0.72	0.08	0.64	yes
F	2.00	3.00	0.72	0.08	0.64	yes
G	3.00	5.00	1.20	0.11	1.08	yes
H	4.00	1.00	0.24	0.15	0.09	yes
I	3.00	2.00	0.48	0.11	0.36	yes
J	4.00	1.00	0.24	0.15	0.09	yes
K	2.00	1.00	0.24	0.08	0.16	yes
L	7.00	2.00	0.48	0.27	0.21	yes
M	4.00	1.00	0.24	0.15	0.09	yes
N	4.00	4.00	0.96	0.15	0.81	yes
O	3.00	15.00	3.59	0.11	3.47	yes
Average*	3.13	2.36	0.56	0.12	0.45	yes
Total	47.00	48.00	11.48	1.78	9.70	yes
*Averages do not include House O						

Table 4-4 Swine ownership, methane supply, and methane demand emissions for a biogas with a methane of 70%.

House	Number of People	Number of Swine	Methane Supply (70%) m^3/day	Methane Demand m^3/day	Difference in Supply and Demand (70%) m^3/day	Does Supply Exceed Demand?
A	2.00	2.00	0.84	0.08	0.76	yes
B	3.00	5.00	2.09	0.11	1.98	yes
C	1.00	2.00	0.84	0.04	0.80	yes
D	3.00	1.00	0.42	0.11	0.30	yes
E	2.00	3.00	1.26	0.08	1.18	yes
F	2.00	3.00	1.26	0.08	1.18	yes
G	3.00	5.00	2.09	0.11	1.98	yes
H	4.00	1.00	0.42	0.15	0.27	yes
I	3.00	2.00	0.84	0.11	0.72	yes
J	4.00	1.00	0.42	0.15	0.27	yes
K	2.00	1.00	0.42	0.08	0.34	yes
L	7.00	2.00	0.84	0.27	0.57	yes
M	4.00	1.00	0.42	0.15	0.27	yes
N	4.00	4.00	1.67	0.15	1.52	yes
O	3.00	15.00	6.28	0.11	6.17	yes
Average*	3.13	2.36	0.99	0.12	0.87	yes
Total	47.00	48.00	20.09	1.78	18.31	yes
*Averages do not include House O						

biogas with a 40% methane content and 9.7 m^3 of excess methane village wide. Furthermore, for a biogas made up of 70% methane, the average household size and swine ownership would produce 0.87 m^3 of excess methane and 18.31 m^3 of excess methane village wide.

To ensure that there would be no danger in producing an abundance of excess methane in this case, it is recommended that additional methods for biogas consumption be investigated for this geographical context. For example, in addition to cooking, methods for utilizing biogas could also include: expanding the delivery of excess biogas to more households, installing biogas lamps or kitchen appliances such as ovens and refrigerators, or produce electricity from a generator (GTZ, 1999).

4.6 Potential Methane, Carbon Dioxide and Carbon Dioxide Equivalence of Excess Biogas per Household

To better understand the potential of each household to impact the environment with greenhouse gases due to an overproduction of biogas, the potential methane, carbon dioxide and carbon dioxide equivalence of excess biogas per household was calculated and organized in Table 4-5 for a biogas with a methane content of 40% and Table 4-6 for a biogas with a methane content of 70%. The differences in supply and demand of biogas were taken from Table 4-3 and Table 4-4 and used to calculate the corresponding methane and carbon dioxide emissions. See Appendix F for the calculations used to determine methane, carbon dioxide and daily carbon equivalence.

Equation 4.2 was used to determine the quantity of methane resulting from excess biogas. This value contributes to greenhouse gas emissions when positive.

Amount of methane from excess biogas (4.2)

$$CH_4 = 1{,}000 * \rho_{CH_4} * \%_{CH_4} * BG_{exc}$$

where CH_4 is the amount of methane produced by biogas [g/day], 1,000 is the conversion from m^3 to liters [l/m^3], ρ_{CH_4} is the density of methane at 1atm and 299K (calculated to be 0.65 [g/l]), $\%_{CH_4}$ is the percent of methane in biogas, and BG_{exc} is excess biogas [m^3/day] (as seen in Table 4-3). See Appendix F for detailed calculations of methane and carbon dioxide from excess biogas production.

The calculation for methane production due to excess biogas from Equation 4.2 was repeated for carbon dioxide and the results were used to determine the carbon dioxide equivalence of biogas in Equation 4.3.

Carbon dioxide equivalence of biogas (4.3)

CO_2eq = CO_2/CH_4*CH_4 + CO_2

where CO_2eq is the total carbon dioxide equivalence of biogas [g_{CO_2eq}], CO_2/CH_4 is the greenhouse gas impact conversion for methane to carbon dioxide (assumed to be 25 [g_{CO_2}/g_{CH_4}] from the IPCC, 2007 and Mihelcic et al., 2014), CH_4 is the amount of methane produced by biogas [g_{CH_4}], and CO_2 is the amount of carbon dioxide produced by biogas [g_{CO_2}]. See Appendix F for detailed calculations of carbon dioxide equivalence from excess biogas production.

Table 4-5 contains the carbon dioxide equivalents of the excess biogas with a methane content of 40% for the fifteen houses in the survey. The minimum carbon dioxide equivalents released daily was 1,962.94 grams and the maximum was calculated to be 8,502.05 grams. The average household size of 3.14 people to 2.36 swine yielded an output of 8,502.05 grams per day of carbon dioxide equivalence where the total demand of the 47 people included in the survey yielded an overall output of 183,477.99 grams per day of CO_2eq from a total of 48 swine. This combined production of extraneous biogas with a methane content of 40% for the fifteen households included in the survey, if released into the atmosphere every day for a year, would introduce 66,969,466.02 grams per year of CO_2eq into the atmosphere. This equates to the amount of carbon dioxide released in burning 7,535.67 gallons of gasoline (EPA, 2014).

Table 4-6 contains the carbon dioxide equivalence of the excess biogas with a methane content of 70% for the fifteen houses in the survey. The minimum carbon dioxide equivalence released daily was 4,609.09 grams and the maximum was calculated to be 104,223.55 grams. The average household

Table 4-5 Potential methane, carbon dioxide and carbon dioxide equivalence of excess biogas per household with a biogas methane content of 40%.

House	Number of People	Number of Swine	Difference in Supply and Demand of Methane (40%) m^3/day	Difference in Supply and Demand of Methane (40%) g CH4/day	Carbon Dioxide (60%) g CO2/day	Daily CO2eq Emissions (40% CH4) g CO2eq/day
A	2.00	2.00	0.40	261.71	1,076.40	7,619.27
B	3.00	5.00	1.08	703.53	2,691.00	20,279.30
C	1.00	2.00	0.44	286.34	1,076.40	8,234.83
D	3.00	1.00	0.13	81.61	538.20	2,578.50
E	2.00	3.00	0.64	417.19	1,614.60	12,044.47
F	2.00	3.00	0.64	417.19	1,614.60	12,044.47
G	3.00	5.00	1.08	703.53	2,691.00	20,279.30
H	4.00	1.00	0.09	56.99	538.20	1,962.94
I	3.00	2.00	0.36	237.09	1,076.40	7,003.70
J	4.00	1.00	0.09	56.99	538.20	1,962.94
K	2.00	1.00	0.16	106.23	538.20	3,194.07
L	7.00	2.00	0.21	138.60	1,076.40	4,541.44
M	4.00	1.00	0.09	56.99	538.20	1,962.94
N	4.00	4.00	0.81	523.43	2,152.80	15,238.54
O	3.00	15.00	3.47	2,258.33	8,073.00	64,531.30
Average*	3.14	2.36	0.45	289.34	1,268.61	8,502.05
Total	47.00	48.00	9.70	6,305.78	25,833.60	183,477.99
*Averages do not include House O						

Table 4-6 Potential methane, carbon dioxide and carbon dioxide equivalence of excess biogas per household with a biogas methane content of 70%.

House	Number of People	Number of Swine	Difference in Supply and Demand of Methane (70%) m^3/day	Difference in Supply and Demand of Methane (70%) g CH4/day	Carbon Dioxide (30%) g CO2/day	Daily CO2eq Emissions (70% CH4) g CO2eq/day
A	2.00	2.00	0.76	494.93	538.20	12,911.57
B	3.00	5.00	1.98	1,286.58	1,345.50	33,510.05
C	1.00	2.00	0.80	519.56	538.20	13,527.13
D	3.00	1.00	0.30	198.22	269.10	5,224.65
E	2.00	3.00	1.18	767.02	807.30	19,982.92
F	2.00	3.00	1.18	767.02	807.30	19,982.92
G	3.00	5.00	1.98	1,286.58	1,345.50	33,510.05
H	4.00	1.00	0.27	173.60	269.10	4,609.09
I	3.00	2.00	0.72	470.31	538.20	12,296.00
J	4.00	1.00	0.27	173.60	269.10	4,609.09
K	2.00	1.00	0.34	222.84	269.10	5,840.22
L	7.00	2.00	0.57	371.82	538.20	9,833.74
M	4.00	1.00	0.27	173.60	269.10	4,609.09
N	4.00	4.00	1.52	989.87	1,076.40	25,823.14
O	3.00	15.00	6.17	4,007.48	4,036.50	104,223.55
Average*	3.14	2.36	0.87	564.20	634.31	14,739.41
Total	47.00	48.00	18.31	11,903.06	12,916.80	310,493.19
*Averages do not include House O						

size of 3.14 people to 2.36 swine yielded an output of 14,739.41 grams per day of carbon dioxide equivalence where the total demand of the 47 people included in the survey yielded an overall output of 310,493.19 grams per day of CO_2eq. This combined production of extraneous biogas with a methane content of 70% for the fifteen households included in the survey, if released into the atmosphere everyday for a year, would introduce 113,330,014.02 grams per year of CO_2eq into the atmosphere. This equates to the amount of carbon dioxide released in burning 12,752.34 gallons of gasoline (EPA, 2014).

Chapter 5: Conclusions and Recommendations for Future Research

5.1 Conclusions

While the thesis author was reviewing the literature of operation of small-scale household anaerobic digesters, between 2 and 10 m^3, gaps in the body of knowledge concerning household demand of biogas and the amount of energy required to prepare meals became apparent. These gaps reflect the lack of focus regarding the end use of biogas and the misunderstanding this can lead to when sizing reactors on an individual household basis.

In an attempt to address these issues, this study tabulated the reported literature values of methane volumes to prepare rice and beans. The mean values from this review concluded that 0.06 m^3 of methane was required to prepare 0.5 kg of rice and 0.06 m^3 of methane was required to prepare 0.5 kg of beans, respectively. Furthermore theoretical calculations were developed to verify the validity of the values found from literature and were determined to be, 0.04 m^3 of methane per 0.5 kg (dry weight) of rice and 0.21 m^3 of methane per 0.5 kg (dry weight) of beans.

The purpose of this research was to consider a technology's capacity to negatively impact the environment through improper design or mismanagement and subsequently refocus conventional design approaches to better address and avoid this outcome. Specifically this research, following the observation introduced by the research of Bruun et al. (2014), investigated the potential of rural anaerobic reactors to serve as overproducers of methane that are not designed based on the household demand of biogas from families. The consequence of this oversight, pointed out by Bruun et al. (2014), was the production of gas emissions from small-scale rural anaerobic reactors which could be contributing up to 1% of all methane production worldwide.

From a survey conducted by the author of a rural town located in the Darien province of Panamá, household size and number of swine owned was recorded to determine: 1) the appropriate amount of livestock to family size and 2) assess whether or not a household would experience an overproduction of biogas if an anaerobic reactor was built and how much this overproduction would affect the environment in terms of CO_2 equivalence.

Daily biogas supply, using results obtained from Rowse's (2011) design model for small-scale rural anaerobic reactors, for swine was concluded to be 0.6 m^3 and 5.2 m^3 for dairy cows located in the Darien Provence of Panamá. These values were then converted into supply volumes of methane based on the normal percent methane range 40-70% of biogas (GTZ, 1999). Personal daily methane demand for a Panamanian was calculated from the method developed in this study to be 0.03 m^3 per day and was further used to calculate household methane demands.

Based on the results for household methane demand and supply rates of biogas for both swine and dairy cows, the average household size of 3.13 people would require 0.35 swine or 0.04 dairy cows for a biogas containing 40% methane to supply sufficient energy for cooking rice and beans. Whereas 0.2 swine or 0.02 dairy cows were found to be sufficient with a biogas of 70% methane. Furthermore, because the 2010 Panamanian census reported a 3.15 people per household average, these results can be extended to apply nationwide (Radio Panamá, 2010).

It was further concluded that all the households that owned swine in the survey would produce excessive greenhouse gases such as methane and carbon dioxide that could be introduced into the atmosphere through neglect and mismanagement of the digester. Based on the methods developed in this study, these excess volumes of biogas represent a total emission rate of CO_2 equivalents of 183,477.99 grams of CO_2eq a day for 40% methane and 310,493.19 grams of CO_2eq a day for 70% methane

Therefore, considering such a high number of households would produce a supply of biogas at a rate that would exceed demand, the result of this study suggests the necessity to size rural anaerobic reactors based on user demand instead of designing reactor size based upon a given quantity of manure or optimal gas production. In addition to investigating household biogas demand as a means of preventing overwhelming excess supplies of biogas, storage methods and alternative domestic uses of biogas such as illumination, refrigeration and power generation should be incorporated into the design and sizing of rural anaerobic digesters.

5.2 Recommendations for Future Research

Future work which would improve the ability of rural anaerobic reactors to provide sustainable energy for developing households without becoming sources of greenhouse gas emissions include: improved understanding of household energy demands, increased monitoring of constructed reactors, increased capacitation of operators, and increased storage and end use options for owners.

Currently the energy demands for rural households are not well defined, especially when estimating the energy required to prepare meals. An increased understanding of household energy would further aid development workers and governmental agencies in their efforts to assess and design projects for rural communities.

Improved monitoring of small-scale anaerobic reactors with regards to energy output and usage informs organizations, designers, and development engineers on the effectiveness of their approach in implementing this technology. Without the data to support the proper management or acceptance of small-scale anaerobic digesters this technology risks becoming an unanticipated source of greenhouse gasses and therefore requires monitoring post project completion.

Furthermore, the knowledge and skill to operate reactors by owners should be both proven and developed. Owners and operators of small sale anaerobic digesters should be equipped with the skills to address sources of fugitive biogas emissions from leaks and improper construction and possess the understanding that excess biogas production should not be directly introduced into the environment without being flared.

Finally research and development to improve and increase the options of end uses for biogas, such as biogas lamps, kitchen appliances such as refrigerators and ovens, and the capacity to produce electricity from generators, can widen the benefits of small-scale anaerobic digestion and contribute towards the mitigation of greenhouse gas production from unused biogas.

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Appendix A: Calculation of the Household Cooking Energy Demand of Rice/ Beans

Energy input required to bring a pot of food and water to boiling point and maintain a simmer throughout the cooking process. Factors contributing to overall energy input include: 1) energy demand to boil food, 2) heat to maintain cooking from convection losses, 3) heat to maintain cooking from evaporation losses, and 4) heat to maintain cooking from radiation losses. With the total energy required for all four factors understood, the biogas required to prepare foods can be calculated and used to quantify personal and household demand of biogas.

- The energy demand to boil food: $Q_t = Q_1 + Q_2 + Q_3 + Q_4$

  where:

  Q_t = total heat [J]

  Q_1 = heat to bring pot to a boil [J]

  Q_2 = heat to maintain cooking from convection losses [J]

  Q_3 = heat to maintain cooking from evaporation losses [J]

  Q_4 = heat to maintain cooking from radiation losses [J]

- Heat to bring pot to a boil: $Q_1 = \sum \{C_p * m\} * (T_{final} - T_{initial})$

  where:

  Q_1 = heat to bring pot to a boil [J]

  C_p = specific heat [J/g-C^o] 4.84 [J/g-C^o] water, 1.84 [J/g-C^o] rice [22], 1.17 [J/g-C^o] kidney beans [26] and 0.45 [J/g-C^o] steel (Urone, 2013)

  m = mass [g]

  $T_{initial}$ = initial temperature [C^o]

  T_{final} = final temperature [C^o]

- Density of: water, foods and cooking wear: ρ = $\frac{\mathrm{m}}{\mathrm{V}}$

  where:

  ρ = density [g/cm^3]

  1 [g/cm^3] water, 0.82 [g/cm^3] rice (FAO, 2012), 0.68 [g/cm^3] kidney beans (FAO, 2012), and 7.74 steel [g/cm^3] (Engineering Toolbox (b.)).

  m = mass [g]

  V = volume [cm^3]

- Volume: V = $\frac{\pi}{4}$*d^2*h

  where:

  V = volume [cm^3]

  d = diameter [cm]

  h = height [cm]

- Heat to maintain cooking from convection losses: Q_2= h*A*($\mathrm{T}_{\mathrm{surface}}$ - $\mathrm{T}_{\mathrm{ambient}}$)*t

  where:

  Q_2 = heat to maintain cooking from convection losses [J]

  h = heat transfer coefficient [W/m^2K]

  A = exposed surface area of pot [m^2] (sides and lid only)

  $\mathrm{T}_{\mathrm{surface}}$ = surface temperature of pot [K]

  $\mathrm{T}_{\mathrm{ambient}}$ = ambient temperature [K]

  t = time [sec]

- Exposed surface area of pot sides and lid only: A = $\frac{\pi}{4}$*$(\mathrm{d})^2$ + π*d*h

  where:

  d = diameter [cm]

  h = height [cm]

- Temperature conversion Celsius to Kelvin: T = T [C^o] + 273 = T [K]

  where:

  T = temperature

- Heat to maintain cooking from evaporation losses: Q_3 = m*L_v

  where:

  Q_3 = heat to maintain cooking from evaporation losses [J]

  m = mass of evaporated water [g]

  L_v = latent heat of vaporization [J/g]

  2256 [J/g] water

- Rate of water evaporation: r = $\frac{m}{t}$

  where:

  r = rate of evaporation for water with lid [g/h]

  88 [g/h] water (Berick, 2006 Figure 5)

  m = mass [g]

  t = time [hour]

- Exposed surface area of pot sides and lid only: A = 2*$\frac{\pi}{4}$*$(d)^2$ +π*d*h

  where:

  d = diameter [cm]

  h = height [cm]

- Heat to maintain cooking from radiation losses: Q_4 = ε*σ*A*($T_{simmer}^4 - T_{ambient}^4$)*t

  where:

  Q_4 = heat to maintain cooking from radiation losses [J]

  ε = emissivity

  σ = Stephan-Boltzmann constant [W/m^2- K^4]

A = exposed surface area of pot $[\mathrm{m}^2]$

$\mathrm{T}_{\mathrm{simmer}}$ = surface temperature of pot at a simmer [K]

$\mathrm{T}_{\mathrm{ambient}}$ = ambient temperature [K]

Sample calculations for cubic meters of biogas required to cook 0.5 kg of rice for 30 minutes with: 22 $[\mathrm{C}^{\mathrm{o}}]$ ambient temperature, 100 $[\mathrm{C}^{\mathrm{o}}]$ boiling temperature and 98 $[\mathrm{C}^{\mathrm{o}}]$ simmering temperature.

- Mass of substance: m = $\rho_{\mathrm{substance}}$*V

  where:

  m = mass [g]

  $\rho_{\mathrm{substance}}$ = density of substance $[\mathrm{g/cm}^3]$

  V = volume $[\mathrm{cm}^3]$

- Volume of rice and water (rice is one part rice to two parts water)

  where:

  $\mathrm{V}_{\mathrm{in\ pot}} = \frac{\pi}{4} * d^2 * h$

  d = 20 [cm]

  h = 15 [cm]

  $\mathrm{V}_{\mathrm{in\ pot}} = \frac{\pi}{4} * (20\ [\mathrm{cm}])^2 * 15\ [\mathrm{cm}] = 4712\ [\mathrm{cm}^3]$

  $\mathrm{V}_{\mathrm{water}} = (2/3) * \mathrm{V}_{\mathrm{in\ pot}} = (2/3) * 4712\ [\mathrm{cm}^3] = 3142\ [\mathrm{cm}^3]$

  $\mathrm{V}_{\mathrm{rice}} = (1/3) * \mathrm{V}_{\mathrm{in\ pot}} = (1/3) * 4712\ [\mathrm{cm}^3] = 1570\ [\mathrm{cm}^3]$

- Volume of pot: $\mathrm{V}_{\mathrm{of\ pot}} = 2(\frac{\pi}{4} * d^2 * t) + \pi * d * h * t$

  where:

  d = 20 [cm]

  t = 0.3 [cm]

  h = 15 [cm]

$V_{\text{of pot}}$ = 2($\frac{\pi}{4}$*$(20\ [\text{cm}])^2$*0.3 [cm]) + π*20 [cm]* 15 [cm]*0.3 [cm] = 471 $[\text{cm}^3]$

- Heat to bring pot to a boil: $Q_1 = \sum \{C_p * m\} * (T_{\text{boil}} - T_{\text{ambient}})$

  where: $C_{\text{p\_ water}}$ = 4.48 [J/g-C^o]

  $m_{\text{water}} = \rho_{\text{water}} * V_{\text{water}}$ = 1 [g/cm^3]*(2/3) 4710 $[\text{cm}^3]$ = 3140 [g]

  $C_{\text{p\_ rice}}$ = 1.84 [J/g-C^o]

  $m_{\text{rice}} = \rho_{\text{rice}} * V_{\text{rice}}$= 0.82 [g/$\text{cm}^3$]*(1/3)*4710 $[\text{cm}^3]$ = 1287.4 [g]

  $C_{\text{p\_stainles steel}}$ = 0.45 [J/g-C^o]

  $m_{\text{pot}} = \rho_{\text{rice}} * V_{\text{of pot}}$ = 7.74 [g/cm^3]*471 $[\text{cm}^3]$ = 3646 [g]

  T_{boil} = 100 [C^o]

  T_{ambient} = 22 [C^o]

  Q_1 = {1287.4 [g rice]*1.84 [J/g-C^o] + 3140 [g water]*4.48 [J/g-C^o] +

  3646 [g steel]*0.45 [J/g-C^o]}*(100 [C^o] - 22 [C^o]) = 1409983 [J]

- Surface area of pot (not counting the bottom): $A = \frac{\pi}{4} * d^2 + \pi * d * h$

  where:

  d = 20 [cm]

  h = 15 [cm]

  A = $\frac{\pi}{4}$*$(20\ [\text{cm}])^2$ + π*20 [cm]*15 [cm] = 1256 $[\text{cm}^2]$ = 0.13$[\text{m}^2]$

- Heat to maintain cooking from convection losses: $Q_2 = h * A * (T_{\text{surface}} - T_{\text{ambient}}) * t$

  where:

  h_{steel} = 25 [W/m^2K] (Engineering Toolbox (c.))

  A = 0.13 $[\text{m}^2]$

  T_{surface} = 371 [K]

  T_{ambient} = 295 [K]

t = 30 [min] = 1800 [sec]

Q_2 = 25 [W/m^2K]*0.13 [m^2]*(371 [K]- 295 [K])*1800 [sec] = 444600 [J]

- Mass of evaporated water: m = r*t

where:

m = mass [g]

r = 88 [g/hour] water (Berick, 2006 Figure 5)

t = 0.5 [hour]

m = 88 [g/hour]*0.5 [hour] = 44 [g]

- Heat to maintain cooking from evaporation losses: Q_3 = m*L_v

where:

m = 44 [g]

L_v = 2256 [J/g]

Q_3 [J] = 44 [g]*2256 [J/g] = 99264 [J]

- Surface area of pot: A = 2*$\frac{\pi}{4}$*d^2 + π*d*h

where:

d = 20 [cm]

h = 15 [cm]

A = 2*$\frac{\pi}{4}$*$(20\ [\mathrm{cm}])^2$ + π*20 [cm]* 15 [cm] = 1570 [cm^2]*$(1\mathrm{m}/100\mathrm{cm})^2$ = 0.16 [m^2]

- Heat to maintain cooking from radiation losses [J]: Q_4 [J] = ε*σ*A*($T_{simmer}^4 - T_{ambient}^4$)* t

where:

ε = 0.25 (Berick, 2006) (new stainless steel)

σ = 5.67 x 10-8 [W/m^2- K^4] (Berick, 2006)

A [m^2] = 0.16 [m^2]

T_{simmer} = 371 [K]

$T_{ambient}$ = 295 [K]

t = 30 [min]* 60 [sec]/ 1 [min] = 1800 [sec]

Q_4 [J] = 0.25*5.67 x 10-8 [W/m^2- K^4]*0.16 [m^2]*($371\ [K]^4$- $295\ [K]^4$)*1800 [sec] = 46424 [J]

- Total energy demand to boil food: Q_t = Q_1+ Q_2+ Q_3+ Q_4

  where:

  Q_1 = 1409983 [J]

  Q_2 = 444600 [J]

  Q_3 = 99264 [J]

  Q_4 = 46424 [J]

  Q_t = 1409983 [J] + 444600 [J] + 99264 [J] + 46424 [J] = 2000271 [J] = 2 [MJ] to cook 1.3 kg of rice

Appendix B: Calculation of Methane to Cook 0.5 kg of Rice/ Beans

Considering the efficiency of stoves, the calorific value of methane, and the energy requirements to prepare a specified quantity of food as calculated in Appendix A, the methane required to cook 0.5 kg of food is calculated. With the amount of methane required to prepare 0.5 kg of food, personal and household methane demand can be defined based on food consumption rates.

- Methane required to cook 0.5 kg of food: MGR = $\frac{Q_t\,C}{\% * m * MG * C_V}$

where:

MGR = methane gas required [m^3/ 0.5 kg of food]

Q_t = heat required to cook m [MJ]

C = mass converter to 0.5 kg of food [kg of food/ 0.5 kg of food]

% = stove efficiency

m = mass of food cooked [kg of food]

MG = calorific value of methane [MJ/ m^3]

C_V = volume converter [kg/m^3]

Sample calculation for calculating biogas for required methane to cook rice.

- Methane required to cook rice: MGR = $\frac{Q_t\,C}{\% * m * MG * C_V}$

where:

MGR = methane gas required [m^3/ 0.5 kg of rice]

Q_t = 2 [MJ]

C = 0.5 [kg of rice/ 0.5 kg of rice]

% stove efficiency = 0.55 (GTZ, 1999)

m = 1.3 [kg of rice]

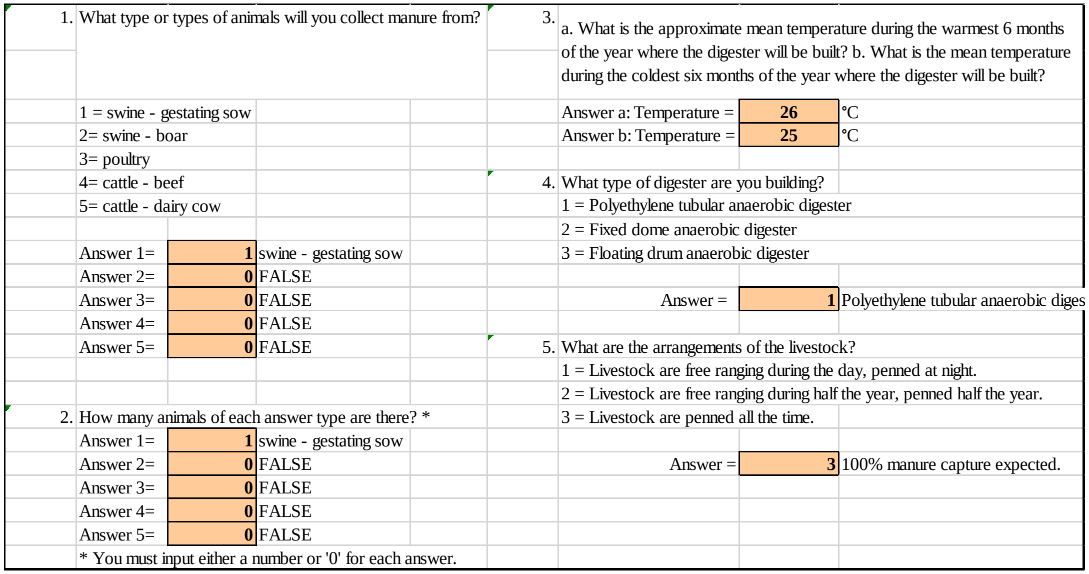
MG = 50 [MJ/m^3] (Engineering Toolbox (a.))

MGR = 2 [MJ]*0.5 [kg rice/ 0.5 kg rice]/ (0.55*50 [MJ/ m^3]*1.3 [kg of rice]*0.714 [kg/m^3]) = …

… = 0.06 [m^3/ 0.5 kg of rice]

Appendix C: Model Inputs and Results for the Design of a Small-Scale Anaerobic Digester for Application in Rural Developing Countries[2]

Model inputs from mathematical model are the following: 1) Swine – gestating sow = 1, 2) quantity = 1, 3) 26 °C and 25 °C, 4) Polyethylene tubular anaerobic digester = 1, and 5) Livestock penned all the time = 3.



1.	What type or types of animals will you collect manure from?		
	1 = swine - gestating sow		
	2= swine - boar		
	3= poultry		
	4= cattle - beef		
	5= cattle - dairy cow		
	Answer 1=	1	swine - gestating sow
	Answer 2=	0	FALSE
	Answer 3=	0	FALSE
	Answer 4=	0	FALSE
	Answer 5=	0	FALSE
2.	How many animals of each answer type are there? *		
	Answer 1=	1	swine - gestating sow
	Answer 2=	0	FALSE
	Answer 3=	0	FALSE
	Answer 4=	0	FALSE
	Answer 5=	0	FALSE
	* You must input either a number or '0' for each answer.		

3.	a. What is the approximate mean temperature during the warmest 6 months of the year where the digester will be built? b. What is the mean temperature during the coldest six months of the year where the digester will be built?		
	Answer a: Temperature =	26	°C
	Answer b: Temperature =	25	°C
4.	What type of digester are you building?		
	1 = Polyethylene tubular anaerobic digester		
	2 = Fixed dome anaerobic digester		
	3 = Floating drum anaerobic digester		
	Answer =	1	Polyethylene tubular anaerobic diges
5.	What are the arrangements of the livestock?		
	1 = Livestock are free ranging during the day, penned at night.		
	2 = Livestock are free ranging during half the year, penned half the year.		
	3 = Livestock are penned all the time.		
	Answer =	3	100% manure capture expected.

Figure C-1 Model inputs from mathematical model.

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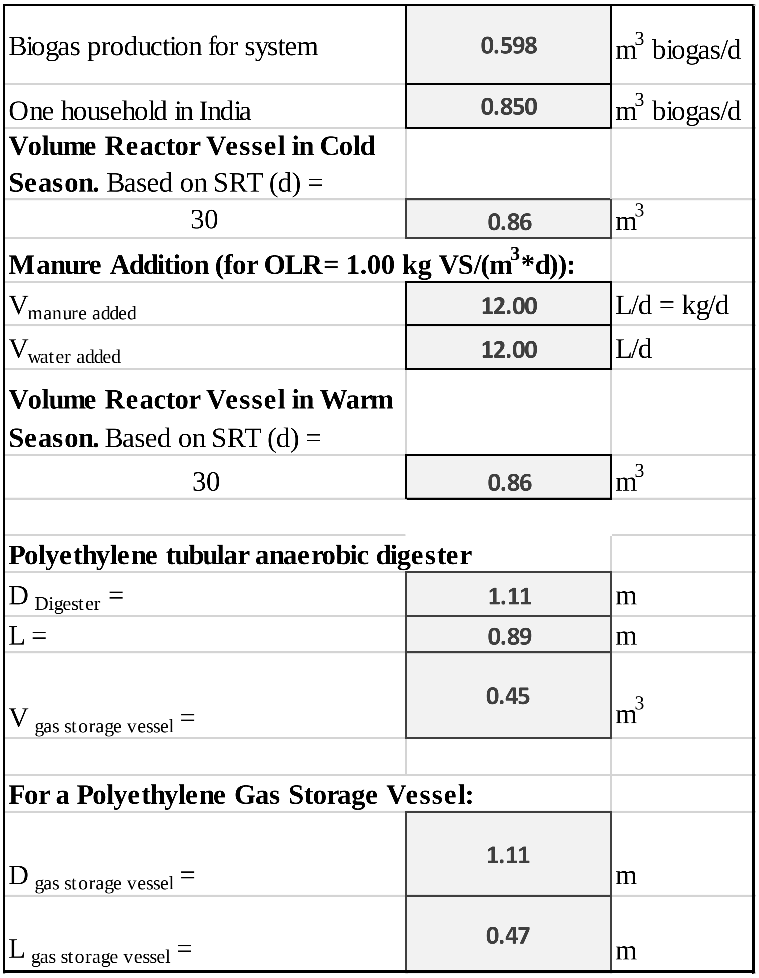
[2] Rowse, Laurel Erika, "Design of Small Scale Anaerobic Digesters for Application in Rural Developing Countries" at http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=4519&context=etd.



Biogas production for system	0.598	m^3 biogas/d
One household in India	0.850	m^3 biogas/d
Volume Reactor Vessel in Cold Season. Based on SRT (d) =		
30	0.86	m^3
Manure Addition (for OLR= 1.00 kg VS/(m^3*d)):		
$V_{\text{manure added}}$	12.00	L/d = kg/d
$V_{\text{water added}}$	12.00	L/d
Volume Reactor Vessel in Warm Season. Based on SRT (d) =		
30	0.86	m^3
Polyethylene tubular anaerobic digester		
D_{Digester} =	1.11	m
L =	0.89	m
$V_{\text{gas storage vessel}}$ =	0.45	m^3
For a Polyethylene Gas Storage Vessel:		
$D_{\text{gas storage vessel}}$ =	1.11	m
$L_{\text{gas storage vessel}}$ =	0.47	m

Figure C-2 Outputs from mathematical model.

Appendix D: Personal Daily Methane Requirement for a Panamanian Living in Study Location

From requirements of methane to prepare food and individual food consumption quantities, personal methane demand is calculated using equation 3.1 below.

- Personal daily methane requirement: PBGR = Σ [$\mathrm{C_{food}}$*$\mathrm{m_{consumed}}$*$\mathrm{C_{0.5\ kg}}$]*$\mathrm{C_{day}}$ (3.1)

  where:

  PMGR = personal daily methane requirement [$\mathrm{m^3}$/person]

  $\mathrm{C_{food}}$ = methane required to cook 0.5 kg of food from Table 3-1 [$\mathrm{m^3}$/ 0.5 kg of food]

  $\mathrm{m_{consumed}}$ = individual mass of food consumed annually from Table 3-2 [kg/person-year]

  $\mathrm{C_{0.5\ kg}}$ = half kg converter [0.5 kg of food/kg of food]

  $\mathrm{C_{day}}$ = year to day converter [year/day]

  Sample calculations for calculating personal daily methane requirements for a Panamanian.

- Personal daily methane requirement: PBGR = Σ [$\mathrm{C_{food}}$*$\mathrm{m_{consumed}}$*$\mathrm{C_{0.5\ kg}}$]*$\mathrm{C_{day}}$

  where:

  PMGR = Personal daily methane requirements for a Panamanian [$\mathrm{m^3}$/person]

  $\mathrm{C_{food}}$ = 0.06 [$\mathrm{m^3}$/ 0.5 kg of rice], 0.06 [$\mathrm{m^3}$/ 0.5 kg of beans]

  $\mathrm{m_{consumed}}$ = 78.1 [kg of rice/person-year], 8 [kg of beans /person-year]

  $\mathrm{C_{0.5\ kg}}$= 2 [0.5 kg of food /kg of food]

  $\mathrm{C_{day}}$ = 1/365 = [year /day]

  PMGR = [(0.06 [$\mathrm{m^3}$/0.5 kg of rice]* 78.1 [kg of rice/person-year]*2 [0.5 kg of rice/kg of rice] + 0.06 [$\mathrm{m^3}$/ 0.5 kg of beans]* 8 [kg of beans/person-year])* 2 [0.5 kg of beans/kg of beans]] (1/365 [year/day]) = 0.03 [$\mathrm{m^3}$/person-day]

Appendix E: Appropriate Amount of Animals for a Household in Study Location

From personal biogas consumption calculated in Appendix D using Equation 3.1, family size and daily animal biogas production rates, an appropriate amount of animals based on family size is calculated.

- Appropriate amount of animals based on family size [animals/family (#)] P = $\frac{\mathrm{PMGR}*\mathrm{FS}}{\mathrm{BG}*\mathrm{MC}}$ (3.2)

  where:

  P = appropriate amount of animals based on family size

  PMGR = personal daily methane requirement [m^3/person]

  FS = family size [# of people/family (#)]

  BG = daily animal biogas produced [m^3/animal]

  MC = methane content [%]

  Sample calculations for calculating appropriate amount of swine based on family size.

- Appropriate amount of animals based on family size [animals/family (#)]: P = = $\frac{\mathrm{PMGR}*\mathrm{FS}}{\mathrm{BG}*\mathrm{MC}}$

  where:

  PMGR = 0.03 [m^3/person]

  FS = 2 [# of people/family (#)]

  BG = 0.6 [m^3/ swine]

  MC = 70%

  P = (0.03 [m^3/person])*(2 [# of people/family (#)])/(0.6 [m^3/ swine]*0.7) =

  0.13 [swine / family (#)]

Appendix F: Calculations for Methane, Carbon Dioxide and Carbon Dioxide Equivalence of Excess Biogas Production at Standard Pressure

To understand the impact excess biogas could have on the environment, the methane and carbon dioxide contents of biogas are calculated and converted into carbon dioxide equivalence. The calculations below first define the volumes of methane and carbon dioxide present in the produced biogas. Next, after calculating the amount of methane and carbon dioxide contributed by excess biogas, carbon dioxide equivalence is defined.

- The Ideal gas law: $P*V = n*R*T$

  where:

  P = pressure [atm]

  V = volume [l]

  n = number of moles of gas [mol]

  R = ideal gas constant = 0.0821 [l atm/ mole-K]

  T = temperature [K]

- Mass of chemical: $n = m/mm$

  where:

  n = number of moles of gas [mol]

  m = mass [g]

  mm = molar mass [g/mol]

- Density: $\rho = m/V$

  where:

  ρ = density [g/m^3]

  m = mass [g]

  V = volume [m^3]

- Amount of methane/carbon dioxide from excess biogas: $CH_4 = \rho_{CH_4} * \%_{CH_4} * BG_{exc}$ (methane)

  (4.2)

  where:

  CH_4 = amount of methane produced by biogas [g/day]

  ρ_{CH_4} = density of methane at 1 atm and 299K [g/l]

  $\%_{CH_4}$ = percent of methane in biogas

  BG_{exc} = excess biogas [l/day]

  $CO_2 = \rho_{CO_2} * \%_{CO_2} * BG_{exc}$ (carbon dioxide)

  where:

  CO_2 = amount of carbon dioxide produced by biogas [g/day]

  ρ_{CO_2} = density of carbon dioxide at 1 atm and 299K [g/l]

  $\%_{CO_2}$ = percent of carbon dioxide in biogas

  BG_{exc} = excess biogas [l/day]

- Carbon dioxide equivalence: $CO_2eq = CO_2/CH_4 * CH_4 + CO_2$ (4.3)

  where:

  CO_2eq = [g_{CO_2eq}]

  CO_2/CH_4 = greenhouse gas impact conversion for methane to carbon dioxide [g_{CO_2}/g_{CH_4}]

  CO_2 = carbon dioxide [g_{CO_2}]

CH_4 = methane [g_{CH_4}]

- Excess biogas: $BG_{exc} = BG_{production} - BG_{demand}$

where:

BG_{exc} = excess biogas [l]

$BG_{production}$ = production of biogas [l]

BG_{demand}= demand of biogas [l]

Sample calculation for for methane, carbon dioxide and carbon dioxide equivalence of excess biogas production at standard pressure.

- Density of methane: $\rho_{CH_4} = \frac{m}{V} = \frac{P*mm}{RT}$

where:

$P*V = n*R*T = \frac{m}{mm}*R*T$

P = 1 [atm]

mm_{CH_4} = 1*12 [g/mol] + 4*1 [g/mol] = 16 [g/mol]

R = 0.0821 [l atm/mol-K]

$\rho_{CH_4} = \frac{m}{V} = \frac{P*mm_{CH_4}}{RT}$ = 1 [atm]*16 [g/mol]/ (0.0821 [l atm/mol-K]*299 K) = 0.65 [g/l]

- Excess biogas: $BG_{exc} = BG_{production} - BG_{demand}$

where:

$BG_{production}$ = 9 [m^3]

BG_{demand}= 0.6 [m^3]

BG_{exc} = 9 [m^3] - 0.6 [m^3] = 8.4 [m^3]

- Methane produced daily: $CH_4 = \rho_{CH_4} * \%_{CH_4} * BG_{exc}$ (methane)

where:

ρ_{CH_4}= 0.6 [g/l]

$\%_{CH_4}$= percent of methane in biogas = 60% (Bruun et al., 2014; GTZ,1999)

BG_{exc} = 8.4 $[m^3/day]$

CH_4 = 0.65 [g/l]* 0.6*8.4 $[m^3]$*1000[l/m^3] = 3276 [g/day]

- Carbon dioxide daily: CO_2 = ρ_{CO_2}* $\%_{CO_2}$* BG_{exc} (carbon dioxide)

  where:

  ρ_{CO_2}= 1.5 [g/l]

  $\%_{CO_2}$= 40% (GTZ, 1999)

  BG_{exc} = 8.4 $[m^3/day]$

  CO_2 = 1.5 [g/l]*0.4*8.4 $[m^3]$*1000[l/m^3] = 5040 [g/day]

- Carbon dioxide equivalence: CO_2eq = CO_2/CH_4*CH_4 + CO_2

  where:

  CO_2/CH_4= 25 $[g_{CO_2}/g_{CH_4}]$ (IPCC, 2007; Mihelcic et al., 2014)

  CO_2 = 5040 [g_{CO_2}/day]

  CH_4 = 3276 [g_{CH_4}/day]

  CO_2eq = 25 $[g_{CO_2}/g_{CH_4}]$* 3276 $[g_{CH_4}]$ + 5040 $[g_{CO_2}]$ = 86940 [g_{CO_2eq}/day]

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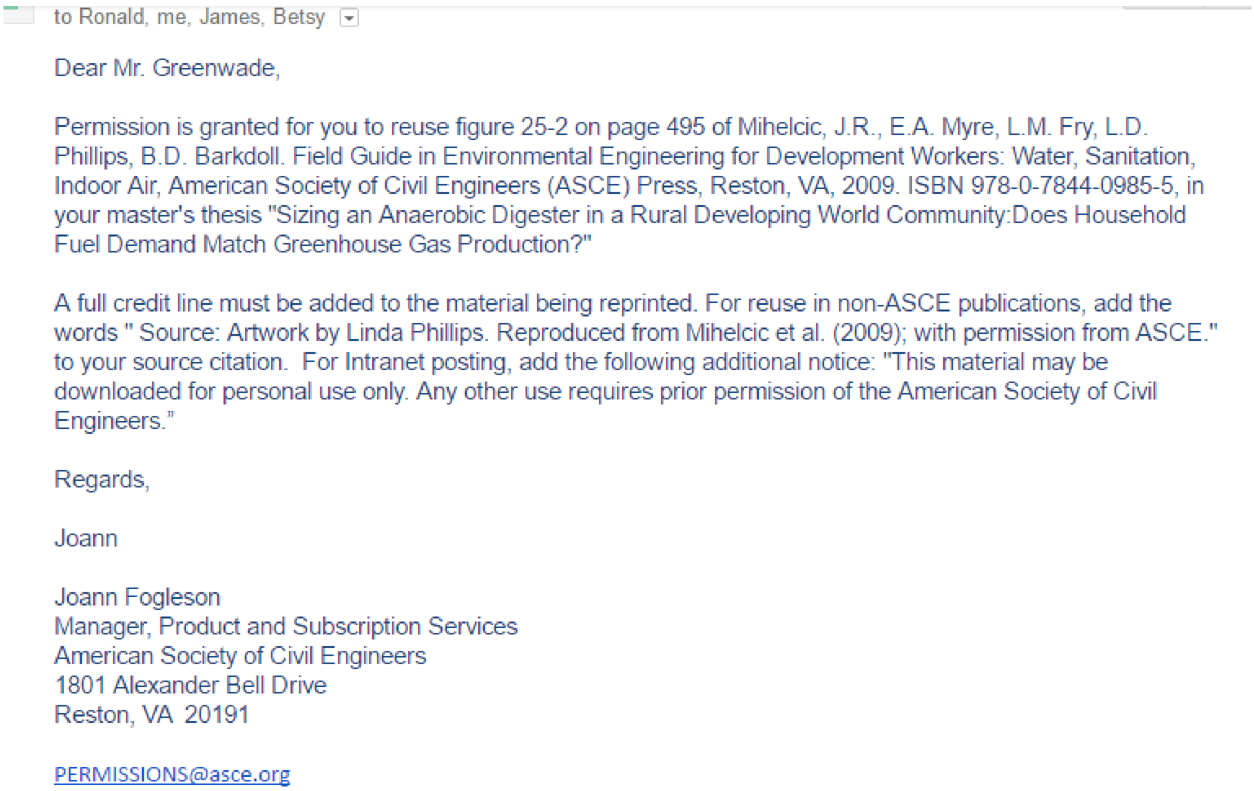

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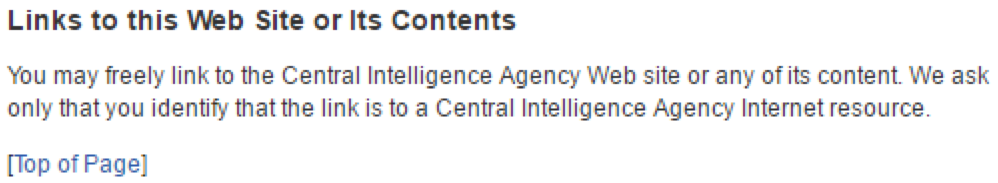

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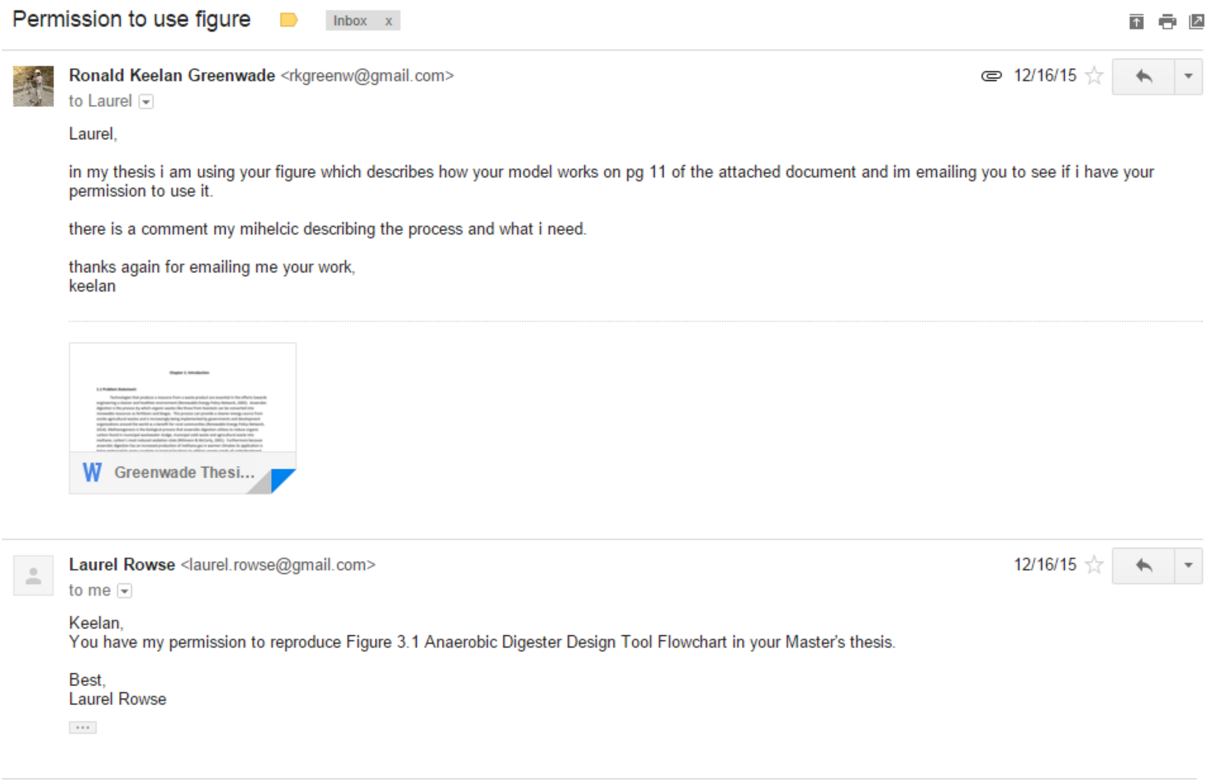

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