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Cow power: the energy and emissions benefits of converting manure to biogas

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Abstract. This report consists of a top-level aggregate analysis of the total potential for converting livestock manure into a domestic renewable fuel source (biogas) that could be used to help states meet renewable portfolio standard requirements and reduce greenhouse gas (GHG) emissions. In the US, livestock agriculture produces over one billion tons of manure annually on a renewable basis. Most of this manure is disposed of in lagoons or stored outdoors to decompose. Such disposal methods emit methane and nitrous oxide, two important GHGs with 21 and 310 times the global warming potential of carbon dioxide, respectively. In total, GHG emissions from the agricultural sector in the US amounted to 536 million metric tons (MMT) of carbon dioxide equivalent, or 7% of the total US emissions in 2005. Of this agricultural contribution, 51 to 118 MMT of carbon dioxide equivalent resulted from livestock manure emissions alone, with trends showing this contribution increasing from 1990 to 2005. Thus, limiting GHG emissions from manure represents a valuable starting point for mitigating agricultural contributions to global climate change.

Anaerobic digestion, a process that converts manure to methane-rich biogas, can lower GHG emissions from manure significantly. Using biogas as a substitute for other fossil fuels, such as coal for electricity generation, replaces two GHG sources—manure and coal combustion—with a less carbon-intensive source, namely biogas combustion.

The biogas energy potential was calculated using values for the amount of biogas energy that can be produced per animal unit (defined as 1000 pounds of animal) per day and the number of animal units in the US. The 95 million animal units in the country could produce nearly 1 quad of renewable energy per year, amounting to approximately 1% of the US total energy consumption. Converting the biogas into electricity using standard microturbines could produce 88 ± 20 billion kWh, or 2.4 ± 0.6% of annual electricity consumption in the US. Replacing coal and manure GHG emissions with the emissions from biogas would produce a net potential GHG emissions reduction of 99 ± 59 million metric tons or 3.9 ± 2.3% of the annual GHG emissions from electricity generation in the US.

Keywords: anaerobic digestion, national study, biogas, animal manure, renewable energy, greenhouse gas emissions

Contents

1. Introduction

In the United States livestock animals produce over one billion tons of manure annually [1]. Currently, most of this manure is collected in lagoons or stored outdoors to decompose. Animal waste stored in this fashion can emit unpleasant odors, harmful air pollutants and greenhouse gases. The air pollutants emitted from manure include ammonia, VOCs, hydrogen sulfide and particulate matter, many of which can cause health problems in humans [2]. Besides polluting the air, ammonia emissions from manure can contaminate ground water and lead to eutrophication of the soil [3]. Manure also emits methane and nitrous oxide, two potent greenhouse gases [4]. Using standards developed by the Intergovernmental Panel on Climate Change (IPCC), methane has 21 times the global warming potential of carbon dioxide and nitrous oxide has 310 times the warming potential of carbon dioxide over a 100 year timespan [5]. According to the Environmental Protection Agency (EPA), in total, GHG emissions from the agricultural sector in the US amounted to 536 million metric tons (MMT) of carbon dioxide equivalent, or 7% of the total US emissions in 2005 [6]. Of this agricultural contribution at least 50.8 MMT of carbon dioxide equivalent (and possibly much more) resulted from methane and nitrous oxide emissions from livestock manure alone [6]. Moreover, methane and nitrous oxide emissions from manure show an increasing trend from 1990 to 2005 [6]. Because of the scale and growth in GHG emissions from manure, finding other approaches to manure management that decrease these emissions represents a valuable starting point for mitigating concerns about global climate change in the agricultural sector.

Notably, through anaerobic digestion, which is a well-known and time-tested process [7, 8], animal manure can be converted to methane-rich biogas and sludge, which is nearly odorless [7, 9] and useful as a fertilizer [10]. Furthermore, the biogas is a valuable fuel that can be used in a variety of applications such as cooking and home heating. It can also be converted into compressed natural gas (CNG) after a scrubbing process that removes carbon dioxide and hydrogen sulfide [11, 12]. Biogas' greatest potential for mitigating greenhouse gas emissions, though, is as a substitute for coal in electricity generation due to coal's role as the primary source of carbon dioxide emissions [13] from the power sector.

Despite the multiple benefits of anaerobic digestion as a waste management strategy, source of renewable energy, and mitigant for greenhouse gas emissions, these combined benefits have never been quantified at a national scale for the US. Many studies have been conducted focusing on energy or the GHG mitigating potential of producing biogas in various countries [7, 14–18] or in a specific region [19]. These studies consider varied biogas sources, from municipal to agricultural waste, and different benefits of a biogas system. An article by Pimentel *et al* quantified the possible energy contribution of biogas by 2050 to be 0.5 quads, yet no methodology was outlined to describe how this conclusion was reached [20]. To the author's knowledge no study has been conducted as to the combined energy and GHG mitigation potential of anaerobically-digesting all of the animal manure available in the United States. The research in this manuscript seeks to fill that knowledge gap. This paper will compare the changes in GHG emissions between two scenarios regarding the treatment of livestock manure.

(1) Scenario A constitutes business as usual; animal manure is collected either in a lagoon or left in the open and coal is burned to produce electricity. Greenhouse gases are emitted both from the decomposing animal manure and from the burning of coal for electricity generation. (See

figure 1.)

(2) Scenario B includes the treatment of livestock manure in anaerobic digesters, which convert the waste to biogas. The resulting biogas is burned to generate electricity and offset coal-fired power. The carbon dioxide from the burning of the biogas is the only GHG emission in this scenario. (See figure 2.)

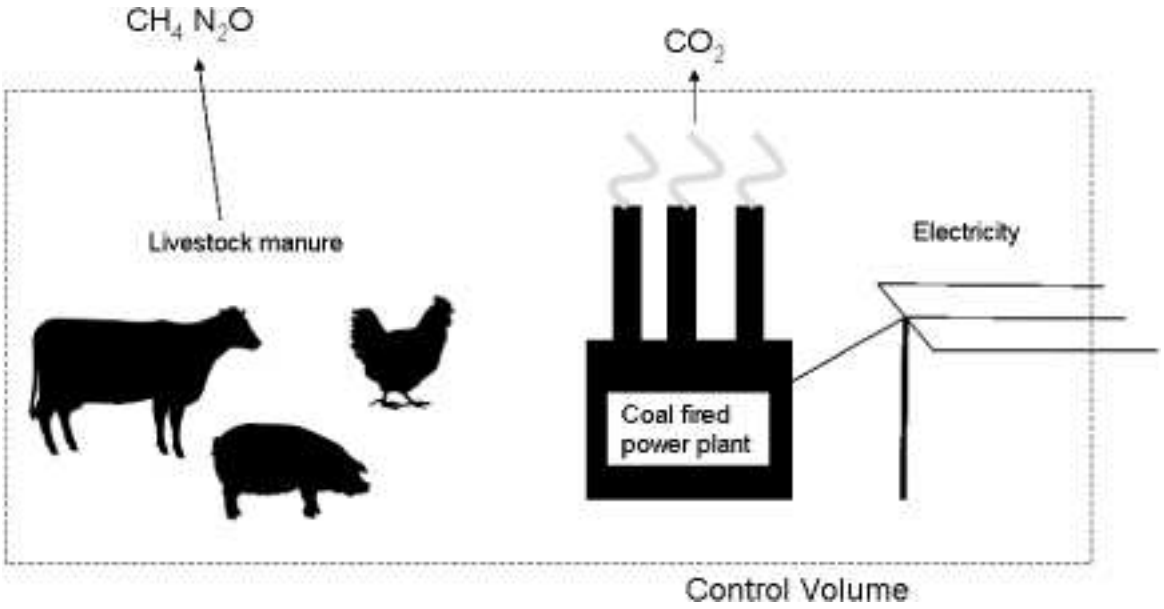

Figure 1. Scenario A: business as usual. Livestock manure and coal-fired power emit greenhouse gases

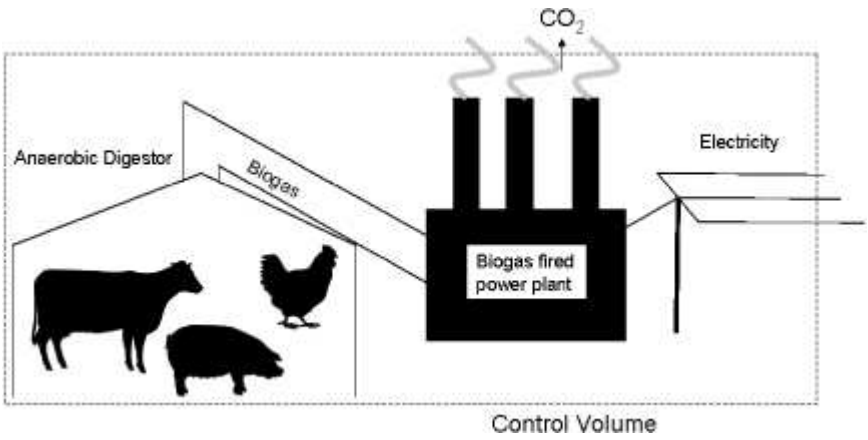

Figure 2. Scenario B: biogas is produced and used for electricity generation, replacing two sources of untreated manure) with one source of GHGs (biogas combustion).

In this discussion, coal was chosen as the primary fuel that biogas would offset in order to determine the greatest possible impact of biogas production and use. Because manure accumulation occurs at a roughly steady pace throughout the year, it is reasonable to consider that the production of biogas could occur in such a way for it to offset baseload production from sources such as coal. However, in practice biogas might be used to offset natural gas generation or the average fuel mix for power production in the US (which includes a combination of coal, nuclear, gas, etc) [21]. Speculating on how manure-based biogas will actually be implemented—if at all—is beyond the scope of this paper. Thus, for the purposes of this analysis comparisons are restricted to coal-fired power to establish a best-case scenario.

The following section will outline the calculations for each scenario and the results of this analysis. Note that the objective of this analysis is to conduct a top-level assessment of the potential for converting manure into biogas as an approach for mitigating GHG emissions. For the sake of this analysis, policy, regulatory, technical, transportation or economical barriers of this approach will not be considered.

2. Analytical methodology

The approach that was used for this analysis began with Scenario B (see figure 2) by considering the total amount of animal units (defined as 1000 pounds of live animal weight) in the US and the amount of energy in the form of biogas they could produce in a year. Using standard efficiencies for biogas combustion, the potential GHG emissions and electricity generation was calculated from biogas produced by livestock manure. For Scenario A, typical coal plant efficiencies were used to determine the energy consumed and GHG emissions from typical power plants producing the same amount of electricity as generated in Scenario B.

By comparing the emissions from Scenario A (that is, N_2O and CH_4 emitted from the manure and CO_2 emitted from coal-fired electricity generation) and Scenario B (manure-originated emissions are avoided and CO_2 is emitted from biogas-fired electricity generation), the maximum potential GHG reductions of Scenario A were calculated.

2.1. Scenario B

To determine the energy potential from the United States livestock population, energy in the form of biogas per animal unit was used. An animal unit is defined as 1000 pounds of animal weight; the number of animal units in the country are listed in table 1 [1]. Chastain *et al* [22] reports the biogas energy obtained per animal unit for fattened cattle, milk cows, swine and poultry calculated using Hill's biogas from manure equation [23]. These values are also listed in table 1.

Table 1. Annual energy available in the US from manure, sorted by animal category [1, 22].

Animal type	Animal units (millions)	Biogas energy per animal unit/day (thousand BTU)	Biogas energy/year (trillion BTU)
Fattened Cattle	9.6	25.7	89.9
Milk cows	12.3	20.6	92.4
Other beef and dairy cattle	58.8	23.2	497
Swine	8.5	39.8	124
Poultry	6.1	56.0	125
Total			928

The report by Chastain did not give an energy potential value for the category of other beef and dairy cattle, so an average of the energy from fattened cattle and milk cows was used to represent the missing category. The report also gave two energy potentials for the swine category; one for feeder to finish (operations that raise pigs from feeder swine to their slaughter weight) and another for farrow to wean (operations where young piglets are born and kept until they are weaned) [24]. Though the exact number of animal units in each kind of operation was not found, reports cite that the number of finishing hogs

imported from Canada is increasing, meaning that many US hog farms are shifting to finishing operations [25]. Another article reports that operations in the cornbelt are now focusing on finishing swine using locally grown grain [26]. Because the energy values are given per animal unit, meaning per 1000 pounds of animal weight, and because grown animals are heavier and therefore contribute more to the total number of animal units than do smaller, younger animals, the authors considered the greater weight of an older animal (i.e. feeder to finish) to be more relevant. Based on this logic, the authors used the feeder to finish value as a suitable representation of the energy potential from swine manure in the United States.

The number of animal units in the country and the energy possible per animal unit per day can be combined to find the total raw energy available on a daily and annual basis from manure-derived biogas (E_{biogas}) in the United States, as shown in table 1.

As noted in table 1, animal manure can yield up to 928 trillion BTU of raw energy in a year, or approximately 1 quad (quadrillion BTU). For reference, in 2005, the total US energy consumption was 100 quads [27], thus livestock manure can potentially be a renewable source for approximately 1% of total annual energy consumption in a flexible form of fuel (biogas) that can be burned onsite to produce heat and electricity or transformed into CNG for more widespread use.

The energy from biogas can be converted to electricity with a typical efficiency of 34–40% for large turbines and with an efficiency of 25% for smaller generators [28, 29]. For this analysis a range of turbine efficiency from 25–40% was used. Equation (1) can be used with the generation efficiency to determine the amount of electricity possible from biogas, e_{biogas}. For this analysis the range of efficiencies used was 25–40%.

$$e_{\text{biogas}} = E_{\text{biogas}} \times \eta. \qquad (1)$$

In equation (1) E_{biogas} represents the unconverted raw energy in the biogas (typically listed in BTUs), e_{biogas} is the total electricity that can be generated from biogas, and η is the overall conversion efficiency. Including unit conversions, the total electricity in kWh that can be produced from biogas can be found with the following equation.

$$e_{\text{biogas}}[\text{kWh}] = E_{\text{biogas}}[\text{BTU}] \times 0.00293 \left[\frac{\text{kWh}}{\text{BTU}}\right] \times \eta. \qquad (2)$$

Equation (2) was evaluated for each animal type for the lower and upper values of the efficiency range. The results of this calculation are summarized in table 2.

Table 2. Electricity possible from biogas for each animal type.

	Electricity possible from biogas (billion kWh)	
Animal type	Low (η = 25%)	High (η = 40%)
Fattened cattle	6.6	10.5
Milk cows	6.8	10.8
Other beef and dairy cattle	36.4	58.2
Swine	9.1	14.5

	Electricity possible from biogas (billion kWh)	
Animal type	Low (η = 25%)	High (η = 40%)
Poultry	9.2	14.7
Total	68.0	108.8

The United States consumes 3.8 trillion kWh of electricity annually [27]. Thus the 68.0 billion kWh possible from biogas at a low-end efficiency of 25% represents 1.8% of the total annual electricity consumption. At the high-end conversion efficiency of 40%, the 108.8 billion kWh from manure represents 2.9% of the total electricity consumed in the country.

To complete the analysis of Scenario B, the GHG emissions from the burning of biogas also need to be considered. The method of Murphy *et al* [17] was followed to determine the emissions that would result from the combustion of biogas with a methane fraction of 60–70% and carbon dioxide content of 30%–40%, which is the typical composition of biogas [10, 17, 30]. The emissions are determined using the stoichiometric amount of carbon dioxide produced by complete combustion of the methane molefraction of biogas plus the balance of CO_2 in the biogas that is assumed, for this analysis, to pass through the combustion process unchanged. The emission factor is then combined with the energy content of biogas and the efficiency of its conversion to electricity to determine the carbon dioxide released per kilowatt hour of electricity produced.

The combustible component of biogas is methane. Equations (3) is the methane combustion reaction for stoichiometric conditions.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O. \qquad (3)$$

This equation shows that the combustion of one mole of methane produces one mole of carbon dioxide. Changing this conversion to a mass basis using molecular weights shows that 16 g of methane produce 44 g of CO_2. In other words, 2.75 kg of CO_2 is produced from the complete combustion of 1 kg of methane. At standard conditions, which nominally prevail for this analysis, methane and carbon dioxide have densities of $\rho_{CH4} = 0.65$ and $\rho_{CO2} = 1.80$ kg m^{-3}, respectively. The total amount of carbon dioxide produced from the combustion of one cubic meter of biogas is shown in equation (4) below, where $x_{\%CH4}$ is the per cent content of methane in the biogas by volume with the balance gas comprised of carbon dioxide.

$$\mathrm{kg}_{\mathrm{CO_2\ total}} = 1\ \mathrm{m}^3_{\mathrm{biogas}}(x_{\%\mathrm{CH_4}} \times \rho_{\mathrm{CH_4}} \times 2.75 + \rho_{\mathrm{CO_2}}(1 - x_{\%\mathrm{CH_4}})).$$

Equation (4) shows that the total carbon dioxide emissions from the combustion of one meter cubed of biogas is the sum of the carbon dioxide content in the biogas and the amount of carbon dioxide resulting from the combustion of methane.

Notably, stoichiometrically combusting one cubic meter of biogas yields 1.8 kg of CO_2 after combustion no matter what portion is comprised of methane. From these results it can be concluded that, theoretically, the emissions of CO_2 from the combustion of biogas are constant in spite of changes in its composition. The energy content of the gas is the only factor that varies with methane content. That is, even though the CO_2 emissions from biogas combustion are dependent only on the volume of gas burned, the amount of useful energy that can be extracted depends on the methane mole fraction of the fuel.

The higher heating value of pure methane is 55.6 MJ kg^{-1}, which yields a volumetric energy density of 36 MJ m^{-3} at standard conditions. The energy density, $E_{\%CH4}$, can be linearly scaled down to diluted concentrations in biogas (for example, biogas with 55% methane content has about 20 MJ m^{-3}, which roughly agrees with the values reported by Murphy *et al* [17]). The values of energy density and CO_2 emissions (if combusted) for a variety of methane molefractions (from 50 to 100%) are plotted in figure 3.

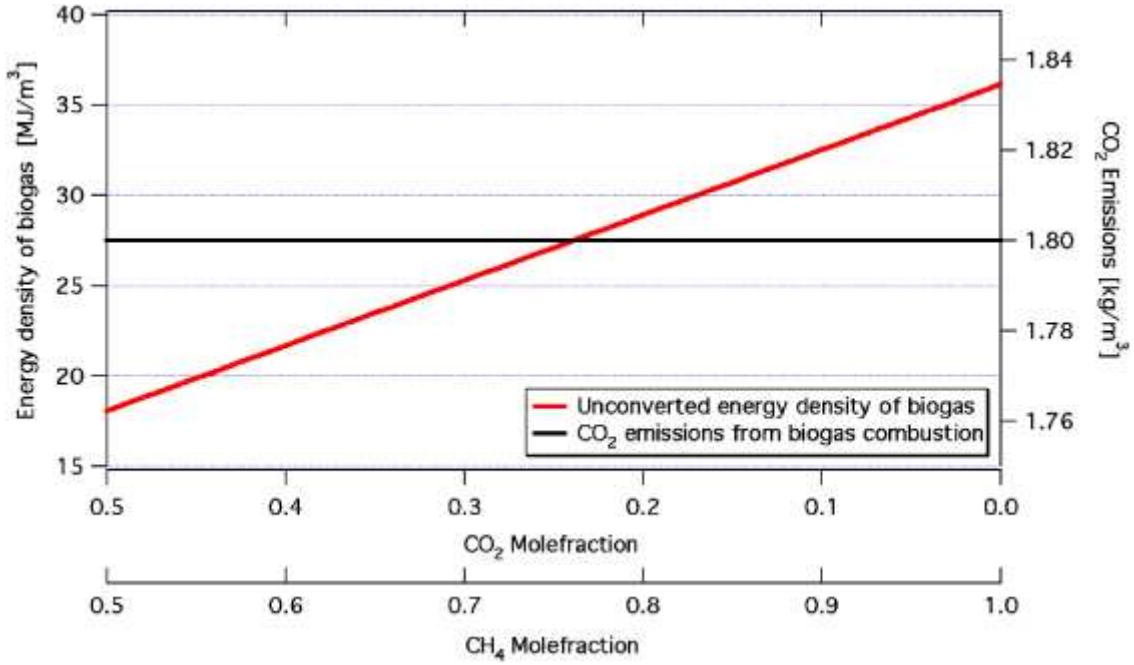

Figure 3. Plot of the energy density of biogas and resulting carbon diox from combustion versus the composition of the biogas.

These values can be converted to kilowatt hours by using the conversion factor of 3.6 million joules per kilowatt hour. To determine the amount of electricity that can be generated from this energy density an efficiency factor (η) of 25–40% was again used to determine that one cubic meter of biogas with 60% methane content produces 1.51 kWh of electricity when converted at 25% efficiency, while a cubic meter of biogas with 70% methane content that is converted at 40% efficiency produces 2.81 kWh of electricity.

This energy content information can be combined with the emissions results to find the carbon dioxide produced per kilowatt hour of electricity generated, which is a function both of the methane molefraction and the conversion efficiency. Equation (5) was used to find the emissions factors. In this equation, $E_{\%CH4}$ is the energy density of biogas as a function of methane molefraction and expressed in kWh m^{-3} of biogas.

$$z_{CO_2} = \frac{1\ \mathrm{m}^3_{\mathrm{biogas}} \left(x_{\%CH_4} \rho_{CH_4} 2.75 + \rho_{CO_2} (1 - x_{\%CH_4}) \right)}{E_{\%CH_4} \eta}. \qquad (5)$$

The resulting emissions factors (z_{CO2}, in kg of CO_2 per kWh of electricity) are plotted in figure 4, showing that CO_2 emissions per kilowatt hour are lowest for efficient combustion of biogas streams that have relatively higher methane content. Biogas containing 60% methane and combusted at 25% efficiency emit 1.13 kg CO_2 per kWh of electricity whereas 70% methane combusted at 40% efficiency emits 0.64 kg CO_2 per kWh of electricity generated. By comparison, pure methane emits approximately 0.52 kg of CO_2 per kWh of electricity under typical combustion conditions [31], which agrees with the values on the plot.

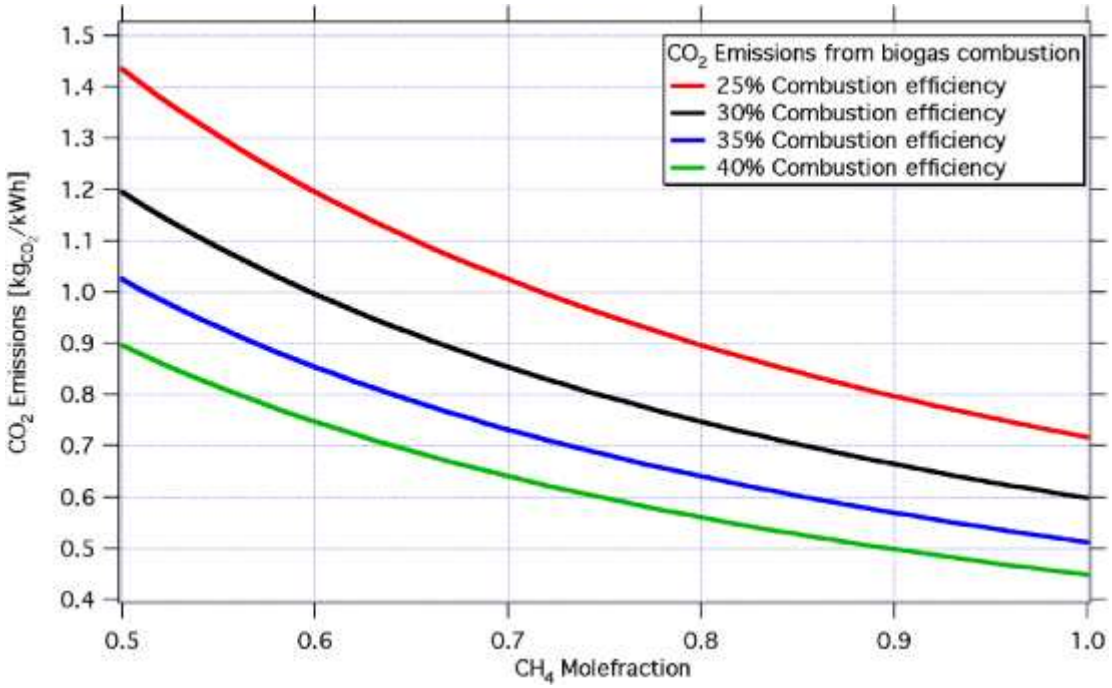

Figure 4. Carbon dioxide emissions from biogas electricity generation depending on the methane molefraction and combustion efficiency.

These emission factors can now be used to determine the annual emissions from biogas (y_{total}) when it is used for power generation. Equation (6) was used for this conversion, which produced the results listed in table 3.

$$y_{total} = e_{biogas} z_{CO_2}. \qquad (6)$$

Table 3. Total annual emissions of carbon dioxide from electricity generation using biogas combustion for the low- and high-efficiency cases with typical methane molefractions of 60% and 70%.

	CO_2 emissions from biogas-fired electricity generation (million metric tons)	
Animal type	60% methane, 25% efficiency	70% methane, 40% efficiency
Fattened cattle	7.4	6.8
Milk cows	7.7	6.9
Other beef and dairy cattle	41.2	37.3
Swine	10.3	9.3
Poultry	10.4	9.4
Total	77.0	69.6

In total, the annual emissions from biogas combustion in Scenario B vary from 69.6 to 76.8 million metric tons of CO_2. Table 3 shows CO_2 emissions from each animal type and the total emissions from all animals.

2.2. Scenario A

In Scenario A, the same amount of electricity is produced as in Scenario B, except that it is produced from coal. To determine the amount of raw coal energy needed to produce the same amount of electricity as in Scenario B, the average efficiency of the conversion from coal to electricity of 33% [32] was used in equation (7).

$$E_{\text{coal}} = \frac{e_{\text{biogas}}}{0.33}. \qquad (7)$$

In this equation e_{biogas} is the electricity produced from biogas and E_{coal} is the raw energy needed from coal to produce the same amount of electricity. The results for the amount of coal energy needed are summarized in table 4 below.

Table 4. Coal energy needed to produce the same amount of electricity as possible from biogas for t (60% methane content and 25% biogas conversion efficiency) and high case (for 70% methane conte biogas conversion efficiency).

	Low case (60% methane, 25% efficiency)	High case (70% methane, 40% efficiency)
Electricity from biogas (billion kWh)	68	108.8
Unburned coal energy needed (billion kWh)	206.1	329.4
Unburned coal energy needed (quad BTU)	0.70	1.1

According to the Energy Information Administration [33], the carbon dioxide emissions from coal are 0.32 and 0.33 kg of CO_2 kWh^{-1} for bituminous and subbituminous coals, respectively. Bituminous and subbituminous coals are the most commonly used in the United States [34]. Thus, the total emissions from coal electricity generation that would be offset by 68 to 108.7 billion kWh of biogas electricity are 65.9 to 109.3 million metric tons (MMT) CO_2.

Assessments by the EPA and EIA indicate that between 50.8 and 117.9 (MMT) of carbon dioxide equivalents were emitted annually in the form of methane and nitrous oxide from undigested animal manure in 2005 and 2006 [6, 35, 36]. The authors acknowledge that there is a significant difference in the values reported by the EPA and EIA, but reconciling those differences is beyond the scope of this report. Moreover, reports have noted that digested manure (left over from the anaerobic digestion process) will emit N_2O if spread on the land [37, 38]. Presumably that digestate would be used in place of other nitrogen-based fertilizers. Since nitrogen-based fertilizers emit N_2O and are tracked by the EPA and EIA under a category other than livestock waste management, the authors consider, for the purposes of this analysis, that the digestate's new emissions are a one-for-one replacement of the emissions for the fertilizers that the digestate displaces.

2.3. Net emissions from Scenario A

Net emissions are calculated by subtracting the displaced coal and manure emissions from the new biogas electricity production emissions. Or, to simplify, by subtracting Scenario A emissions from Scenario B emissions as in equation (8).

$$y_{netGHG} = y_B - y_A [kg_{CO_2}]. \quad (8)$$

To obtain a range for the possible GHG mitigation, the maximum coal emissions (from subbituminous coal) and maximum manure emissions were subtracted from the minimum biogas emissions and the minimum possible coal emissions (bituminous coal) and minimum manure emissions were subtracted from the maximum biogas emissions. The calculation is shown in equation (9).

$$y_{netGHG} = y_{biogas} - y_{manure} - y_{coal} [kg_{CO_2}]. \quad (9)$$

In this equation the emissions from undigested manure, y_{manure}, and emissions from coal electricity generation, y_{coal}, are subtracted from the emissions from biogas used to produce electricity, y_{biogas}. This calculation gives a maximum net emissions value of –157.5 billion kg and minimum net emissions value of –39.9 MMT of carbon dioxide. The negative net values indicate that the GHG emissions decrease if Scenario B is implemented at a comprehensive scale. These net values represent the maximum potential GHG emission offset that is possible by converting manure from a GHG source into a fuel used to displace coal. The total emissions from electricity generation in the US is reported as 2.5 trillion kg of carbon dioxide equivalents by the EIA [36, 39] meaning that the use of biogas to produce electricity could decrease the US carbon dioxide emissions from electricity by 3.9 ± 2.3%. The emissions calculated in this report are all summarized in figures 5 and 6 in their respective scenarios.

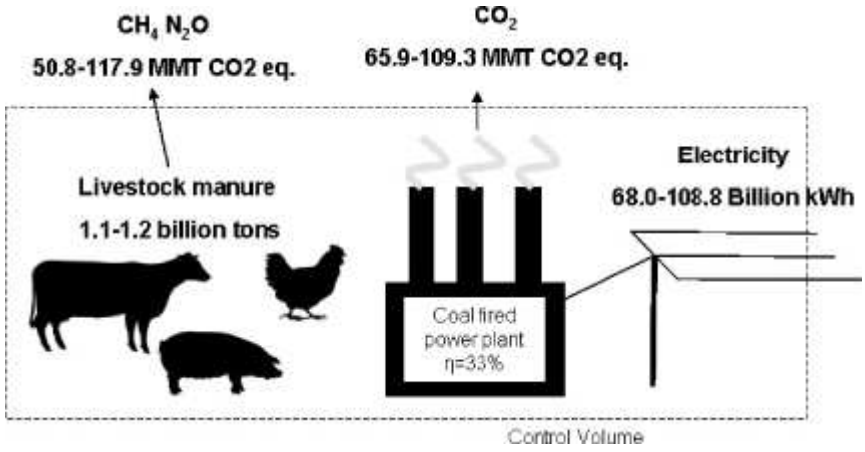

Figure 5. Scenario A, business as usual with calculated values for emissions and electricity production.

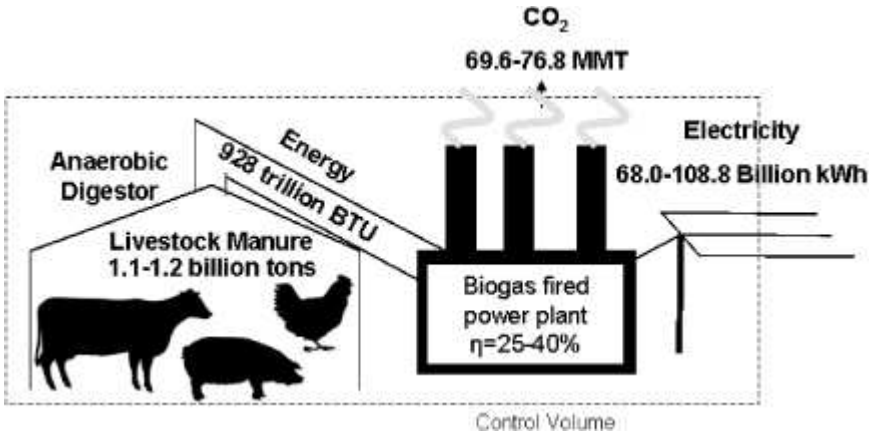

Figure 6. Scenario B, comprehensive biogas production and electricity generation with calculated values for emissions and electricity production.

3. Conclusion

The results in this paper quantify the potential for anaerobic digestion of animal manure to both decrease GHG emissions and provide a renewable energy source. By changing the `business as usual scenario' of electricity production and manure management (Scenario A) to a scenario in which animal waste is anaerobically digested and the resulting gas is used to make electricity that displaces coal-fired generation (Scenario B), the net GHG emissions from electricity production can decrease by 3.9 ± 2.3%. Scenario B also yields 2.4 ± 0.6% of the total electricity consumed in the United States in one year. In light of the criticism that has been leveled against the report by the US Departments of Energy and Agriculture that advocates the commitment of 1.3 billion tons of biomass to producing biofuels [15], biogas production from manure has the less-controversial benefit of reusing an existing waste source and the potential to improve the environment. Nonetheless, the logistics of widespread biogas production, including feedstock and digestate transportation, must be determined at the local level to produce the most environmentally advantageous, economical, and energy efficient system. Other issues such as the best methods to process and distribute biogas should also be analyzed before biogas production and use are implemented in widespread fashion. Though this report has demonstrated that converting manure to biogas could make substantial positive contributions towards reducing GHG emissions if widely used, future research might consider the policy, regulatory or economic barriers to widespread implementation of such an approach.

Acknowledgments

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