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A Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures

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Abstract: Recent construction of a number of successful biogas systems for livestock manures and an increased awareness of their merits has produced an increased level of interest by livestock producers. Concurrently, the number of system developers has increased and several different system design approaches have emerged with claims of performance superiority. In some instances, these claims are supported by results of rigorous performance evaluations, whereas others are based on minimal data.

To address this problem, the Association of State Energy Research and Technology Transfer Institutions, the U.S. Environmental Protection Agency AgSTAR Program, and the U.S. Department of Agriculture Rural Development Program jointly supported the development of a standard protocol for quantifying and reporting the performance of anaerobic digestion systems for livestock manures. The protocol was developed with the objectives of providing: a) project developers with a standard approach for quantifying performance of their systems and supporting claims that will receive general acceptance as credible, and b) third parties with the same approach for independent performance evaluations.

The protocol specifies prerequisites for performance evaluations and required assembly of background information. It also describes acceptable methods for data collection to characterize system performance with respect to waste stabilization, biogas production, and utilization. Additionally, a uniform approach for evaluating economic viability is established.

Keywords. Anaerobic digestion, livestock manure, waste stabilization, biogas production and utilization, economic analysis, protocol.

Introduction

Anaerobic digestion of livestock manures under controlled conditions to produce biogas can provide livestock producers with the opportunity to increase net farm income, typically by using captured biogas to generate electricity for on-site use, or delivery to a local electric utility, or both. This biogas utilization approach also provides the opportunity to utilize waste heat captured from the engine-generator set to reduce on-farm demand for conventional fuels (*e.g.,* fuel oil and propane) for water and space heating. Direct combustion of biogas for on-farm water and space heating in place of conventional fuels also is an option. An added benefit of anaerobic digestion is that potentially negative impacts of these wastes on air and water quality are reduced. This includes but is not limited to reducing emissions of methane, a greenhouse gas, when manure decomposes anaerobically under uncontrolled conditions. Methane has approximately 21 times the heat trapping capacity of carbon dioxide. In addition, producing, capturing, and using biogas as a fuel reduces emissions of carbon dioxide and various pollutants from fossil fuel combustion to generate electricity or produce heat.

The recent construction of a number of successful systems and an increased awareness of their merits has produced an increased level of interest by livestock producers in manurial biogas production and utilization. Concurrently, the number of system developers has increased and several different system design approaches have emerged with claims of process superiority. In some instances, these claims are supported by results of rigorous performance evaluations, whereas others are based on minimal data.

To address this problem, the Association of State Energy Research and Technology Transfer Institutions, the U.S. Environmental Protection Agency AgSTAR Program, and the U.S. Department of Agriculture Rural Development Program jointly supported the development of a standard protocol for quantifying and reporting the performance of anaerobic digestion systems for livestock manures. The protocol was developed with the objectives of providing:

1. System developers with a standard approach for quantifying the performance of their systems and supporting claims that will receive general acceptance as credible,
2. Third parties with the same approach for independent performance evaluations.

Adherence to this protocol will allow for comparisons of similar and different types of systems based on directly comparable and unbiased information. The protocol also establishes the standard for acceptance of performance evaluation reports in a central repository for easy access by interested third parties and possibly for a design certification program in the near future. At this time (January 2007), options for establishing and supporting a repository, which most probably will be a web site, and a certification program, are being discussed. All performance evaluation reports submitted will be peer reviewed and accepted or rejected based on the recommendations of the peer reviewers.

Development

The development of this protocol began with the preparation of a first draft to focus an initial discussion of desired structure and content at a workshop held in Chicago in January 2006. Thirty-eight stakeholders from academia, government, and the private sector were invited to attend or submit written comments and suggestions. Twenty-one of the invitees either attended the workshop or submitted written comments and suggestions.

Following the workshop, the first draft of the protocol was revised to reflect the comments and suggestions that were received. The second draft was sent to all of the original workshop invitees for additional comments and suggestions, which then were incorporated into an interim final draft. This draft was then posted on the Association of State Energy Research and Technology Transfer Institutions (ASERTTI) and the U.S Environmental Protection Agency AgSTAR Program websites with a request for additional comments and suggestions by 31 December 2006. After those comments and suggestions were reviewed and the interim final draft was modified when appropriate, the final version of the protocol was published by posting on the ASERTTI (www.asertti.org/partenerships/digester/ASERTTI_Digester_Protocol.pdf) and AgSTAR www.epa.gov/agstar/pdf/protocol.pdf) websites.

Structure and Contents

The protocol specifies prerequisites for performance evaluations and the required assembly of background information. It also describes acceptable methods for data collection to characterize system performance with respect to waste stabilization and biogas production and utilization. Additionally, a uniform approach for evaluating economic viability is established.

Prerequisites for Performance Evaluations

The following mandatory prerequisites were established for acceptable performance evaluations of anaerobic digestion systems for livestock manures. The purpose of these prerequisites is to insure that all results reported are from performance evaluations of commercial scale systems conducted under steady-state conditions over a period that is long enough to insure any variability in performance is reflected in the results reported. Therefore, all performance evaluations should be:

1. Conducted on full-scale systems serving commercial livestock operations,

2. At least 12 months in duration,
3. Conducted only after the start-up phase of operation has been completed and the following conditions met:
    a. Plug-Flow and Mixed Digesters—Continuous operation for a period equal to the sum of at least five hydraulic retention times (HRTs) after the end of the start-up phase of digester operation.
    b. Covered Lagoons—Continuous operation for at least one year after startup.
    c. Attached Film Digesters—Continuous operation for at least three months after startup with the three months occurring during warm weather for unheated digesters.

Required Background Information

Because adequate background information is critical for evaluating the results of a performance evaluation in the proper context, the protocol also requires assembly and reporting of the general information, listed in Tables 1 and 2, regarding the livestock operation and the biogas production and utilization system being evaluated. If the performance evaluation is of a centralized system, the information specified in Table 1 is required for each livestock operation served.

Process Performance Characterization

The protocol requires the characterization of process performance with respect to both waste stabilization and biogas production and utilization based on a minimum of monthly collection of digester influent and effluent samples for analysis and other data for no less than one year.

<u>Waste Stabilization</u>—For mixed, plug-flow, and attached film digesters, the protocol requires that the degree of waste stabilization claimed should be based on differences, if statistically significant, between mean influent and effluent pH and concentrations of total solids (TS), total volatile solids (TVS), chemical oxygen demand (COD), and total volatile acids (TVA) as determined using U.S. Environmental protection Agency (1983) or American Public Health Association (2005) methods. In addition, it must be demonstrated that the observed changes in these parameters are due to microbial processes and not significant settling by showing that there is no statistically significant difference ($P<0.05$) between influent and effluent fixed solids (FS) concentrations. Ideally, changes in total Kjeldahl nitrogen, organic nitrogen, ammonia nitrogen, total phosphorus (TP) and total sulfur also should be determined and reported but not required. If influent and effluent TP concentrations are determined, they should be used to confirm the absence of significant settling indicated by the FS mass balance results. The samples collected for analysis are required to be shown as representative of composites of 24-hour flow.

For covered lagoons, differences between influent and effluent concentrations for those parameters present in both particulate and soluble form (*e.g.* TS, TVS, COD) represent changes due to the combination of microbial processes and settling and are not valid indicators of the degree of waste stabilization being realized. Therefore, the protocol requires that quantification of the degree of waste stabilization be based on the difference between influent and effluent TVA concentrations and estimated COD reduction based on methane production assuming 0.3496 m^3 of methane is produced per kg of COD destroyed (5.60 ft^3 per lb COD destroyed) under standard conditions (0 °C and 1 atm) (Madigan *et al.*, 1997).

The protocol does not require evaluation of performance with respect to reduction in the densities of indicator organisms (*e.g.* the fecal coliform and fecal streptococcus groups) or specific pathogens (*e.g. Mycobacterium avium paratuberculosis* in dairy manure and *Salmonella spp.* in swine and poultry manures). It does, however, require that influent and effluent densities, when reported, are compared on a $\log_{10}$ colony forming units per unit volume (*e.g.* 100 ml) basis to: 1) avoid the confounding effect of TS destruction on influent/effluent comparisons, and 2) allow valid use of statistical methods that assume normally distributed populations.

<u>Biogas Production and Utilization</u>—The protocol requires that both total and utilized biogas production be measured and recorded because biogas disposed of by flaring when production exceeds utilization is not accounted for when only biogas utilized is measured. Similarly, measuring only total biogas production precludes estimating the thermal efficiency of the conversion of biogas to electricity or heat. In addition, the protocol requires monthly determinations of biogas carbon dioxide and hydrogen sulfide concentrations using appropriate detection tubes and quarterly laboratory analysis to determine methane, carbon dioxide, ammonia, and hydrogen sulfide concentrations. Acceptable methods for measuring biogas production and biogas analyses are identified in the protocol.

When biogas is used to generate electricity, the protocol requires that the kJ (kWh) of electricity generated be measured and recorded during each sampling episode using a permanently installed utility type meter or a comparable substitute. Then the thermal conversion efficiency, biogas to electricity, should be calculated and reported using the lower heating value for methane, 35,770 kJ per m^3 (960 BTU per ft^3) under standard conditions (0 °C, 1 atm) (Mark's Standard Handbook for Mechanical Engineers, 1978). The protocol also requires recording hours of engine-generator set operation to allow calculation and reporting of on-line efficiency, output, and capacity utilization efficiency. Finally, it is required that any engine-generator set waste heat recovered for other than digester heating (*e.g.* potable water or space heating) be measured and reported. Although determination of recovered waste heat used for digester heating is not required, it is recommended.

Greenhouse Gas Emissions Reductions—The protocol also requires estimates of the reductions in methane emissions and avoided fossil fuel carbon dioxide emissions resulting from biogas production, capture, and utilization. Estimates of reductions in methane emissions should not be based on methane production. For existing operations, they should be based on emissions from the conventional manure storage practice (*e.g.,* storage tanks or ponds or conventional anaerobic lagoons) in place prior to anaerobic digestion. For new livestock operations, estimates in reductions in emissions should be based on the conventional manure storage practice that would have been utilized without anaerobic digestion. For example, a new dairy operation without anaerobic digestion would store scraped dairy manure in a storage tank or pond and not a conventional anaerobic lagoon. Therefore, an estimate of the reduction in methane emissions due to anaerobic digestion based on emissions from a conventional anaerobic lagoon would not be acceptable. The methodology employed for estimates of reductions in methane emissions required by the protocol is the methodology used for the most recent inventory of U.S. greenhouse gas emissions and sinks. This methodology (U.S. Environmental Protection Agency, 2006) was based on the then current IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2000). The current draft of the USEPA Climate Leaders Program accounting methodology for calculating greenhouse gas reductions for livestock waste management (www.epa.gov/climateleaders/docs/ClimateLeaders_DraftManureOffsetProtocol.pdf) also is based on the 2000 IPCC Guidelines. However, the IPCC Guidelines have been revised (IPCC, 2006) and will be followed for the next U.S. inventory. Therefore, the methodology used for the 2006 inventory should be followed until the next inventory is published.

Estimates of carbon dioxide emissions avoided by reducing the demand for electricity generated from fossil fuels should be estimated using the U.S. Environmental Protection Agency's Power Profiler (www.epa.gov/cleanenergy/powpro/screen1.html). The Power Profiler provides estimates of carbon dioxide and other emissions per unit of electricity generated based on geographic region specific fuel mixes.

Reporting—If co-digestion of livestock manure and another waste is being practiced, reporting of biogas and methane production and electricity generated on a per head basis is inappropriate and misleading. In such situations, the protocol requires that these performance parameters only be reported as a function of average daily loading of TVS and COD over the duration of the study.

Economic Analysis

The protocol requires that all manurial biogas system performance evaluations include a financial analysis performed in accordance with the general principles of engineering economics as outlined by Grant *et al.*, 1976) and others. Although results of payback period and present worth (net present value) calculations may be reported, the cash flow approach, in which total annual cost and annual revenue are calculated and compared, is required.

General Approach—The protocol requires that the economic analysis of manurial biogas systems be performed from the perspective that the system is an independent enterprise with annual net income or loss being the single metric used to characterize financial viability. When part of a livestock operation, the biogas energy used by other parts of the operation is treated as a source of revenue along with payments received for any biogas energy sold to a third party.

Boundary Conditions—Because manurial biogas production and utilization is an optional component of manure management systems, delineation of appropriate boundary conditions that exclude costs and revenue sources that are not dependent on the biogas enterprise is critical for cost analysis credibility. For example, the cost of storage of digester effluent should not be included because it is not required for biogas production. Several other examples of complementary operations that should not be considered in biogas system financial analyses are presented and discussed in the protocol including a discussion of the treatment of solids separation.

Annual Capital Cost—The protocol requires that calculation of annual capital cost be based on the following two assumptions. The first is the recovery of the internally derived capital invested and the retirement of debt financing will occur at the same interest rate and in a uniform series of annual payments over the useful life of the system. Thus, a second assumption, an estimate of the useful life of the system, also is necessary. It is recommended in the protocol that the generally used standard of 20 years for structural components be used with the cost of repair or replacement of any system component with a useful life of less than 20 years (*e.g.*, pumps, flexible covers, engine-generator sets, *etc.*) considered as an operation and maintenance cost component. Finally, the protocol requires that all determination of annual capital cost be based on the turnkey cost of the system and not the net cost to the owner after any form of subsidy such as a grant or below interest loan. One of the objectives of the protocol is to allow comparisons of the economics of different types of systems and similar systems in different geographical locations.

Annual Operation, Maintenance, and Other Costs—Because most performance evaluations of manurial biogas systems are most likely evaluations of new or relatively new systems, it is unlikely that the operation and maintenance costs incurred will be representative of the average annual cost over the useful life of the system. In addition, there currently is a paucity of information from long-term studies about these costs. Therefore, the protocol requires that the standard assumption of three percent of the turnkey capital cost be used until better information becomes available. In addition, reporting of the management and labor required for routine system operation during the period of the performance evaluation is required to begin an effort to more clearly delineate manurial biogas system operation and maintenance costs. Finally, it is required that all other related annual costs (*e.g.* property taxes, insurance, *etc.*) be included in the estimate of non-capital annual cost.

Annual Revenue—Because of the way rate schedules for electricity are are structured, the average unit cost decreases as the amount of electricity purchased increases. Therefore, reducing the amount of electricity purchased due to the onsite use of biogas-generated electricity can significantly increase the unit cost of purchased electricity. In addition, demand charges may increase or decrease and a standby charge added. Therefore, the annual revenue derived from the onsite use of biogas electricity under surplus sale and net metering contracts may be either under- or over estimated by assuming the average value of biogas electricity used onsite is equal to the to the average cost of purchased electricity. Thus, the protocol recommend that the value of the biogas generated electricity used onsite be determined based on the difference between the total cost of electricity purchased for the 12 months prior to the performance evaluation with the total cost for the 12 months of the performance evaluation. For new operations and operations that changed significantly with the addition of anaerobic digestion, the only option is to use the record of onsite use of biogas generated electricity and purchased electricity to estimate the cost of purchased electricity without biogas production.

For combined heat and power systems where engine-generator set waste heat is being recovered for beneficial use in addition to digester heating, the revenue realized from the waste heat utilized should be based on the cost per unit of energy of the conventional fuel being replaced. The same approach is required when biogas is being used directly as a boiler or furnace fuel in place of a conventional fuel such as liquefied petroleum gas or No. 2 fuel oil. In both cases, the protocol requires that the impact of the typical seasonal variation in the cost of conventional fuels be reflected in the revenue estimate.

Net Income—The protocol only requires an estimate of net income before income taxes given that the effective income tax rate will be a function of total farm income, which may vary significantly over the life of the biogas system. In addition, the issue of dealing with confidential business information is avoided.

Summary

As noted earlier, the protocol for quantifying and reporting the performance of anaerobic digestion systems for livestock manures is posted on the AgSTAR and ASERTTI websites. Although the version posted is considered to be final, it is probable that revisions in response to comments will occur in the future. One suggestion that is being considered is the addition of a checklist or template to simplify use of this protocol.

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Table 1. General information about livestock operations.

1. Name of operation
2. Address (including county)
3. Type of operation (e.g. dairy, swine, layer, etc.)
4. If dairy,
    a. Breed (e.g. Holstein, Guernsey, etc.)
    b. Average milking herd size
    c. Average number of dry cows
    d. Average number of replacements
    e. Respective fraction of the manure from the milking herd, dry cows, and replacements collected for digestion
    f. Type(s) of manure collection systems (e.g. scrape, flush, etc.) and frequency of manure collection
5. If swine,
    a. Type of swine operation (e.g. farrow-to-wean, farrow plus nursery, farrow-to-finish, etc.)
    b. Average number of sows and pregnant gilts and number of litters per sow-year
    c. Average number of nursery pigs and number of nursery stage cycles per year
    d. Average number of feeder pigs and number of grow/finish cycles per year
    e. Type(s) of manure collection systems (e.g. flush, pull-plug pit, etc.) and frequency of manure collection
6. If layer,
    a. Average number of hens
    b. Type of manure collection system (e.g. scrape, flush or pull-plug pit) and frequency of manure collection
7. If another type of animal,
    a. Numbers and ages
    b. Type of manure collection system

Table 2. Biogas system Information

<u>Biogas Production</u>

1. Type of digester (e.g. mixed, plug-flow, attached film, or covered lagoon)
2. Name of system designer, address, and other contact information
3. Digester design assumptions
    a. Number and type of animals
    b. For lactating cows, average live weight or average milk production
    c. For swine, type or types (e.g. gestating sows, lactating sows, feeder pigs, etc.) and average live weight
    d. Bedding type and estimated annual quantity used
    e. Manure volume, ft^3/day
    f. Wastewater volume, ft^3/day (e.g. none, milking center wastewater, confinement facility wash-down, etc.)
    g. Other waste volume(s), ft^3/day (e.g. none, food processing wastes, etc.) with physical and chemical characteristics (e.g. concentrations of total solids, total volatile solids, chemical oxygen demand, etc.)
    h. Pretreatment before digestion (e.g. none, gravity settling, stationary screen, screw press, etc.)
    i. Treatment of digester effluent (e.g. none, solids separation by screening, etc. with details including use or method of disposal)
    j. Method of digester effluent storage (e.g. none, earthen pond, etc.)

Table 2. Continued

4. Physical description
    a. General description including types of construction materials (e.g. partially below grade, concrete channel plug-flow with flexible cover, etc.)
    b. Dimensions (length and width or diameter and height or depth)
    c. Type(s), location(s), and thickness(s) of insulation
    d. Operating volume and ancillary biogas storage volume if present
    e. Design hydraulic retention time
    f. Design operating temperature
    g. Compliance, yes or no, with the applicable Natural Resources Conservation Service Conservation Practice Standard (No. 365: Anaerobic Digester—Ambient Temperature or No. 366: Anaerobic Digester—Controlled Temperature)
5. Monthly summaries of operational details
    a. Number and type of animals
    b. Other waste volume(s) and physical and chemical characteristics
    c. Frequency of waste addition (e.g. once per day, twice per day, etc.)
    d. Pretreatment of digester influent (e.g. none, solids separation by gravitational settling, screening, etc. with details)
    e. Average daily digester temperature and monthly range
    f. Use of monensin or any other antibacterial growth promoters that could affect biogas production

<u>Biogas Utilization</u>

1. Biogas utilization (e.g. none, generation of electricity, use on-site as a boiler or furnace fuel, or sale to a third party)
2. If generation of electricity,
    a. Type of engine-generator set (e.g. internal combustion engine, micro turbine or fuel cell with the name of the manufacturer, model, power output rating (kW) for biogas, and nominal voltage
    b. Component integration (factory or owner)
    c. Origin of equipment controller (manufacturer integrated, third party off-the-shelf, or third party custom)
    d. System installer
    e. Stand-alone capacity (yes or no)
    f. Pretreatment of biogas (e.g. none, condensate trap, dryer, hydrogen sulfide removal, etc. with the names of manufacturers, models, etc.)
    g. Exhaust gas emission control (e.g. none, catalytic converter, etc.)
    h. If interconnected with an electric utility
        i. Name of the utility
        ii. Type of utility contract (e.g. sell all/buy all, surplus sale, or net metering)
    i. If engine-generator set waste heat utilization
        i. Heat source (e.g. cooling system or exhaust gas or both) and heat recovery capacity (Btu/hr)
        ii. Waste heat utilization (e.g. digester heating, water heating, space heating, etc.)
3. If use on-site as a boiler or furnace fuel, a description of the boiler or furnace including manufacturer, model, and rated capacity
4. If biogas sale to a third party, a description of the methods of processing, transport, and end use

<u>Cost Information</u>

1. "As built" cost of total system
2. Cost basis (e.g. turnkey by a developer, owner acted as the general contractor, constructed with farm labor, etc.)
3. An itemized list component costs (e.g. the digester, the biogas utilization system, etc.)