Economic Assessment of Biogas and Biomethane Production from Manure

White Paper

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EXECUTIVE SUMMARY

Biogas is a naturally occurring byproduct of the breakdown of organic material, and is actively produced from a variety of sources, including animal waste, municipal solid waste, sewage and agricultural wastes using a process called anaerobic digestion. The main constituent of biogas is methane. When further cleaned and upgraded, biogas can be turned into biomethane, a high-quality methane fuel that is indistinguishable from conventional natural gas. Biomethane can be used as a blend with or replacement for natural gas, and can be used as a renewable transportation fuel.

This white paper reviews and analyzes production costs of biogas from animal manure and its upgrading to biomethane, and shows that biomethane has the potential to be produced cost-competitively with conventional natural gas using feedstocks and processes available today. The costs of cleaning up biogas to biomethane are very scale-sensitive and can be three times higher than biogas production for a small facility and two times higher for a medium facility. The calculated production cost for biomethane is $9.0 per MMBTU for a small facility and $5.9 per MMBTU for a medium facility. While the price is highly sensitive to scale of operation, delivered costs of biomethane from medium volume production processes, derived from manure feestocks, fall in the range of price variability of North American natural gas.

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1. INTRODUCTION

Purpose

The purpose of this paper is to provide a high level economic analysis of biogas production from agricultural wastes and conversion to a usable transportation fuel, biomethane or renewable natural gas. In order to understand the economics of biogas production and upgrade, we provide a brief overview of the two main stages;

1) Production of biogas via anaerobic digester
2) Upgrading biogas to biomethane.

The two stages are the primary components of biomethane production. The economic analysis provided in this white paper offers the reader an understanding of the costs associated with investments into anaerobic digester systems and raw biogas to biomethane upgrading facilities for the production of biomethane and the cost of biogas and biomethane produced.

Background

With the increase of crude oil prices to record highs, and possibly more increase on the way, the need for an alternative source of fuel in the United States is urgently required. In addition, growing concern about climate change is driving the need for "low-carbon" fuels. One highly promising form of renewable and low-carbon fuel is biogas from anaerobic digestion of organic wastes. Anaerobic digestion is a naturally occurring process of decomposition of organic matter by microbes in an oxygen-free environment. Anaerobic digestion has been used throughout the globe for many years, especially in areas outside of the United States. However, it has not been applied widely for production of biomethane as a transportation fuel [1].

Millions of tons of wastes are generated each year from agricultural, municipal, and industrial sources. Agricultural wastes, including livestock manure, are another source of solid waste that can be used as the feedstock to produce biogas. The solid waste can be converted into usable biogas through anaerobic digestion. This can reduce the adverse impact on the environment and can be used on the farm to take care of a part, if not all, of its energy needs. In addition, biogas can be cleaned and upgraded to biomethane, a gas indistinguishable from conventional natural gas that can be used as a transportation fuel (as compressed natural gas – CNG – or liquefied natural gas – LNG) or sold to utilities by injection into a natural gas pipeline.

The complete process of biogas production, cleanup to biomethane and usage is summed up and shown schematically in Figures 1 and 2.

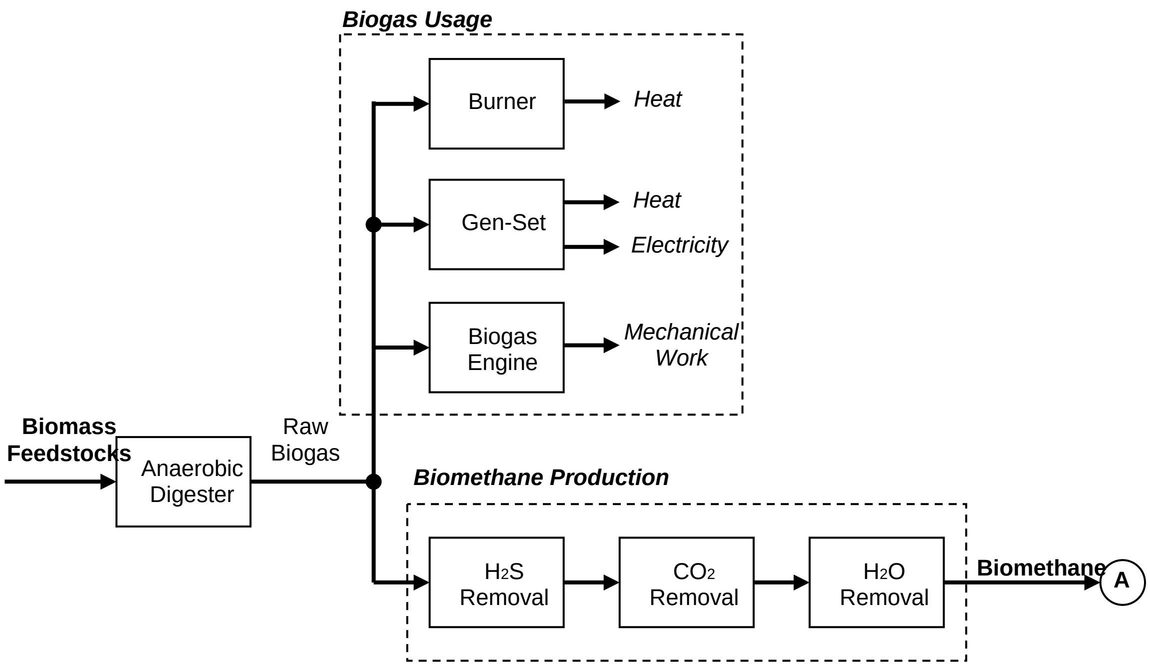

Figure 1: Schematic diagram of biogas and biomethane production and utilization (Part 1)

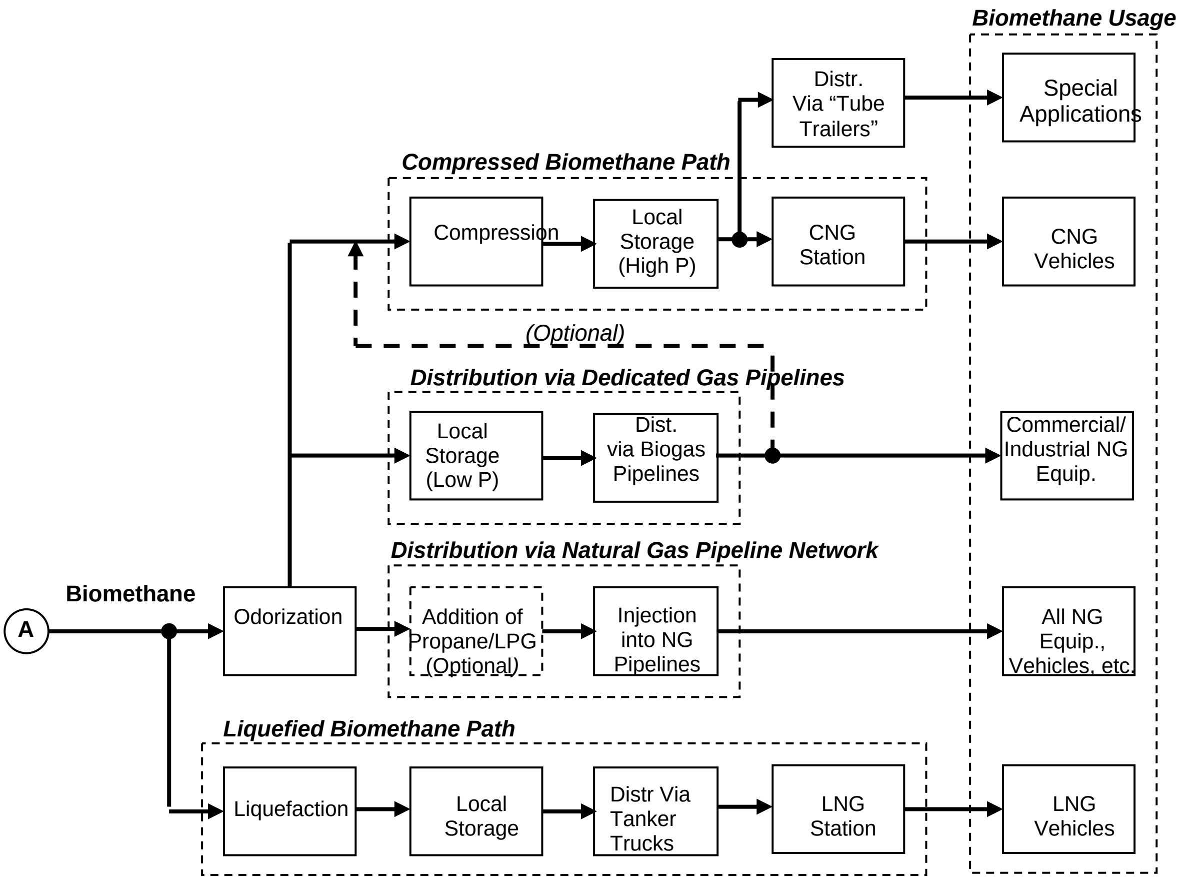

Figure 2: Schematic diagram of biomethane distribution and utilization (Part 2)

For the purpose of this white paper, the focus is placed on biogas and biomethane production, ending in point A on the schematic diagram shown in Figure 1. Biomethane distribution and utilization, shown in Figure 2, are not included in the economic analysis of this white paper, as these stages are well established and will be the same for conventional natural gas or biomethane.

2. BIOGAS PRODUCTION

Potential Biomass Feedstocks

Almost any organic material is a potential source of biomass feedstock to produce biogas. The following is a brief list of the most common biomass feedstocks that can be used to produce biogas:

- Sewage
- Organic portion of municipal solid waste (e.g. in landfills)
- Manure (e.g. dairy, pig, cattle)
- Forestry wastes
- Agricultural wastes

- “Energy crops” (e.g. clover grass, corn)
- Industrial food processing wastes

For this white paper and the economic analysis, the main focus is placed on agricultural wastes, specifically manure feedstock.

Anaerobic Digestion and Types of Digesters

Anaerobic digestion is a biochemical process whereby organic biomass sources are broken down by a diverse population of microorganisms in a low-oxygen environment, thus producing biogas as a natural byproduct. Since the microorganisms are already present in all organic material (such as animal manure), the process is triggered once the biomass is placed in a low-oxygen environment, such as underwater in a manure lagoon.

Anaerobic digestion occurs in a digester that can be of various configurations. The following is a brief description of the major types of anaerobic digesters currently used listed from simple to more complicated configurations:

- *Covered Lagoon* – This is the simplest and least expensive type of anaerobic digester. It is intended to be used on large volume, liquid manure lagoons, typically on a dairy or swine farm. It is intended for use on farms where plug flow and complete mix digesters may not be suitable for use due to the high water content. The design consists of a non-porous, plastic cover over a manure lagoon with a built-in biogas collection system. The cover traps gas produced during the decomposition of the manure.

- *Complete Mix* – This type of anaerobic digester is more expensive than a covered lagoon. It consists of either above- or below-ground tanks with a built-in mixing and biogas collection system. The mixing system, either mechanical or gas-based, helps to speed up the digestion process and increase the overall efficiency.

- *Plug-Flow* –The design is similar to the complete mix digester but without the mixing system. Plug-flow digesters are cheaper to construct and operate than complete mix digesters but are also less efficient. The design of a plug flow digester is a long trench that is built either above or below ground sealed with an airtight cover on top. The manure is fed through one end of the digester over a specific period of time. As new manure is added, the old manure is pushed across the trench, where it is continuously being decomposed, producing biogas underneath the airtight cover. This system requires raw manure to be mechanically scraped rather than flushed.

- *Multiple-Tank (2-Stage)* – This type of anaerobic digester is similar to the complete mix digester design except that digestion occurs sequentially in two phases. The first phase is a higher temperature phase at 55ºC followed by a second, lower temperature phase at 35ºC. While laboratory tests of this design show promise for increased digester efficiency, there is very little data on field-scale systems yet.

Biogas properties and usage

The composition of the biogas produced is highly dependent on the biomass feedstock and anaerobic digestion technology used; therefore there is no standard composition of biogas, rather a range of compositions. Generally speaking biogas is a low quality (meaning low calorific or low heating value) gas with limited uses. It is typically used as a fuel source for local heat and electrical power generation. The boilers and engine-generator sets ("gen-sets") used to produce heat and/or electric power from biogas are specifically designed or modified to operate with biogas. For example, biogas typically has a heating value of around 600 BTUs (British Thermal Units) per cubic foot [2] whereas natural gas (a high quality gas) typically has an average heating value of around 1,020 BTUs per cubic foot [3].

Biogas consists primarily of methane (CH_4) and carbon dioxide (CO_2), trace amounts of hydrogen sulfide (H_2S) and other components. The exact composition of biogas depends on the composition of the starting feedstock and digestion process. Biogas produced on agricultural facilities typically contains between 60 to 70% methane and 30 to 40% carbon dioxide by volume. In comparison, natural gas contains close to 90% methane and has a corresponding higher heating value.

In practice, some "clean up" of the raw biogas may be performed prior to using raw biogas in biogas gen-sets and boilers for heat, electricity or mechanical work (see Figure 1). This typically consists of removing enough of the hydrogen sulfide (H_2S), water vapor (H_2O) and particulates from the biogas to prevent damage from occurring to the engine or burner jets. In some cases biogas may be combusted directly (i.e. without prior "clean up") if minor necessary engine modifications are made and a more frequent engine oil change schedule is implemented.

For usage as a transportation fuel or injection into a pipeline, the biogas must be upgraded to biomethane. This phase is described in more detail below.

3. BIOMETHANE PRODUCTION

Biomethane production involves upgrading, or "cleaning-up", raw biogas to a higher quality gas. This involves primarily removal of carbon dioxide, hydrogen sulfide, water vapor, as well as trace gases. The resulting biomethane will have a higher content of methane and a higher energy content making it essentially identical to conventional natural gas.

The primary steps in the biogas upgrading process are:

- Removal of Carbon dioxide (CO_2)
- Removal of Hydrogen sulfide (H_2S)
- Water (H_2O) removal
- Removal of other contaminants
- Odorization (not applicable to liquefied biomethane)

Depending on the technology used, some of the biogas upgrading steps may be performed simultaneously or as separate steps in the process. In addition, there may be further processing required depending on the composition of the raw biogas, the final form of the biomethane (e.g. low pressure gas, compressed, liquefied) and its intended usage.

Removal of carbon dioxide (CO_2)

Reducing the relative amount of carbon dioxide (CO_2) in the biogas is the main task of the biogas upgrading process. Raw biogas contains typically 60 – 70% methane and 30 – 40% carbon dioxide and biomethane contains 97 – 99% methane and 1 – 3% carbon dioxide. (Note that typical natural gas pipeline specifications require a CO_2 content of less than 3% whereas vehicle fuel specifications require a combined $CO_2 + N_2$ content of 1.5 – 4.5%). Since the methane content of the gas is directly proportional to its energy content, increasing the relative methane content by removing CO_2 results in gas with a higher heating (calorific) value.

The following are the most common methods used to decrease the CO_2 content and increase the methane content of biogas:

- Membrane separation
- Pressure Swing Adsorption (PSA)
- Water scrubbing (with and without regeneration)

Removal of hydrogen sulfide (H_2S)

Hydrogen sulfide is a contaminant present in biogas produced during the digestion process. Depending on the biomass feedstock and biogas production process, the H_2S content of the raw biogas may vary from 50 to 3000 ppm (parts per million) or higher. H_2S should be removed from the gas stream early in the treatment process because of its corrosive nature. In addition, the release of the compound into the atmosphere is carefully regulated as it is extremely toxic and it contributes to air pollution. Pipeline gas and vehicle fuel standards require an H_2S content of less than 16 ppm. Some of the technologies used to reduce the H_2S content to acceptable levels are:

- In-situ reduction of H_2S within the digester vessel by adding metal ions
- Removal of H_2S with metal oxides
- Oxidation with air
- Adsorption of H_2S on activated carbon
- Biological H_2S removal

Water Removal

Raw biogas is saturated with water vapor. Depending on the biogas upgrading technology used, later stages in the biogas upgrading process may also be fully or partially saturated with water. Since water is potentially damaging to natural gas pipeline equipment and engines, pipeline and vehicle fuel requirements regarding water content and dewpoint are very strict. Pipeline quality gas standards require a maximum water content of 7 lbs/million standard cubic feet (approximately 0.5% by weight) and compressed natural gas (CNG) vehicle fuel standards require a dewpoint of at least 10º below the 99% winter design temperature for the local geographic area.[1]

The removal of water can be performed via a number of different methods at varying points in the biogas upgrading process. The following are some of the most common methods used for removing water from biogas (sometimes referred to as drying the biogas):

- Refrigeration
- Adsorption
- Absorption

Removal of Other Contaminants

In addition to H_2S, H_2O and CO_2, there may be other trace contaminants present in the biogas which are potentially harmful to equipment and/or people and must therefore be removed or reduced to acceptable levels. These additional contaminants include particles, halogenated hydrocarbons, ammonia, nitrogen, oxygen and organic silicon compounds (e.g. siloxanes). A number of effective, commercially available technologies exist to reduce or eliminate these contaminants including filters, membranes, activated carbon and other absorption media.

Odorization

Odorization is normally accomplished by introducing sulfur containing compounds such as tetrahydrotiophen or mercaptans into the gas via a controlled dosing process. Concentrations are typically in the range of 5 to 30 mg/m^3 and their presence in the gas helps identify leaks. This is required if the biomethane will be injected into a dedicated pipeline, a natural gas pipeline network, or used as a vehicle fuel for CNG vehicles.

4. ECONOMIC ANALYSIS OF BIOMETHANE PRODUCTION

The aim of this paper is to provide an economic reference point for the production of biogas and biomethane from bio-waste materials. We specifically focus on the costs to establish production of biogas and biomethane using dairy waste (or other animal waste) at a farm location. We recognize that a high level of customization goes into developing the best digester for each farm's specific characteristics, including taking into account the farm's size, location, manure management, and climate. That being said, this section presents a general estimate of costs for production of biomethane from bio- waste, or manure. As described previously in Figure 1, there are two main steps in production of biomethane:

1) Biogas production – anaerobic digester
2) Biogas upgrading to biomethane – removal of CO_2, H_2S and water

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[1] Dewpoint is the temperature at which water becomes a gas at a given pressure.

The capital and operating and maintenance costs of biogas production and upgrading systems vary significantly due to the different types of technologies currently available as well as the scale of production. Currently, upgrading biogas to biomethane for transportation use is only possible for large biogas producers due to the high initial capital and operating and maintenance costs. As discussed in this paper, the initial capital costs take into account the startup costs, planning necessary, as well as the cost of the equipment and its installation. Operations and maintenance costs take into account what it costs to run the equipment on a daily basis, including its energy costs, small and large repairs, and various other aspects necessary for the successful performance of the systems. While this information is still very sparse due to its relatively new adoption in this country, meaningful data was collected from various sources including reports from manufacturers of the technologies, government sponsored research projects, and data from the literature.

Cost of Biogas Production

In this section we evaluate the cost of biogas production (not biomethane) using a digester system on a farm. The AgSTAR Handbook provided by the AgSTAR program, operated by the US EPA, gives a detailed list of costs associated with dairy waste management systems [4]. It provides a sample of economic data for anaerobic digesters with an estimated capital cost of approximately \$500 to \$800 per cow. However, as stated in the handbook, the capital cost per cow does not tell the full economic story, and so this report aims to provide a broader analysis by taking into account not just capital costs, but also operations and maintenance costs. Furthermore, it is recommended in the handbook to consider costs in terms of dollars per million BTU (MMBTU).[2] This will provide a direct comparison to the cost of conventional natural gas.

As the data is not readily available, we performed an extensive literature review to obtain costs per cubic foot of biogas produced. Digester information was collected from literature review of farms across the United States, information from digester manufacturers, individual farm reports and interviews, and published reports and articles.

Data from twenty farms employing four different digester systems were analyzed. Table 1 contains the collected information for each of the farms including the daily volume of biogas produced, capital cost of digester, and operation and maintenance cost and the source of the data.

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[2] MBTU stands for one million BTUs and is occasionally used as a standard unit of measurement for natural gas and provides a convenient basis for comparing the energy content of various grades of natural gas and other fuels. One ft^3 of natural gas produces approximately 1,000 BTUs, so 1,000 ft^3 of gas is comparable to 1 MBTU. MBTU is occasionally expressed as MMBTU, which is intended to represent a thousand thousand BTUs. (Source: Energy Dictionary, /www.energyvortex.com/energydictionary/british_thermal_unit_(btu)__mbtu__mmbtu.h)

Table 1: Digester biogas production data and costs

Farm	Ref.[1]	Digester Type	Biogas Produced (ft^3/day)	Capital Cost ($)	O & M ($/yr)	Cost of Biogas ($/1000 ft^3)
Agway	[5]	Slurry tank	12,000	175,000	3650	2.83
Brendle	[5]	Slurry loop	28,000	125,000	5,000	1.10
Oregon Dairy	[5]	Slurry loop	19,000	120,000	4,000	1.44
Cushman	[5]	Complete Mix	42,500	450,000	11,000	2.16
Darrel Smith	[5]	Complete Mix	42,000	225,000	5,000	1.06
Cooperstown	[5]	Complete Mix	25,000	500,000	4,125	3.29
Rocky Knoll	[5]	Complete Mix	60,000	225,000	8,000	0.88
Colorado Pork	[6]	Complete Mix	11,333	368,000	8,000	6.38
SWUSA	[6]	Complete Mix	12,600	576,000	8,000	8.00
Carroll	[5]	Covered Lagoon	35,000	191,500	9,000	1.45
Martin	[5]	Covered Lagoon	12,000	95,200	2,500	1.66
Royal	[5]	Covered Lagoon	70,000	220,000	8,000	0.74
Hilarides Dairy	[7, 8]	Covered Lagoon	232,681	639,397	Negligible[2]	0.38
Langerwerf	[5]	Plug Flow	17,500	200,000	6,154	2.53
Eden Vale	[7]	Plug Flow	62,105	617,659	3,600	1.52
Craven Farms	[6]	Plug Flow	60,000	287,300	9,900	1.11
AA Dairy Farm	[6]	Plug Flow	42,000	295700	15,000	1.94
Kirk Carrel	[5]	Plug Flow	20,000	100,000	4,500	1.30
Fairgrove	[5]	Plug Flow	53,500	150,000	6,500	0.72
Foster Bros	[5]	Plug Flow	28,000	185,000	10,000	1.88

[1] For specific reference see the Reference section

[2] Hilarides reports negligible costs through their strict use of materials already available on hand to repair and replace, making as small an investment as possible.

The last column in Table 1 shows the calculated cost per 1000 ft^3 of biogas produced based on the capital costs and operation and maintenance costs. In order to relate the initial investment to the annual costs attributed to operations and maintenance (O&M), a lifespan of 20 years was chosen as a conservative estimate attributed to the digesters, allowing for the gradual aging of the equipment. The assumptions do not include financing costs. Dividing the capital costs by the equipment's lifespan in years, this capital cost can be broken down to a $/yr value and the annual O&M cost can be combined and divided by the annual biogas production to yield a cost per 1000 cubic feet value. The calculation is described by the following formula:

$$C_{Bg} = \frac{\frac{I_{cap}}{20_{yr}} + I_{OM}}{V_{day} \times 365} \times 1000$$

Where:

C_{Bg} - Cost of biogas produced per 1000 ft^3, \$/1000 ft^3
I_{cap} - Capital investment, \$
I_{OM} - Annual operations and management investment, \$/yr
V_{day} - Biogas produced per day, ft^3/day

For the purposes of the analysis, digester lifespan is estimated to be 20 years and facility assumed to be running at full capacity during this period

We used the data above to plot the cost of biogas per cubic foot produced against the amount of biogas production rate to investigate the relationship of cost to volume of biogas produced (see Figure 3).

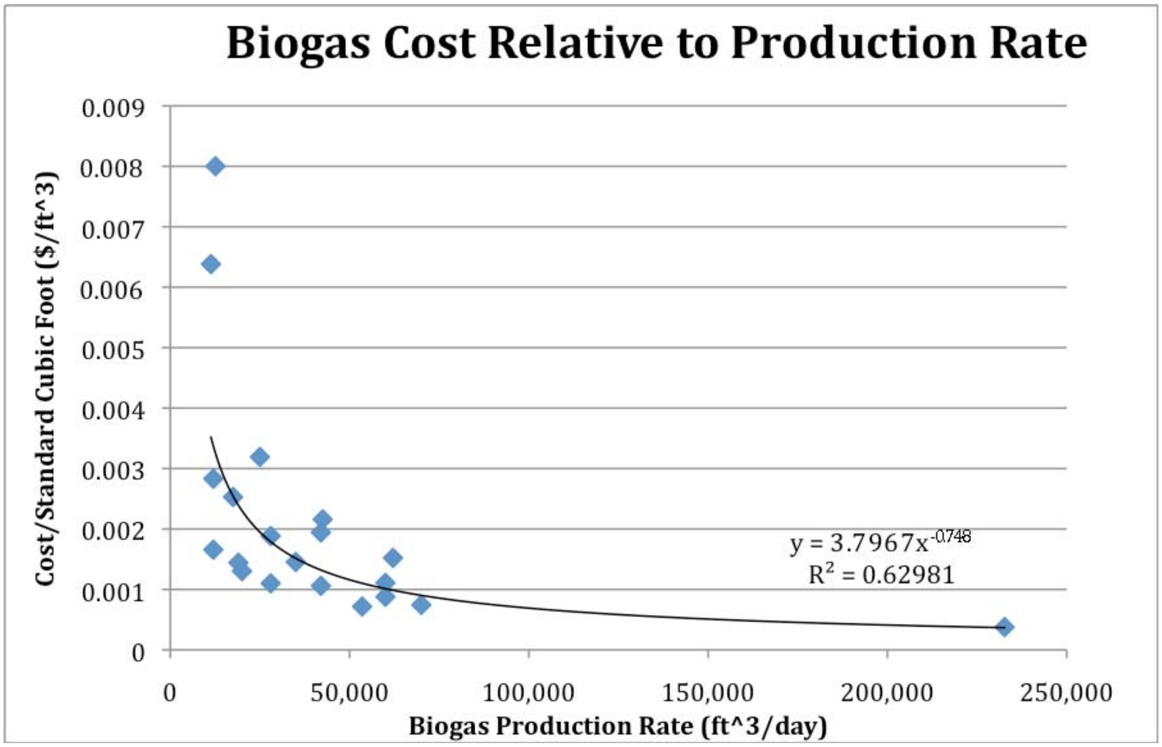

Figure 3: Biogas cost relative to production rate of biogas

As expected, the shape of the curve indicates that the cost of biogas produced drops significantly with increase in production volume. The average value for the twenty farms is about \$2.11 per 1000 ft^3 with the cost for the smallest production rate at \$6.38 (production of 11,333 ft^3/day) compared to \$0.376 per 1000 ft^3 for the largest production rate (production of 232,681 ft^3/day).

Cost of Biogas Upgrading to Biomethane

Once the digesters convert the bio-waste materials into raw biogas, the next step towards biomethane production requires upgrading of the biogas and removal of CO_2, H_2S, and water. This can be done in several steps or through the use of a single method, allowing for many combinations of equipment types to be employed on farms.

In collecting data for biogas upgrading, cost figures from 33 facilities were amassed. Due to the lack of data for biogas to biomethane upgrading facilities specifically for farms, information was gathered not just from farms, but from landfills as well from upgrading process technologies. Because the biogas collected from landfills has about the same quality and heating value as biogas collected from digested animal waste (about 600 BTU/ft^3 of gas), the cost to upgrade landfill gases to the 1,020 BTU/ft^3 quality of natural gas will be presumed comparable to the upgrading cost of animal waste-derived biogas upgrading. While collecting the data, the largest of the landfill operations were not considered due to the effects that their scale had on their relative costs. The data for each upgrading process and calculated costs for biogas upgrading to biomethane are shown in Table 2.

Table 2: Data and Costs for Biogas Upgrading to Biomethane

Upgrade Method	**Action[1]**	**Ref.**	**Capital Cost ($)**	**O&M ($/yr)**	**Biomethane Produced (ft^3/day)**	**Cost of Biogas to Biomethane Upgrading ($/1000 ft^3)**
$FeCl_3$	1	[9]	12,800	29,300	3,530	23.2
Packed bed absorber	1	[10]	28,100	4,500	7,420	2.18
Biological	1	[10]	22,300	3,930	7,420	1.86
Iron oxide (SulfaTreat)	1	[11]	8,000	13,500	47,800	0.797
Iron oxide (Sulfur-Rite)	1	[11]	43,600	23,800	47,800	1.49
KOH-activated-carbon bed (Westates)	1	[11]	50,000	5,440	47,800	0.455
Membrane (SeparexTM)	2-3	[12]	970,000	29,100	100,000	2.13
Iron oxide (ISET)	1	[13]	593,000	156,000	106,000	4.80
PSA	2	[14]	799,000	75,200	120,000	2.63
PSA	2	[8]	1,000,000	204,000	150,000	4.65
Skid mounted prototype and selexol	1-2-3	[12]	400,000	12,000	200,000	0.438
PSA	2	[14]	1,520,000	108,600	200,000	2.53
Amine	1-2	[2]	1,500,000	321,000	237,000	4.58
Selexol	1-2-3	[2]	1,200,000	491,000	297,000	5.08
Biological	1	[15]	76,800	9,160	387,000	9.21E-02
PSA	2	[14]	2,390,000	204,000	400,000	2.22
Water Scrubber	2	[2]	2,130,000	5,500	807,000	0.381
Dessicant Dehydration	3	[16]	28,000	4,660	1,000,000	1.66E-02
Glycol (TEG) Dehydration	3	[16]	43,000	6,440	1,000,000	2.36E-02
Amine-Guard	1-2	[17]	850,000	95,000	3,600,000	0.105
Hot Potassium Carbanate (Catacarb)	1-2	[17]	672,000	71,200	3,600,000	7.98E-02

Membrane	2-3	[17]	230,000	28,500	3,600,000	3.04E-02
Glycol (TEG) Dehydration	3	[18]	15,000	2,000	10,000,000	7.53E-04
Selexol	1-2-3	[17]	2,840,000	531,000	36,000,000	5.13E-02
Amine-Guard	1-2	[17]	2,170,000	643,000	36,000,000	5.72E-02
Hot Potassium Carbanate (Benfield)	1-2	[17]	1,840,000	461,000	36,000,000	4.21E-02
Hot Potassium Carbanate (Catacarb)	1-2	[17]	2,120,000	537,000	36,000,000	4.89E-02
Membrane	2-3	[17]	1,030,000	304,000	36,000,000	2.70E-02
Selexol	1-2-3	[17]	5,510,000	1,160,000	108,000,000	**3.64E-02**
Amine	1-2	[17]	4,280,000	1,530,000	108,000,000	4.43E-02
Hot Potassium Carbanate (Benfield)	1-2	[17]	3,800,000	1,010,000	108,000,000	3.05E-02
Hot Potassium Carbanate (Catacarb)	1-2	[17]	4,100,000	1,220,000	108,000,000	3.61E-02
Membrane	2-3	[17]	2,190,000	601,000	108,000,000	1.80E-02

[1] The “actions” represent the different step of biomethane upgrading the technique deals in: 1 - H_2S removal, 2 - CO_2 removal, and 3 - H_2O removal

After amassing all the data, the cost per 1000 cubic feet of biogas upgraded to biomethane was calculated (last column in Table 2) just as the cost per cubic foot of biogas produced by the digester was. The calculation is described by the following formula:

$$C_{Bm} = \frac{\frac{I_{cap}}{20_{yr}} + I_{O\ \&\ M}}{V_{day} \times 365} \times 1000$$

Where:

C_{Bm} is cost of biomethane produced per 1000 ft^3, \$/ft^3
I_{cap} is capital investment, \$
$I_{O\&M}$ is annual operations and management investment, \$/yr
V_{day} – Volume of biomethane produced per day, ft^3/day.
Lifespan estimated to 20 years and facility assumed to be running at full capacity.

Two other steps were necessary in this analysis. First, the costs of the biogas upgrade facilities were generalized to reflect the overall process. This is mainly due to the different technologies available with different costs. In addition, not all facilities examined underwent all three upgrading steps, some only removing the H_2S, CO_2, or water, or a combination of these, as indicated in by the number referring to the action step. Therefore, it was necessary to group the incomplete processes with information from other facilities to have a single concerted process with which costs could be derived for biogas upgrading to biomethane. This was done by combining the cost numbers so that the complete upgrading process costs would be included – removal of H_2S, CO_2, and water.

Second, groupings were also made to categorize the size of these facilities. On average, a single cow can lead to the production of about 40 ft^3/day of biomethane, creating useful utility to determine the capabilities of individual farms [5]. Using the range of biomethane production rates for the facility cases listed in Table 2, we ranked the facilities analyzed and created the following convention:

Small facility <100,000 ft^3/day
Medium facility 100,000 to 1,000,000 ft^3/day
Large facility >1,000,000 ft^3/day.

For each size classification we calculated the average cost of upgrading biogas to biomethane. These costs are shown in Table 3.

Table 3: Size Classifications of Upgrading Facilities and corresponding average costs

Facility size	Biomethane Produced Per Day (ft^3)	Calculated Cost of Upgrading to Biomethane ($/1000 ft^3)
Small	< 100,000	7.12
Medium	100,000 to 1,000,000	3.92
Large	> 1,000,000	0.0489

We draw several conclusions from the above cost values. First, the cost of upgrading decreases significantly with the size of the facility. From the relationship above we note that going from a small to medium facility the cost of upgrading dropped by close to half from $7.12 to $3.92 per 1000 ft^3, and down to only $0.0489 per 1000 ft^3 for the large facility size. Second, when we compare the cost of upgrading to biomethane vs the cost of producing raw biogas from the previous section, we note that the cost of upgrading to biomethane is much greater. In comparison, the average cost of $2.11 per 1000 ft^3 for biogas production is two to three times lower than the cost of upgrading to biomethane for the small and medium size facility. The comparison can not be made for the large facility due to its scale.

Total Cost of Biomethane Production

In order to determine a total cost for the production of biomethane, it is necessary to consider both steps discussed above; biogas production and biogas upgrading to biomethane. For the sake of this paper, no losses are assumed between the two steps.

As shown previously, the digestion costs are dependent on how much biogas is produced per day. However, because the cost to upgrade the biogas to biomethane is two to three times larger than the raw biogas production cost (in the small and medium scale), it is reasonable to use the average biogas production cost in determining the total cost. If the raw biogas is not being upgraded into biomethane, however, this would not be appropriate.

Since each value is in $/1000 ft^3, we combine them to find the total cost in $/1000 ft^3. We then convert to the total cost per MMBTU (million British Thermal Units) for ease of comparison with natural gas prices. The conversion was done using the relationship that 1 ft^3 of biomethane (or natural gas) is equal to 1,020 BTU [17]. The following Table 4 summarizes the results.

Table 4: Total Cost Summary Related to Facility Size

Facility Size	Averaged Biogas Production Cost (\$/1000 ft³)	Biogas Upgrading to Bomethane Cost (\$/1000 ft³)	Total cost (\$/1000 ft³)	Total Cost (\$/MMBTU)
Small	\$ 2.11	\$ 7.12	\$ 9.23	\$ 9.06
Medium	\$ 2.11	\$ 3.92	\$ 6.03	\$ 5.92

In summary, for small facility size of less than 100,000 ft^3 per day the total cost to produce biomethane is around \$9.0 per MMBTU and for a medium size facility (100,000 to 1,000,000 ft^3 per day) the cost is around \$5.9 per MMBTU.

These results are in the range of values reported in an earlier study [2] which estimated the costs for a small dairy plant (45,000 ft^3 per day of methane) to be \$8.1 per 1000 ft^3 and for a large diary plant (240,000 ft^3 per day methane) to be \$5.5 per 1000 ft^3. Our values, derived from actual production cost data, are slightly higher but in general agreement with the earlier estimated values. This provides good confirmation of our empirical data.

These results can now be compared to the market value of conventional natural gas, which on November 2nd, 2009 was \$4.824/MMBTU (see Figure 4).

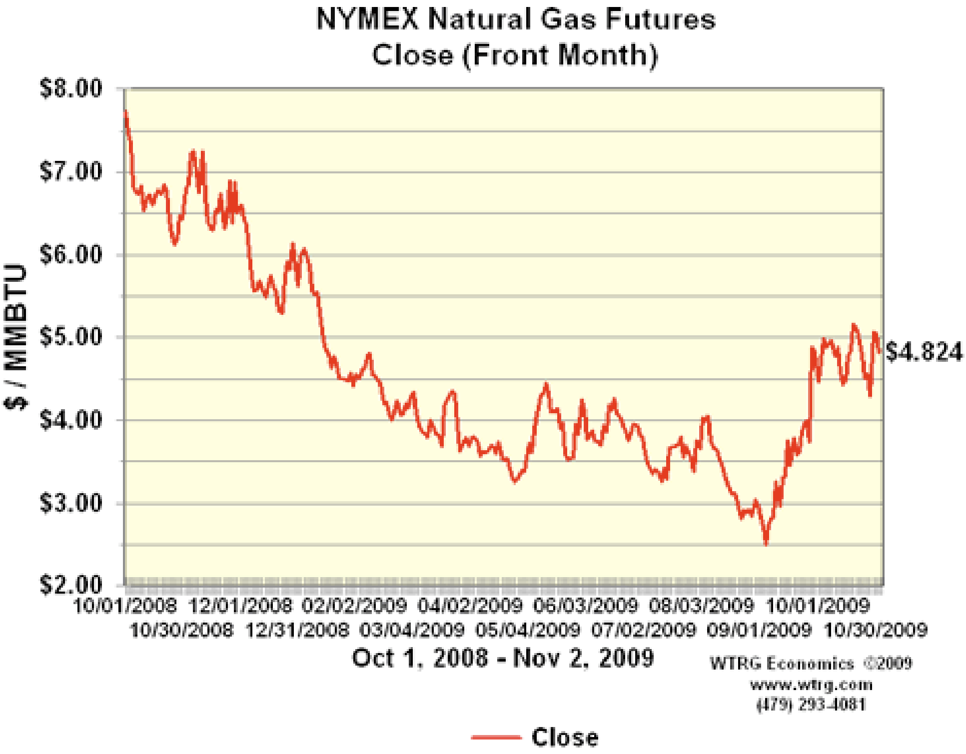

Figure 4: Natural Gas Prices for One Calendar Year (Source: WTRG Economics, www.wtrg.com/daily/gasprice.html)

For a medium size facility the cost of biomethane is a third higher than the current cost of conventional natural gas while for a small facility the cost of biomethane is more then two times higher than the current cost of conventional natural gas. However, it should be noted that the price of natural gas is quite volatile as seen in the Figure 4 which charts the price of natural gas over the last calendar year. Biomethane costs fall mostly within the same range of costs as did conventional natural gas costs over the specified period.

5. SUMMARY AND DISCUSSION

This paper focused on evaluating the economic costs of producing biogas and biomethane from agricultural waste such as animal manure. We used actual capital and operating costs for a number of farms as well as upgrading to biomethane costs from actual facilities. We calculated that the average biomethane cost for a small facility is around \$9.0 per 1000 ft^3 and for a medium-size facility is \$5.9 per 1000 ft^3. Of the two production steps, we find that biogas upgrading to biomethane is more expensive than biogas production. Specifically, the cost of biogas upgrading to biomethane is two to three times higher than biogas production- \$7 vs. \$2 per 1000 ft^3 for a small facility and \$4 vs. \$2 per 1000 ft^3 for a medium-size facility.

We found that in terms of total production cost, biomethane is competitive with conventional natural gas: biomethane cost is \$9.0 per MMBTU for a small facility and \$5.9 per MMBTU for a medium-size facility compared to \$4.9 per MMBTU for conventional natural gas (in Nov 2009). However, the scales of production are important and production is much more economical at larger facilities. Presently most small farms go only as far as digesting waste into biogas and then using a biogas gen-set to make electricity, and in this case, the largest costs incurred are the capital and operation and maintenance costs of the digester. For such smaller farms, the upgrading costs can be three times larger than the raw biogas production costs, preventing many from pursuing this use for the biogas.

With conventional natural gas priced at \$4.9/MMBTU (as of November 2nd, 2009), upgrading costs in the long run are competitive, and will probably continue to decline as more efficient systems are developed in the future. In addition to this, with the unpredictability of natural gas prices (a year earlier the price was close to \$8/MMBTU), biomethane is a good alternative, especially when produced on a larger scale.

Similar to other alternative fuel technologies used in transportation, the implementation of a biomethane facility is not currently cost effective for a private developer without public funding assistance, because of issues of scale and price volatility. If capital costs can be covered, however, the operations and maintenance costs are much smaller and allow reasonable production cost for pipeline quality biomethane.

6. RECOMMENDATIONS FOR FUTURE WORK

The capital cost of producing biogas and upgrading it to biomethane reflects only part of the actual cost incurred by the user; however, it does reflect an important portion. There are a number of different costs that will need to be determined before implementing a biogas and biomethane production and upgrade facility, including cost for storage, transport, market rate of natural gas, and incentives, among other factors. These are important if the biomethane is to be used outside of the location at which it was generated. Other costs such as avoided costs of emissions and tipping fees for removal of manure should also be taken in account, and can improve the business case. Examination of production and upgrading costs for other feedstocks is also a relevant analysis to be conducted

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