Final
March 2011

Protocol for Quantifying and Reporting the Performance of

Anaerobic Digestion Systems for

Livestock Manures

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U.S. Environmental Protection Agency AgSTAR Program

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PREFACE

The development of this document was supported by the AgSTAR Program, which is a voluntary effort jointly sponsored by the U.S. Environmental Protection Agency, the U.S. Department of Agriculture, and the U.S. Department of Energy. The program encourages the use of methane recovery (biogas) technologies at the confined animal feeding operations that manage manure as liquids or slurries. These technologies reduce methane emissions while achieving other environmental benefits.

Methane is a greenhouse gas that is approximately 21 times more effective in trapping heat in the atmosphere than carbon dioxide over a 100-year period. Anthropogenic sources of methane include landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial processes. Methane is also a primary constituent of natural gas and an important energy source. As a result, efforts to prevent or utilize methane emissions can provide significant energy, economic and environmental benefits.

ACKNOWLEDGMENTS

This protocol was developed by Eastern Research Group and Hall Associates.

The following individuals deserve recognition for their contributions to the revision of this protocol:

Steve Dvorak, GHD Inc.
Thomas Fiesinger, New York State Energy Research and Development Authority
Curt Gooch, Cornell University
M. Charles Gould, Michigan State University
Darren Hickman, USDA Natural Resources Conservation Service
Richard Hegg, USDA Cooperative State Research, Education, and Extension Service
John Katers, University of Wisconsin – Green Bay
Joseph Kramer, Energy Center of Wisconsin
William Lazarus, University of Minnesota
Norma McDonald, Organic Waste Systems, Inc.
Steffan Mueller, University of Illinois at Chicago
Jenny Pronto, Cornell University
Kurt Roos, U.S. Environmental Protection Agency
Diane Saber, Renewable Energy and Environmental Consultants
Joe Schultz, Wisconsin Focus on Energy
Daniel Scruton, Vermont Agency of Agriculture, Food, and Markets
Melissa VanOrnum, GHD Inc.

The AgSTAR Program would also like to recognize the financial supporters for the development of the original protocol, including the Association of State Energy Research and Technology Transfer Institutions (ASERTTI) and the U.S. Department of Agriculture Rural Development.

In addition, the AgSTAR Program would like to acknowledge the reviewers of the original protocol:

Norman Scott, Cornell University
Leonard Bull, North Carolina State University
James Converse, University of Wisconsin-Madison
Thomas Fiesinger, New York State Energy Research and Development Authority
Richard Hegg, USDA Cooperative State Research, Education, and Extension Service
Frank Humenik, North Carolina State University
Joseph Kramer, Energy Center of Wisconsin
Barry Kintzer, USDA Natural Resources Conservation Service
Gaétan Lantague, Hydro-Québec
Jeffery Lorrimore, Curry-Wille & Associates
David Ludington, DLtech, Inc
Ruth MacDougall, Sacramento Municipal Utility District
Mark Moser, RCM Digesters, Inc.
Steffan Mueller, University of Illinois at Chicago
Kurt Roos, U.S. Environmental Protection Agency
Leland Saele, USDA Natural Resources Conservation Service
William Schrock, U.S. Environmental Protection Agency
Daniel Scruton, Vermont Agency of Agriculture, Food, and Markets
Joseph Visalli, New York State Energy Research and Development Authority
Ann Wilkie, University of Florida
Douglas Williams, Williams Engineering Associates

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1.0 INTRODUCTION

Interest in anaerobic digestion as a livestock manure management option has expanded rapidly in recent years as concern about methane emissions and other environmental impacts from livestock wastes has increased, along with recognizing the potential to capture and utilize methane as a renewable energy source. As interest has increased, a number of system design approaches have evolved and been followed by construction of full-scale systems. Many of these design approaches have been accompanied by claims of process superiority. Generally, data supporting these claims have been minimal at best and not collected following a standardized methodology. Thus, the ability to compare different system design approaches with respect to biogas production, waste stabilization, and cost-effectiveness on a uniform basis has been lacking.

To address this situation, the U.S. Environmental Protection Agency (EPA) AgSTAR program, in cooperation with the Association of State Energy Research and Technology Transfer Institutions and the U.S. Department of Agriculture Rural Development program, released the initial version of the *Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures* (*Protocol*) in January 2007. Recently, the U.S. EPA prepared the *International Guidance for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures* (*International Guidance*) at the request of the Agriculture Subcommittee of the Global Methane Initiative. This revised version of the *Protocol* was prepared to provide consistency with the Global Methane Initiative's *International Guidance* and to address the increased use of digesters and gas use processes in the U.S.

Modifications and additions in this revised protocol are summarized below:

- Four levels of performance evaluation are included, as discussed later in Section 1.0.
- Additional digester types have been added to the list of digesters that may be evaluated by the *Protocol* in Section 2.0.
- The discussion of gas use technologies is expanded in Section 5.0.
- Digestion of commingled waste streams is included in Section 6.2.

Anaerobic digestion is a waste stabilization process. Stabilization occurs by the microbially-mediated reduction of the carbon in complex organic compounds to methane and carbon dioxide. Because anaerobic digestion occurs under controlled conditions, it provides the opportunity for the capture and combustion of the methane produced. It is the capture and combustion of the methane produced, along with the ability to maximize the degree of waste stabilization, that differentiates anaerobic digestion from anaerobic decomposition, which occurs naturally in lagoons and other livestock manure storage structures and may provide only partial stabilization. As a unit process in the management of livestock manures, anaerobic digestion can provide the following benefits:

- Reduction in methane emissions to the atmosphere. Methane is a greenhouse gas with approximately 21 times the global warming potential of carbon dioxide.

- Reduction in emissions of noxious odors. Noxious odors associated with livestock manures result from the accumulation of products of incomplete anaerobic decomposition.

- Reduction in water pollution potential. Oxygen-demanding organic compounds are removed by reduction to methane and carbon dioxide and densities of enteric pathogenic microorganisms are reduced with negligible or no energy input.

- Renewable energy production. The captured mixture of methane and carbon dioxide, known as biogas, can be used as a fuel for generating electricity or water or space heating. With removal of carbon dioxide and other impurities and compression, processed biogas can be used as a transportation fuel or sold as renewable natural gas (RNG), which also is known as biomethane.

- Revenue to offset costs. Revenue can be realized by using biogas to generate electricity or displace on-farm fossil fuel. This energy use will partially offset costs or, ideally, provide an increase in net income. Selling RNG or carbon emission reduction credits can also be a source of income for the anaerobic digestion system.

Although it is most desirable to conduct a comprehensive performance evaluation, evaluations including all of the elements listed above may not always be possible due to resource or other constraints. Therefore, four options have been developed and are outlined below:

- **Level I:** Assembly of background information, measurement of biogas production, and determination of biogas composition
- **Level II:** Level I, plus measurement of biogas utilization for generating electricity or replacing fossil fuels by direct combustion, engine-generator set waste heat recovery, conversion to RNG, or some combination thereof and estimation of methane emission reductions
- **Level III:** Level II, plus economic analysis
- **Level IV:** Level III, plus quantification of the degree of waste stabilization

Adherence to this protocol will provide an objective and unbiased assessment of individual system performance and provide vendors with the ability to demonstrate the validity of performance claims. Furthermore, it will provide a common basis for comparing the performance of different design approaches. It also will provide a standard for acceptance of performance evaluation reports if a central repository is created in the future and can serve as an appropriate basis for developing technology-specific certification programs. Such information should be useful to:

- Allow livestock producers considering construction of anaerobic digestion systems to make informed choices about which technologies to install.
- Provide consultants with the ability to compare various technologies to develop the best possible system or to improve their existing technologies to meet the standards of others.
- Provide policymakers with a basis for considering or developing incentives and public waste-to-energy or rural sanitation education programs.
- Furnish the financial community with information to quantify the benefits of anaerobic digestion projects.

Certification of specific design approaches for the anaerobic digestion of livestock manures using this protocol should be considered by governmental agencies or non-governmental organizations. It is suggested that only Level II, III, or IV should be used as a basis for certification, as these evaluations are based on measured system performance. Certification could:

(1) Streamline the technical review process when public funds are used to support digestion and gas recovery from livestock waste waters, and

(2) Facilitate the due diligence process for financial institutions when making risk determinations with anaerobic digestion-related loans.

As a recommended certification process, determinations would be made by at least three professionals with the requisite expertise, by virtue of a combination of education and experience, which are identified by the certifying agency. The evaluations could be conducted by anyone, including vendors or their authorized representatives. There should be at least three peer reviews of each report, where only those performance evaluation reports judged to be complete and technically sound should be accepted as the basis for certification. Certification would be based on the review and acceptance of at least two, and preferably three or more performance evaluation reports of the same design by at least two of the three reviewers. If an evaluation is found to be unacceptable, at least one other reviewer would need to concur with the recommendation.

The basis for certification—Level II, III, or IV—should be indicated and briefly described. Peer reviewers should evaluate each performance evaluation report with respect to the following:

- Adherence to the requirements of this protocol for the level of performance evaluation conducted and the boundary conditions specified for the evaluation;
- Demonstration of the validity of data collected based on a limited degree of variance and consistency with or the ability to provide a scientifically sound explanation for any deviation from expected values;
- Support for all conclusions, based on the data presented in the report; and
- Adherence to the required format for report preparation.

All peer reviews should recommend that the report be:

- Accepted as submitted,
- Revised based on reviewer's comments/suggestions and resubmitted, or
- Rejected.

All peer reviews should be retained in the permanent records of the certifying agency and be available for public inspection with the names of the peer reviewers deleted.

2.0 PREREQUISITES FOR PERFORMANCE EVALUATIONS

All performance evaluations complying with the protocol should be conducted only for full-scale systems that serve commercial livestock operations. The evaluation should be at least 12 months in duration to capture any impact of seasonal ambient temperature variation. In addition, evaluations should be conducted after the startup phase of operation has been completed and the digester is operating under steady-state conditions, as defined below:

- **Heated plug flow and mixed digesters:** Continuous operation for a period equal to the sum of at least five hydraulic retention times (HRTs) after startup phase.
- **Ambient temperature covered lagoons and standard rate (unheated and unmixed) anaerobic digesters:** Continuous operation for at least one year after startup phase.
- **Other types of reactors:** Evidence of steady-state conditions based on a consistent rate of biogas production under reasonably constant volatile solids and hydraulic loading rates for at least six months for heated reactors and one year for ambient temperature reactors after the startup phase of operation is completed.

Evidence that the system fulfills the required prerequisites should be included in the evaluation report, including documentation of reasonably constant volatile solids and hydraulic loading rates prior to the commencement of the performance evaluation and during the applicable period specified above, and a record of the rate of biogas production.

3.0 REQUIRED BACKGROUND INFORMATION

The importance of assembling and reporting adequate background information cannot be overemphasized. Such information is critical for evaluating reported results in the proper context. Lists of the information that should be assembled describing the livestock operation and the anaerobic digestion system are presented in Tables 1 and 2. This information should be included in all reports. If the performance of a centralized system is being evaluated, the information specified in Table 1 should be provided for each livestock operation served.

In addition to the background information about the farm, a site- and system-specific plan for data collection should be developed for each evaluation. This plan should identify the sampling locations, the sampling methods to be used, the frequency and number of samples to be collected, and any other data necessary to perform the evaluation described in this protocol. This information should be included in the evaluation report.

Table 1. General Information

1. Name of operation

2. Postal address and other contact information

3. Type of operation (e.g., dairy, swine, beef, poultry, etc.)

4. If dairy,
   a. Breed (e.g., Holstein, Guernsey, etc.)
   b. Average number of lactating cows
   c. Average number of dry cows
   d. Average number of heifers (females more than 6 months old)
   e. Average number of calves (females less than 6 months old)
   f. Respective fractions of manure from lactating cows, dry cows, and replacements collected for digestion
   g. Method(s) of manure collection (e.g., scrape, flush, etc.) and frequency of manure collection
   h. Type of bedding used

5. If swine,
   a. Type of operation (e.g., farrow-to-wean, farrow plus nursery, farrow-to-finish, etc.)
   b. Average numbers of sows and pregnant gilts, litters per sow-year, and weaned pigs per litter if applicable
   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. Respective fractions of manure from sows and pregnant gilts, nursery pigs, and feeder pigs collected for digestion
   f. Method(s) of manure collection (e.g., scrape, flush, pull-plug pit, etc.) and frequency of manure collection

6. If beef,
   a. Average number of feeder cattle and number of grow/finish cycles per year
   b. Fraction of manure collected for digestion
   c. Method(s) of manure collection (e.g., scrape, flush, etc.) and frequency of manure collection

7. If poultry,
   a. Type of operation (e.g. layers or broilers)
   b. Average number of birds
   c. Method(s) of manure collection (e.g., scrape, flush, pull-plug, etc.) and frequency of manure collection
   d. Type of bedding used

8. If other livestock,
   a. Type of operation
   b. Average number of animals
   c. Fraction of manure collected for digestion
   d. Method(s) of manure collection (e.g., scrape, flush, etc.) and frequency of manure collection

9. If other waste(s) is/are to be digested with the manure,
   a. Source(s) of waste
   b. Type(s) of waste
   c. Amount of waste(s)

Table 2. Anaerobic Digestion System Information

Biogas Production

1. Type of digester (i.e., plug flow, mixed, attached film, covered lagoon, etc.).

2. Name of system vendor, postal address, and other contact information.

3. Digester design assumptions
    a. Average manure volume, ft^3/day (m^3/day)
    b. Average wastewater volume, ft^3/day (m^3/day) (e.g., none, milking center wastewater, confinement facility wash water, etc.)
    c. Other waste volume, ft^3/day (m^3/day) (e.g., none, food processing waste, etc.) with physical and chemical characteristics (e.g., concentrations of total solids, volatile solids, chemical oxygen demand)
    d. Processing of digester influent (e.g., none, gravity settling, screening, solids separation, etc.)
    e. Volumetric loading rate, ft^3 per 1,000 ft^3 digester volume per day (m^3 per 1,000 m^3 per day)
    f. Organic loading rate, lb total volatile solids per 1,000 ft^3 digester volume per day (kg volatile solids per 1,000 m^3 per day)
    g. Hydraulic retention time, days
    h. Operating temperature, °C
    i. Average monthly ambient temperatures, °C
    j. Rate of biogas production, ft^3 per lb volatile solids added (m^3 per kg volatile solids)
    k. Presence or absence of monensin or any other antibacterial growth promoters
    l. Expected methane content, percent
    m. Compliance (yes or no) with an established engineering design standard (*e.g*., an applicable U.S. Department of Agriculture Natural Resources Conservation Service Conservation Practice Standard)

4. Physical description
    a. General description, including types of construction materials (e.g., partially below grade, concrete channel plug flow with flexible cover, upright steel or concrete silo with flexible cover, etc.)
    b. Dimensions (length, width, and depth or diameter and depth or height), ft (m)
    c. Type(s), location(s), and thickness(s) of insulation when applicable, in (cm)
    d. Operating volume and ancillary gas storage capacity, if present, ft^3 (m^3)
    e. Digester effluent treatment (e.g., none, solids separation, phosphorus precipitation, etc.)
    f. Method of digester effluent storage (e.g., none, earthen pond)

5. Monthly summaries of operational details during the period of evaluation
    a. Numbers and types of animals
    b. Other waste volume(s) and physical and chemical characteristics
    c. Frequency of digester influent addition (e.g., hourly, twice per day, once per day)
    d. Average daily digester temperature and monthly range
    e. Use of monensin or any other antibacterial growth promoters
    f. Any other deviation from digester design assumptions (e.g., change in manure volume, addition or deletion of an additional waste stream, etc.)
    g. Maintenance activities, including labor hours and material cost

Table 2 (continued). Anaerobic Digestion System Information

Biogas Utilization

1. Biogas utilization (e.g., none, generation of electricity, use on site as a boiler or furnace fuel, sale to a third party, etc.).

2. If generation of electricity:
    a. Type of engine-generator set (e.g., internal combustion engine, microturbine) or fuel cell with name of manufacturer, model, and power output rating (kW or MJ) for biogas and nominal voltage
    b. Expected rate of electricity generation (kWh/day)
    c, Integration of the engine-generator set with a control module and interconnection with the grid (i.e., vendor or owner)
    d. Origin of equipment controller (i.e., manufacturer integrated, third-party off shelf, or third-party custom)
    e. System installer with postal address and other contact information
    f. Stand-alone capacity (yes or no)
    g. Pretreatment of biogas (e.g., none, condensate trap, dryer, hydrogen sulfide removal) with names of manufacturer(s) and model(s)
    h. Exhaust gas emission regulation (yes or no). If yes, type of control (e.g., none, catalytic converter, etc.)
    i. If interconnected to an electric utility:
        i. Name of utility
        ii. Type of contract (e.g., sell all/buy all, surplus sale, net metering, etc.)
    j. If engine-generator set waste heat utilization:
        i. Heat source (e.g., cooling system, exhaust gas, both, etc.) and heat recovery capacity (Btu/hr or kJ/hr)
        ii. Waste heat utilization (e.g., digester heating, potable water heating, space heating, etc.)

3. If use on-site as a boiler or furnace fuel, description of the boiler or furnace, including manufacturer, model, and rated capacity for biogas (Btu/hr or kJ/hr).

4. If processing to produce RNG, description of all unit processes and equipment employed, including manufacturer(s), model(s), and rated capacities (ft^3/hr or m^3/hr).

5. If biogas or RNG sale to third party, description of method of processing, delivery, and end use.

Cost Information

1. System "as built" cost, excluding site cost.

2. Cost basis (e.g., turnkey by a developer, owner acted as general contractor, constructed with farm labor, etc.).

3. An itemized list of component costs (e.g., digester, biogas utilization system, etc.).

4.0 BIOGAS PRODUCTION AND COMPOSITION

This protocol requires measurement of total biogas production and composition for all evaluations.

4.1 Biogas Production

Biogas production measurements must account for all biogas produced, including biogas used in an energy recovery device and biogas that is flared (e.g., when biogas production exceeds engine-generator set demand or when biogas is flared during periods of maintenance). Biogas production should be measured using an appropriate meter. Top inlet mechanical meters designed to measure and record corrosive gas flows are suitable for this measurement. Other types of gas meters, such as thermal mass flow meters, also are acceptable. Temperature- and pressure-compensated meters should be used. All biogas production reporting should be under standard conditions (0°C, 1 atm) to allow direct comparisons of production among different systems (See Appendix A).

4.2 Biogas Composition

The concentration of carbon dioxide by volume should be determined at least monthly using a gas detection tube or a fluid chemical absorption instrument appropriate for the expected concentration. Monthly determination of the biogas hydrogen sulfide concentration in the same manner also is desirable. The concentration should be based on the average of at least three replicate measurements during each sampling episode. In addition, laboratory biogas analysis to determine methane, carbon dioxide, hydrogen sulfide, and ammonia content by volume should be performed at least quarterly to assess the accuracy of the monthly collection data. Each sample should be collected in a suitable gas collection bag and analyzed to determine methane, carbon dioxide, hydrogen sulfide, and ammonia composition by volume using gas chromatography ASTM Method D 1945-03 (ASTM International, 2009) for methane and carbon dioxide, ASTM Method D 5504-01 (ASTM International, 2009) for hydrogen sulfide, and EPA Method 350.1 for ammonia.

Results of samples containing more than 10 percent of unidentified gases, typically nitrogen and oxygen, should be discarded due to an unacceptable degree of atmospheric contamination reflecting a poor sample collection technique. Real-time electronic gas analysis for biogas methane content (using continuous gas analyzers) is an acceptable method for this evaluation, with evidence of precision and accuracy by testing at the frequency recommended by the manufacturer of the analyzer.

4.3 Reporting

Evidence of the verification of the precision and accuracy of all meters used to measure biogas production is required. All meters should be calibrated, or recalibrated if previously used, using the method and frequency recommended by the manufacturer. In addition, each meter should have a totalizer that is not manually resettable to avoid accidental data loss, and all meter readings should be recorded during every sampling episode (or more often) with the date and time of the meter reading noted. Also, a copy of the digester operator records should be obtained monthly.

If co-digestion of livestock manure and another waste or feedstock is being practiced, reporting biogas and methane produced on a per head basis is inappropriate. This practice, which has been employed in the past, is misleading and will not be acceptable in submitted reports. When the performance of systems co-digesting manure and another waste or feedstock is being evaluated, biogas and methane produced and electricity generated should be reported as a function of the average daily loading of volatile solids (VS) and chemical oxygen demand (COD) over the duration of the study. In addition, the average daily loadings of VS and COD for manure and other wastes should be reported concurrently.

5.0 Biogas Utilization and Processing

Each Level II, III, and IV performance evaluation also must include and report the fraction of captured biogas utilized beneficially, the thermal conversion efficiency of the process used, the reliability of the process in terms of actual versus maximum potential operating hours, and information about the gas processing practices used.

Most biogas production from livestock manures is used to generate electricity, but biogas can also be used directly in place of liquefied petroleum gas (LPG), fuel oil, or natural gas for space or water heating or a source of process heat. Also, it can be processed for use or sale as RNG, which can be introduced into a pipeline or used as liquefied natural gas (LNG) to power vehicles. Below are the requirements for the evaluation of the performance of these various utilization approaches. Biogas utilization should be measured and recorded using the same type of meter used to determine total biogas production.

5.1 Biogas Utilization to Generate Electricity

When biogas is used to generate electricity, the electricity generated (kWh or MJ) should be measured and recorded at least monthly using a permanently installed utility-type meter or a comparable substitute. The rate of electricity generation, rate of biogas combustion,biogas composition, and lower heating value (LHV) of methane should be used to calculate the thermal efficiency of the conversion of biogas energy to electrical energy using Equation 1a or 1b:

$$TCE = \left[\left(\frac{kWh \times 3{,}412}{Biogas \times CH_4 \times LHV}\right)\right] \times 100 \qquad (1a)$$

where:

TCE	=	Thermal conversion efficiency, percent
kWh	=	Rate of electricity generation, kWh per unit time
3,412	=	Btu/kWh
Biogas	=	Rate of biogas combustion, ft^3/unit time
CH_4	=	Biogas methane content, decimal
LHV	=	Lower heating value of methane, Btu/ft^3

or

$$TCE = \left[\left(\frac{MJ_E}{Biogas \times CH_4 \times LHV}\right)\right] \times 100 \qquad (1b)$$

where:

TCE	=	Thermal conversion efficiency, percent
MJ_E	=	Rate of electricity generation, MJ per unit time
Biogas	=	Rate of biogas combustion, m^3/unit time
CH_4	=	Biogas methane content, decimal
LHV	=	Lower heating value of methane, MJ/m^3

The LHV of methane is the heat of combustion less the heat of vaporization of the water formed as a product of combustion. The LHV of methane should be used in this calculation because condensation of water with an engine-generator set, microturbine, or fuel cell is unlikely. The LHV of methane under standard conditions (0°C, 1 atm) is 960 Btu per ft^3 or 35,770 kJ per m^3

(Mark's Standard Handbook for Mechanical Engineers, 1978). However, the LHV of methane varies with temperature and pressure in accordance with the universal gas law and the LHV of methane used to calculate thermal efficiency should be determined for the temperature and pressure at which biogas production is being measured (see Appendix A for a description of the universal gas law). When reporting thermal conversion efficiency, the assumed heating value should be stated along with the time period involved.

Engine-generator set, microturbine, or fuel cell operating hours should be measured and recorded at least monthly to calculate and report monthly and annual online efficiency, as shown in Equation 2.

$$\text{Online efficiency, \%} = \frac{\text{hr of operation per unit time}}{\text{hr per unit time}} \times 100 \tag{2}$$

Average output should also be calculated as shown in Equation 3a or 3b.

$$\text{Average generator set output, kW} = \frac{\text{kWh per unit time}}{\text{hr of operation per unit time}} \tag{3a}$$

or

$$\text{Average generator set output, MJ} = \frac{\text{MJ per unit time}}{\text{hr of operation per unit time}} \tag{3b}$$

Capacity utilization efficiency should be calculated as shown in Equation 4a or 4b.

$$\text{Average capacity utilization efficiency, \%} = \frac{\text{Average electricity output, kW}}{\text{Rated maximum output for biogas, kW}} \times 100 \tag{4a}$$

or

$$\text{Average capacity utilization efficiency, \%} = \frac{\text{Average electricity set output, MJ}}{\text{Rated maximum output for biogas, MJ}} \times 100 \tag{4b}$$

When there is utilization of a cooling system or exhaust heat for water or space heating, the heat energy (in Btu or kJ) beneficially used should be measured and recorded using appropriate meters. In addition, determination of heat energy that is utilized for digester heating is recommended.

5.2 Biogas Utilization in Place of a Fossil Fuel

When biogas is used in place of a fossil fuel such as fuel oil, LPG, or natural gas, the fuel that was previously used should be identified and the average of the past three years' consumption reported. For new livestock operations, the volume of the fossil fuel that would have been used if biogas was not available should be determined based on the volume and Btu or MJ content of the biogas consumed and the Btu or MJ content of the fossil fuel replaced as follows:

$$\text{Volume of fossil fuel replaced, gal} = \frac{\text{Volume of biogas consumed, ft}^3 \times \text{Btu/ft}^3}{\text{Energy density of the fossil fuel replaced, Btu/gal}} \qquad (5a)$$

or

$$\text{Volume of fossil fuel replaced, m}^3 = \frac{\text{Volume of biogas consumed, m}^3 \times \text{kJ/m}^3}{\text{Energy density of the fossil fuel replaced, kJ/m}^3} \qquad (5b)$$

5.3 Biogas Conversion to Renewable Natural Gas

For operations where biogas is processed to produce RNG by removal of carbon dioxide and other impurities, the gross thermal conversion efficiency (Equations 6a and 6b) as well as the thermal conversion efficiency of biogas processing (Equations 7a and 7b) should be determined. For these calculations, the parasitic load, which is the electrical energy required for biogas processing, must be included.

$$\text{GTCE} = \left[\left(\frac{\text{RNG} \times \text{LHV}}{(\text{Biogas} \times \text{CH}_4 \times \text{LHV}) + (\text{PAR} \times 3{,}412)}\right)\right] \times 100 \qquad (6a)$$

where:

GTCE = Gross thermal conversion efficiency, percent
RNG = Rate of RNG production, ft^3 per unit time
LHV = Lower heating value of methane, Btu per ft^3
Biogas = Rate of biogas production, ft^3 per unit time
CH_4 = Biogas methane content, decimal
PAR = Parasitic load, kWh per unit time
3,412 = Btu per kWh

or

$$GTCE = \left[\left(\frac{RNG \times LHV}{(Biogas \times CH_4 \times LHV) + (PAR \times 35.8)}\right)\right] \times 100 \qquad (6b)$$

where:

GTCE	=	Gross thermal conversion efficiency, percent
RNG	=	Rate of RNG production, m^3 per unit time
LHV	=	Lower heating value of methane, MJ per m^3
Biogas	=	Rate of biogas production, m^3 per unit time
CH_4	=	Biogas methane content, decimal
PAR	=	Parasitic load, kWh per unit time
35.8	=	MJ per kWh

and

$$PTCE = \left[\left(\frac{RNG \times LHV}{(Biogas_p \times CH_4 \times LHV) + (PAR \times 3{,}412)}\right)\right] \times 100 \qquad (7a)$$

where:

PTCE	=	Processing thermal conversion efficiency, percent
RNG	=	Rate of RNG production, ft^3 per unit time
LHV	=	Lower heating value of methane, Btu per ft^3
$Biogas_p$	=	Rate of biogas processing, ft^3 per unit time
CH_4	=	Biogas methane content, decimal
PAR	=	Parasitic load, kWh per unit time
3,412	=	Btu per kWh

or

$$PTCE = \left[\left(\frac{RNG \times LHV}{(Biogas_p \times CH_4 \times LHV) + (PAR \times 35.8)}\right)\right] \times 100 \qquad (7b)$$

where:

PTCE	=	Processing thermal conversion efficiency, percent
RNG	=	Rate of RNG production, m^3 per unit time
LHV	=	Lower heating value of methane, MJ per m^3
$Biogas_P$	=	Rate of biogas processing, m^3 per unit time
CH_4	=	Biogas methane content, decimal
PAR	=	Parasitic load, kWh per unit time
35.8	=	MJ per kWh

Results of monthly calculations of gross and processing thermal conversion efficiencies should be reported.

5.4 Biogas Processing

For operations where biogas is processed using scrubbers to remove hydrogen sulfide, the biogas hydrogen sulfide concentrations by volume should be monitored prior to entering and after exiting the scrubber. The concentrations should be determined at least monthly using the gas detection tube appropriate for the expected concentration. Concentrations should be based on the average of at least three replicate measurements during each sampling episode. In addition, laboratory analysis to determine hydrogen sulfide content in the biogas prior to and following scrubbing should be performed at least quarterly using the same methods as described in Section 4.2.

For operations where biogas is being upgraded to RNG, the natural gas pipeline purchasing the RNG will require monitoring to ensure that the RNG meets their pipeline quality standards. Results of all gas quality analyses performed pursuant to the contractual agreement for sale should be included in the performance evaluation report.

5.5 Reporting

All meters used to measure biogas utilization, electricity generated, conversion system operating hours, and waste heat beneficially utilized should be calibrated or recalibrated, if previously used, by the manufacturer prior to the beginning of each performance evaluation. In addition, each meter should have a totalizer that cannot be reset manually to avoid accidental data loss and all meter readings should be recorded during every sampling episode (or more often) with the date and time of the meter reading noted. In addition, a copy of the digester operator records should be obtained monthly.

When the performance of systems co-digesting manure and another waste or feedstock is being evaluated, electricity generated or RNG produced should be reported as a function of the average daily loading of VS and COD over the duration of the study. Again, the average daily loadings of VS and COD for manure and other wastes should be reported concurrently.

6.0 REDUCTIONS IN METHANE EMISSIONS

Level II, III, and IV performance evaluations must include an estimate of the gross and net reductions in methane emissions resulting from the use of anaerobic digestion for the production, capture, and combustion of biogas. Gross reductions are total reductions, not accounting for any project-related emissions, such as leakage of methane from the digester or biogas handling equipment and emissions associated with methane combustion. Net reductions are total reductions less losses due to leakage and combustion efficiency, among others.

Estimates of gross methane emission reductions should not be based on the mass of methane produced by the digester. This approach would overestimate the emission reduction because digesters are designed to optimize methane production and may produce more methane than the system replaced. Therefore, methane reductions should be based on estimated emissions from the manure management system that was in place before anaerobic digestion was added to the manure management system. These emissions are typically referred to as "baseline emissions" as specified in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. If, for example, the farm had originally used a conventional anaerobic lagoon as the primary waste management system and replaced it with an anaerobic digester, the gross methane reduction would be based on the estimated emissions from the anaerobic lagoon that was in place prior to adding the anaerobic digester.

For new operations, baseline emissions should be based on the manure storage system without anaerobic digestion that is typical for the method of manure handling. For example, the typical system when manure is removed from confinement facilities hydraulically, such as by flushing, would be a conventional anaerobic lagoon or earthen manure storage. Conversely, manure removed by scraping would be stored in a storage tank or pond. When co-digestion with another waste is being practiced, the avoided methane emissions associated with this other waste can be included in the gross reduction estimate if ownership of the emissions reduction is transferred. The methods for determining baseline emissions from these sources are the IPCC methods for solid waste disposal, wastewater, land application, and composting.

To estimate net emission reduction, the gross reduction in methane emissions should be adjusted to account for leakage from the system, efficiency of combustion, and any additional fossil fuel use (adapted from the UNFCCC 2008 methodology), as follows:

$$EF_P = \left(\sum_{i=1}^{n} EF_M + \sum_{i=1}^{n} EF_W \right) - \left(LK_P + CE_{Pf} + CE_{Putil} + FF_P \right) \qquad (8)$$

where:
- EF_P = Annual project net methane emission reduction, kg CH_4 per year
- EF_M = Annual gross methane emissions from manure, kg CH_4 per year (Equation 10)
- EF_W = Annual gross methane emissions from co-digested waste, kg CH_4 per year (Equation 11)
- LK_P = Methane leakage, kg CH_4 per year (Equation 12)
- CE_{Pf} = Flare-related emissions, kg CH_4 per year (Equation 13)
- CE_{Putil} = Methane utilization-related emissions, kg CH_4 per year (Equation 14)
- FF_P = Fossil fuel-related carbon dioxide emissions on a methane equivalent basis, kg CH_4 per year (Equation 15)

The net project methane emission reduction may be converted to a carbon dioxide equivalent basis by multiplying by 21, which is the global warming potential (GWP) of methane, and adjusting for the reduction in carbon dioxide emissions from fossil fuel combustion avoided by the capture and use of biogas (Equation 9). The estimated carbon dioxide equivalents represent the carbon emission reduction (CER) credits that the project may be eligible to sell on a carbon trading exchange or directly to a third party.

$$EF_{PCO2} = \left(EF_P \times 21 \right) + CO_{2\,red} \qquad (9)$$

where:
- EF_{PCO2} = Annual project net methane emission reduction, kg CO_2 per year
- EF_P = Annual project net methane emission reduction, kg CH_4 per year (Equation 8)
- CO_{2red} = Annual reduction in fossil fuel carbon dioxide emissions, kg CO_2 per year (Equation 16)

6.1 Manure-Related Reductions

Baseline methane emissions from those components of the manure management system that will be replaced by anaerobic digestion should be estimated using the approach outlined below, which is based on the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* and shown in Equation 10.

- Estimate the mass of volatile solids excreted daily that will be anaerobically digested for each livestock category (e.g. sows, feeder pigs, lactating cows, dry cows, etc.) based on either the results of sample collection and analysis or values found in Chapter 4 of the Natural Resource Conservation Service Agricultural Waste Management Field Handbook (U.S. Department of Agriculture, 2008).

- Calculate baseline methane emissions for each manure management system component being replaced by anaerobic digestion based on the mass of volatile solids entering the component, the maximum methane production potential of the volatile solids, and the methane conversion factor for the manure management system component.

- Sum the baseline methane emissions for each livestock category (T), and prior manure management system component (S), based on the climate (k) of that system.

$$EF_M = \sum_{T,S}\left[\left(VS_T \times H_T \times 365\right)\times\left(B_{0,T} \times 0.67 \times \frac{MCF_{S,k}}{100}\right)\right] \quad (10)$$

where:

EF_M	=	Annual methane emissions from manure, summed by livestock category (T) and prior manure management system (S), kg CH_4 per year
VS_T	=	Daily volatile solids excretion rate for livestock category (T), kg VS per animal-day
H_T	=	Average daily number of animals in livestock category (T)
365	=	Basis for calculating annual volatile solids production, days per year
$B_{0,T}$	=	Maximum methane production capacity for manure produced by livestock category (T), m^3 CH_4 per kg volatile solids excreted
0.67	=	Conversion factor, kg CH_4 per m^3 CH_4
$MCF_{S,k}$	=	Methane conversion factor for manure management system (S) for climate (k), percent

The maximum methane production capacity (B_0) of manure varies by species and diet. Generally accepted default values can be found in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (EPA, 2010). This source should also be consulted for default MCF values. Default B_0 and MCF data from the U.S. inventory are provided in Appendix B.

6.2 Baseline Emissions From Co-Digested Wastes

When another waste is being co-digested with manure, there is an additional reduction in methane emissions if that waste previously was a source of methane emissions. For example, there will be a reduction in methane emissions if the waste being co-digested with manure was previously sent to a landfill or a conventional anaerobic lagoon. Conversely, there will be no reduction if the waste was previously treated using an aerobic process such as activated sludge or land application, or the previously employed treatment or disposal practice has been prohibited by statute or regulation. These processes may also increase nitrous oxide emissions, which are not addressed in this protocol.

The avoided methane emissions associated with this other waste can be included in the gross reduction estimate if ownership of the emission reduction is transferred. Equation 11 should be used for estimating the reduction in methane emissions for each waste being co-digested with manure.

$$EF_w = (VS_W \times 365) \times \left(B_{0,W} \times 0.67 \times \frac{MCF_{S,k}}{100} \right) \tag{11}$$

where:
- EF_W = Annual methane baseline emissions from waste (W), kg CH_4 per year
- VS_W = Mass of volatile solids in waste (W) digester influent, kg dry matter per day
- $B_{0,W}$ = Maximum methane production capacity of the waste (W), m^3 CH_4 per kg influent volatile solids
- 0.67 = Conversion factor, kg CH_4 per m^3 CH_4
- $MCF_{S,k}$ = Methane conversion factor for waste management system (S) for climate (k), percent

If a published maximum methane production capacity (B_o) value is not available, B_o must be determined experimentally. These assessments should estimate the readily biodegradable and refractory fractions of VS using long-term, bench-scale batch studies conducted at the operating temperature of the digester being evaluated. The assessments should be conducted for at least 30 days with the refractory fraction of VS (VS_∞/VS_0) determined by plotting VS_t/VS_0 versus ($1/VS_0$*t) and using linear regression analysis to identify the y-axis intercept. The fraction of the VS remaining at the y-axis intercept is an estimate of the refractory fraction of VS remaining as time approaches infinity.

6.3 Leakage and Combustion Emissions

Very little information is available regarding methane leakage from anaerobic digestion systems. However, some leakage probably occurs from most systems and should be incorporated into estimates of net methane emission reductions from anaerobic digestion systems. The IPCC (2006) provides no guidance. Therefore, this protocol recommends using the UNFCCC CDM (2008) default leakage rate of 10 percent unless a lower rate can be demonstrated using the following equation (adapted from UNFCCC, 2010).

$$LK_P = CH_{4\,prod} \times LK_F \times 0.67 \quad (12)$$

where:
LK_P = Project methane leakage, kg CH_4 per year
$CH_{4\,prod}$ = Measured methane production, m^3 CH_4 per year
LK_F = Assumed fraction of leakage, decimal
0.67 = Conversion factor, kg CH_4 per m^3 CH_4

Because no combustion process is 100 percent efficient, some methane will be emitted and should be accounted for in estimating a project's net methane emissions. For open and enclosed flares, methane emissions should be based on the measured volume of methane combusted and calculated as follows:

$$CE_P = \left[CH_{4comb} \times \left(1 - C_{eff}\right)\right] \times 0.67 \quad (13)$$

where:
CE_P = Flare-related emissions, kg CH_4 per year
CH_{4comb} = Measured methane sent to flare, m^3 CH_4 per year
C_{eff} = Combustion efficiency, decimal
0.67 = Conversion factor, kg CH_4 per m^3 CH_4

Unless higher combustion efficiency values can be justified by supporting documentation, the UNFCCC CDM (2008) default values listed in Table 3 should be used.

Table 3. Default Values for Methane Flare Combustion Efficiencies (UNFCCC, 2008)

Combustion Process		Default Value, Decimal (C_{eff})
Open flare	Continually operational	0.50
	Not continually operational	0
Enclosed flare	Continuous monitoring of compliance with manufacturer's specifications* or continuous monitoring of methane destruction	0.90

*In any hour when there is noncompliance with the manufacturer's specifications, a 0.50 default value should be used for that hour.

Methane emissions associated with combustion in lean and rich burn internal combustion engines, boilers, and furnaces should be based on the measured amount of methane combusted and calculated using Equation 13, unless the IPCC default values listed in Table 4 are being used. In that case, methane emissions should be calculated as shown in Equation 14.

$$CE_{Putil} = CH_{4util} \times 33{,}898 \times \frac{CH_{4emitted}}{1 \times 10^6} \tag{14}$$

where: CE_{Putil} = Methane utilization related emissions, kg CH_4 per year
CH_{4util} = Measured methane utilized, m^3 CH_4 per year
33,898 = Conversion factor, Btu per m^3
$CH_{4emitted}$ = Methane emission rate from combustion in lean burn or rich burn internal combustion engines, boilers, or furnaces, kg CH_4
$1x10^6$ = Conversion factor, Btu

Table 4. Default Values for Methane Emissions from Combustion in Lean Burn and Rich Burn Internal Combustion Engines and Boilers and Furnaces (IPCC, 2006)

Combustion Process	Default Value, kg CH_4emitted/10^6 Btu ($CH_{4\ emitted}$)
Lean burn internal combustion engine	597
Rich burn internal combustion engine	110
Boiler/furnace	1

6.4 Fossil Fuel Use Related Emissions

An anaerobic digestion project may result in increased fossil fuel use, such as use of gasoline or diesel fuel for manure transport to a centralized anaerobic digestion facility, transport of another waste to the facility for co-digestion, or use of compressors and other equipment required to process the biogas for use. The resulting increase in carbon dioxide emissions also should be accounted for using the default emission factors for fossil fuel use, as shown in Table 5.

The values in Table 5 should be used with Equation 15 to estimate the carbon dioxide emissions resulting from increased fossil fuel use due to transportation and stationary fuel combustion.

$$FF_P = \frac{(FF_{use} \times C_{factor})}{21} \tag{15}$$

where: FF_P = Fossil fuel-related carbon dioxide emissions on a methane equivalent basis, kg CH_4 per year
FF_{use} = Additional fossil fuel use, L per year
C_{factor} = Conversion factor, kg CO_2 per L
21 = GWP of CH_4 as compared to carbon dioxide, kg CO_2/kg CH_4

Table 5. Default Values for Carbon Dioxide Emissions from Gasoline and Diesel Fuel Use (derived from 2006 IPCC values)

Fuel	Default Value, kg CO_2/L (C_{factor})
Gasoline	2.4
Diesel	2.7
Liquefied petroleum gas	2.2

6.5 Reduction in Carbon Dioxide Emissions from Avoided Fossil Fuel Use

Estimates of carbon dioxide emissions avoided by reducing the demand for electricity generated from fossil fuels should be determined using EPA's Power Profiler (http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html). This tool provides carbon dioxide emissions estimates associated with the generation of electricity based on geographic location and associated fuel mix. Emissions data for the Power Profiler is obtained from E-Grid, EPA's Emission and Generation Resource Integrated Database (www.epa.gov/cleanenergy/egrid/index.htm).

When biogas is being directly substituted for a fossil fuel, the reduction in carbon dioxide emissions from that substitution should be calculated based on the volume of the fossil fuel replaced (Equation 16) and the emission factor for that fuel listed in Table 5.

$$FF_R = \frac{(FF_{use} \times C_{factor})}{21} \quad (16)$$

where:
- FF_R = Fossil fuel-related carbon dioxide emission reduction on a methane equivalent basis, kg CH_4 per year
- FF_{use} = Additional fossil fuel use, L per year
- C_{factor} = Conversion factor, kg CO_2 per L
- 21 = GWP of methane as compared to carbon dioxide, kg CO_2/kg CH_4

7.0 ECONOMIC ANALYSIS

It is generally accepted that the anaerobic stabilization of livestock manure under controlled conditions can significantly reduce the potential impacts of these wastes on air and water quality, while also recovering a substantial amount of usable energy. However, the decision to construct and operate an anaerobic digestion system depends ultimately on the anticipated ability to at least recover any internally derived capital investment with a reasonable rate of return and to service any debt financing over the life of the system. As indicated earlier, each Level III and IV performance evaluation performed in accordance with this protocol must include a financial analysis of the project being evaluated in addition to the Level I and II requirements. This analysis should be performed as outlined below and in accordance with the general principles of engineering economics.

In the past, several approaches have been used for assessing the economic attractiveness of these systems. One is the simple determination of the time required to recover the internally derived and borrowed capital investment from the revenue generated. This payback period approach is simple but does not consider the time value of money. Calculation of present worth or net present value is another approach in which the value of future revenue is discounted to present worth and compared to the required capital investment. However, the result obtained is dependent on the assumption of a single discount rate over the life of the system. In addition, it does not account for annual net income or loss from biogas production and utilization. Therefore, this protocol requires a cash flow approach, described below, in which total annual cost and annual revenue are calculated and compared to determine the annual net income or loss. However, results of payback period and present worth calculations also can be included in performance evaluation reports if desired.

7.1 General Approach

Financial analysis of anaerobic digestion systems for Level III and IV performance evaluations should be performed from the perspective that the system is an independent enterprise with annual net income or loss for the system being the single metric used to characterize financial viability. When the digester system is part of a livestock operation, as opposed to a centralized system, the biogas energy used by other parts of the operation is treated as a source of income for the biogas enterprise, along with payments received for any biogas energy sold to a third party.

7.2 Boundary Conditions

Because anaerobic digestion is an optional component of manure management systems, appropriate boundary conditions that exclude costs and revenue sources that are not dependent on the biogas enterprise must be defined. Only costs for system components that are required for anaerobic digestion and biogas utilization should be included.

For example, costs associated with digester effluent storage following anaerobic digestion should not be included as components of either biogas system capital or annual operation and maintenance costs, because biogas production and utilization does not require storage beyond what is required without a digester. Costs associated with manure storage are costs of an independent decision to store manure to minimize environmental impacts associated with current land application practices or to maximize manure value as a source of plant nutrients for crop production. However, when another waste that is not a byproduct of the farm enterprise is being co-digested with manure, the cost for storing and disposing the additional effluent should be included.

Another example of an inappropriate cost component would be including the cost of a pump to transfer manure to an anaerobic digester when a pump is required without digestion to transfer manure to a storage structure. However, if the anaerobic digester effluent cannot be transferred to the storage structure by gravity and a pump is needed, then the cost of the pump should be included in the estimate.

With respect to complementary operations, such as the separation of coarse solids from anaerobically digested dairy or pig manure, there has been debate about the inclusion or exclusion of the associated cost and revenue. Commonly, the capital and operating costs of solids separation have been considered as part of the biogas production and utilization system total cost, and the sale or onsite use of the separated solids (e.g., as bedding or soil amendment) is considered a source of revenue. However, this activity is not necessary for biogas production and utilization because separation of coarse solids from dairy manure can be accomplished without prior anaerobic digestion. Thus, solids separation should be considered as a separate enterprise in this context. However, if anaerobic digestion results in a reduction in the final stabilization cost for the solids used on site or sold, that reduction in cost should be included as revenue to the biogas enterprise.

Similarly, the cost of separating coarse solids from dairy manure entering a covered lagoon digester should not be considered as part of the cost of biogas production and utilization, because removal of these solids is necessary for the satisfactory performance of conventional anaerobic lagoons and the cost is the same. In addition, the revenue derived from the separated solids with and without biogas production will be the same and should not be included.

This guidance recognizes that variation among biogas production and utilization systems and site-specific conditions may justify different boundary conditions for financial analysis, based on best professional judgment. When the rationale for the specified boundary conditions is not entirely clear, a brief explanation of the underlying logic should be included with the results of the economic analysis. In all cases, the report presenting the results of the performance evaluation must include a schematic that identifies the boundary conditions assumed for the economic analysis.

7.3 Methodology

This section describes the methodology required by this protocol for estimating annual capital cost, annual operating and maintenance cost, other annual costs, annual revenue, and net income.

7.3.1 Annual Capital Cost

The first step in determining annual net income or loss from biogas production is the calculation of the annual capital cost of the system using the annual cash flow approach. To do so, three initial assumptions are necessary. The first assumption is that the total capital cost is comprised of internally-derived capital (e.g., monetary investment by the operator) and borrowed capital, not just the borrowed capital. The second assumption is that the retirement of total capital cost will occur by a uniform series of annual payments over the useful life of the system, or a shorter period if desired. The third assumption is an estimate of the useful life of the system. Although a useful life of 20 years generally is standard for structural components, it clearly is unrealistically long for some system components. Flexible covers generally have a useful life of about 10 years and mechanical equipment has a useful life of 7 years. However, all system components can be considered to have a useful life of 20 years if the reconditioning or replacement costs for components having a useful life of less than 20 years are accounted for in the annual operation and maintenance costs. This assumption allows for simplicity and standardization. A more detailed approach is acceptable if reconditioning and replacement costs are not included in the estimate of annual operation and maintenance cost, as will the less conservative assumption of capital recovery over 10 years instead of 20 years.

Generally, anaerobic digestion systems are financed with a combination of internally-derived and borrowed capital. In some instances, projects may receive cost-sharing assistance in the form of a grant or a below-market interest rate loan. One of the objectives of this protocol is to establish a basis that allows the comparison of different types of anaerobic digestion systems and of similar systems in different geographical locations. Therefore, all determinations of the annual capital cost for individual systems should be based on the final total cost, not the net cost to the owner.

In calculating the annual capital cost of the system, it is recommended for simplicity that the rate of interest being paid for borrowed capital is a reasonable rate of return to the internally-derived capital invested. Therefore, the annual capital cost is calculated simply by multiplying the turnkey cost of the system by the capital recovery factor for a uniform series of payments over 20 years, or 10 years if desired, at the interest rate being paid for borrowed capital.

7.3.2 Annual Operation and Maintenance Cost

One of the more uncertain aspects of the economic analysis of anaerobic digestion systems has been the ability to realistically estimate annual operation and maintenance costs. This lack of information is due, in part, to two factors. First, system owners generally do not maintain a detailed record of operation and maintenance costs during performance evaluations. Second, most performance evaluations will be for relatively new systems and it is unrealistic to assume that the operation and maintenance costs incurred during a 12-month performance evaluation will be representative of the average annual operation and maintenance costs over the life of the system, given that maintenance costs tend to increase with age. Therefore, the standard assumption that the average annual operation and maintenance costs will be three percent of the total capital costs should be used unless better information is available. However, management and labor requirements for routine system operation should be recorded and reported as part of all performance evaluations in an effort to delineate more clearly the cost of biogas system operation and maintenance.

7.3.3 Other Annual Costs

The construction of an anaerobic digestion system may increase the assessed value of a livestock operation and therefore increase annual real estate taxes. It also may increase the annual cost of insurance on structures and equipment and possibly the cost of liability insurance. In addition, other costs may increase, plus new costs may occur. For example, the cost of manure collection may increase if collection frequency increases. Also, an operating permit with an annual fee may be required. The magnitude of these increases should be determined and added to the estimated annual capital and operation and maintenance costs to determine the total annual cost of operating the system. Similarly, other annual costs in addition to operation and maintenance costs (e.g., insurance, real estate taxes, salaries, fringe benefits, transportation) will be incurred for centralized systems. All of these costs should be identified and included in the economic analyses of anaerobic digestion systems when possible, or their absence should be noted.

7.3.4 Annual Revenue

For some manure biogas systems, electricity generated may be the primary source of revenue. For systems with sell all/buy all utility contracts, the annual revenue generated by the system simply will be the sum of payments received from the utility annually. The estimation of annual revenue from electricity generation for operations with surplus sale or net metering utility contracts is more difficult due to the problem of placing a value of the biogas-generated electricity being used on site. Because of the way rate schedules for electricity generally are structured, the average cost per kWh decreases as the amount of electricity purchased increases. Therefore, reducing the amount of electricity purchased can increase its unit cost. In addition, onsite use of biogas-generated electricity may either increase or decrease demand charges and may result in the addition of a stand-by charge. If there is no onsite use of biogas-generated electricity, the revenue realized should be based on the payment received from the utility purchasing the biogas generated electricity. It should not be based on the cost of electricity being purchased, which may be at a higher rate.

The recommended approach for dealing with this issue is to compare the total amount of electricity purchased from the local utility for the 12 months prior to startup of the anaerobic digestion system with the total amount for the 12 months of the performance evaluation. The difference, multiplied by the utility rate during the performance evaluation, is the revenue generated by onsite use. If, however, the livestock operation is a new operation or there were significant changes, such as expansion when biogas production began, the cost of electricity without biogas production should be estimated. This should be done from the record of onsite biogas electricity consumption and purchases from the local utility for the 12 months of the performance evaluation. If the 12 months of the performance evaluation have atypical average monthly ambient temperatures, an earlier 12-month period should be used if possible. Other situations can be addressed on a case-by-case basis.

For combined heat and power systems where engine-generator set waste heat is being recovered for beneficial use, the revenue derived from waste heat utilization should be calculated based on the cost per unit of energy for the conventional fuel being replaced and the amount of waste heat energy being utilized. When estimating revenue derived from only using biogas as a boiler or furnace fuel, the same approach should be used. Because costs of the conventional fuels most likely to be replaced, LPG or No. 2 fuel oil, vary seasonally, the impact of seasonal variation in biogas use and value must be incorporated in revenue estimates.

For systems processing biogas to produce RNG, the revenue derived from on-site use in place of a fossil fuel, such as gasoline or diesel fuel, should be the avoided cost of the fuel replaced. When RNG is sold to a third party, the revenue realized is simply the sum of the payments received, which may include a premium added to the current wholesale price for natural gas.

7.3.5 Net Income

After calculations of total annual cost and annual revenue are made, net income from the biogas enterprise before income taxes can be quantified. An attempt to estimate net income after income taxes should not be made because income from the biogas system will be a component of total income from the livestock operation, which may vary significantly over the life of the biogas system. In addition, using the value before income taxes allows the digester operation’s income tax information to remain confidential.

8.0 WASTE STABILIZATION

Waste stabilization is the process by which complex organic compounds are converted to gas and inert substances that can be managed in an environmentally safe manner. As indicated earlier, each Level IV performance evaluation performed in accordance with this protocol must include the quantification of the degree of waste stabilization being realized during anaerobic digestion in addition to the Level I, II, and III requirements. The required and optional parameters to quantify the degree of waste stabilization are discussed below. Also described are required methods for sample collection, preservation, and analysis, as well as the determination of digester hydraulic retention time and reporting of results.

8.1 Waste Stabilization Parameters

For mixed, plug flow, and attached film digesters, the degree of waste stabilization claimed should be based on differences, when statistically significant, between mean influent and effluent concentrations of the following parameters:

- Total solids (TS)
- Volatile solids (VS)
- Chemical oxygen demand (COD)
- Total volatile acids (TVA)

In addition, it must be demonstrated that the observed changes in concentrations of these parameters are due to microbial processes rather than settling of particulate matter (solids) by showing that there is no statistically significant difference ($P<0.05$) between influent and effluent fixed solids and, preferably, total phosphorus (TP) concentrations. Ideally, changes in concentrations of the following chemicals should be determined, but are not required:

- Total Kjeldahl nitrogen (TKN)
- Organic nitrogen (ON)
- Ammonia nitrogen (NH_4-N)
- Total phosphorus (TP)
- Total sulfur (S)

Mean influent and effluent pH values must be reported in conjunction with the parameters listed above.

For covered lagoons, differences between measured influent and effluent concentrations for those parameters present in both particulate and soluble forms (i.e., TS, VS, and COD) represent changes due to the combination of microbial processes and settling and are not valid indicators of the degree of waste stabilization being achieved. Although these differences have value in characterizing effluent water pollution potential and should be reported, quantification of the degree of waste stabilization should be based on the difference between influent and effluent TVA concentrations and COD reduction, which are estimated based on methane production.

Stoichiometrically, 5.60 ft^3 of methane is produced per lb COD destroyed (0.3496 m^3 of methane is produced per kg of COD destroyed) under standard conditions (0°C and 1 atm) (Madigan et al., 1997). The assumed quantity of methane produced per unit COD destroyed under other than standard conditions must be adjusted to standard conditions using the universal gas law (see Appendix A). It is recommended that estimates of COD reduction based on methane production be compared to COD reduction estimates based on the difference between mean influent and effluent concentrations in the evaluation of the performance of other types of digesters (see Appendix C for a discussion of the construction of materials balances).

Although methane production can be expressed as a function of VS destruction, the nature of this relationship is variable depending on the chemical composition of the VS destroyed. The variation in chemical composition among different types of livestock manure as well as the impact of different feeding programs (and possibly other variables) within the different animal sectors suggests that there is no single, generally applicable conversion factor as with COD. For example, the generally accepted degree of variation in total biogas production during the anaerobic digestion of domestic wastewater biosolids can vary from 12 to 18 ft^3 per lb VS destroyed (0.7492 to 1.124 m^3 per kg of VS destroyed) (Metcalf and Eddy, Inc., 2003). A defensible basis for estimating VS destruction during the anaerobic digestion of livestock manures based on methane production seems to be lacking at this time but may emerge in the future.

Finally, it is recommended that long-term, bench-scale batch studies be conducted at the operating temperature of the digester being evaluated to estimate the readily biodegradable and refractory fractions of VS. Such studies should be for no less than 30 days and with the refractory fraction at infinity (VS_∞/VS_0), determined by plotting VS_t/VS_0 versus ($1/VS_0*t$), where t equals zero at the beginning of the study, and determining the y-axis intercept using linear regression analysis.

8.2 Pathogen Reduction

Under this protocol, estimating pathogen reduction is optional. At a minimum, all claims of pathogen reduction potential must be supported by results of the analyses of the digester or covered lagoon influent and effluent samples collected and analyzed for the waste stabilization parameters previously listed. Claims of pathogen reduction potential may be based solely on reductions in the densities of the total coliform and fecal streptococcus groups of indicator organisms. It should be clearly explained that reductions in these groups of microorganisms are only indicative of the potential for pathogen reduction. If the demonstration of reduction of a specific pathogen is desired, preference should be given to *Mycobacterium avium paratuberculosis* in dairy manure and *Salmonella spp* in swine and poultry manures.

8.3 Sample Collection

Given the inherent variability in animal manures, care should be taken to insure that all influent and effluent samples collected for analysis are representative of the average daily flow. While the most desirable approach would be to collect 24-hour flow composite samples, it is recognized that this approach generally is impractical for collection of livestock manure samples. Thus, the following alternatives are recommended.

- With influent and effluent lift stations, a series of at least five grab samples should be collected at different depths when the lift station is at maximum capacity and then combined into a single composite sample. When possible, the contents of the lift station should be mixed before sample collection.
- When samples have to be collected from a continuously or periodically flowing influent or effluent stream, a series of at least six grab samples should be collected over a period of no less than one hour and combined into a single composite sample.

Composite samples should be no less than 20 L (~5 gal) and subsamples withdrawn for analysis should no less than 1 L (~ 1 qt). To insure that samples collected are representative of the waste, there should be an ongoing review of analytical results to determine if the degree of variability is reasonable or if a modification of the sample collecting protocol is necessary.

Because of inherent variability over time, all claims with respect to waste stabilization must be based on the results of the analysis of a minimum of 12 monthly influent and effluent samples with the following caveat. If the coefficient of variation for influent or effluent TS concentrations exceeds 25 percent, or there is more than one extreme observation determined to be an outlier statistically, more frequent sample collection and analysis may be necessary, with at least 24 semi-monthly sampling episodes recommended.

With co-digestion of livestock manure and another waste or combination of other wastes, a sampling plan must be devised that will characterize the digester influent and effluent to accurately delineate the degree of waste stabilization being realized as well as the relationship between waste stabilization and biogas production. If the same waste or combination of wastes is being combined with manure continually and at a constant rate, periodic sampling as described above should be sufficient. If, however, different wastes are being combined with manure at different times, co-digestion is intermittent, or both, adequate evidence must be provided that the physical and chemical characteristics of the digester influent and effluent reported as mean values are representative.

An additional requirement for all performance evaluations involving co-digestion is that a record be maintained of all additions of other wastes for a period equal to at least five HRTs prior to and through the 12-month duration of the performance evaluation. This record must be included in the report of the performance evaluation and include at least the following:

- Type and source of the waste(s) or other feedstock(s),
- Date(s) of addition,
- Volume added,
- TS, TVS, COD, and TVA concentrations and pH using the same analytical protocols being used for determining digester influent and effluent physical and chemical characteristics.

8.4 Sample Preservation

All anaerobic digester influent and effluent samples should be collected, immediately iced or refrigerated, and delivered for analysis within 24 hours. Given the high concentrations of organic matter, subsamples should not be acidified for preservation even if acidification will not interfere with subsequent analyses.

8.5 Analytical Methods

Only analytical methods described in Methods for Chemical Analysis of Water and Wastes, EPA-600/4-79-020 (U.S. EPA, 1983), Standard Methods for the Examination of Water and Wastewater, 21st edition (American Public Health Association, 2005), or equivalent methods having the same degree of precision and accuracy should be used. Particular analytical methods are not specified because there may be more than one suitable option for a parameter. A laboratory with appropriate certification, which could be certification that satisfies the National Pollutant Discharge Elimination System requirements and includes an ongoing quality assurance/quality control (QA/QC) program, should be used to analyze influent and effluent samples.

In the event that an analytical laboratory without the appropriate certification is used, such as a university research laboratory, that laboratory must have a QA/QC program that is comparable to such programs required for certification. The laboratory used should have previous experience in analyzing samples with high solids concentrations. Duplicate, or preferably triplicate, analyses of individual samples should be performed for all parameters.

The multiple-tube fermentation techniques described in Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 2005) should be used to estimate fecal coliform, fecal streptococcus, and *Salmonella spp.* densities. For estimation of *M. avium paratuberculosis* densities, either the National Animal Disease Center or the Cornell Method (described in Stabel, 1997) is acceptable.

8.6 Hydraulic Retention Time and Temperature

Because the degree of waste stabilization will vary with HRT and actual HRT may differ from the design value, the determination of actual digester or covered lagoon influent or effluent flow rate to calculate actual HRT is a requirement of this protocol. Because of differences among digesters, no specific flow measurement techniques are specified. However, the method used, as well as the underlying rationale, must be fully described in the performance evaluation report.

In addition, digester or covered lagoon operating temperature must be determined and recorded at least during each sampling episode with the concurrent measurement of influent and effluent temperatures also being desirable. At least monthly, the accuracy of all thermometers or other temperature measuring devices should be checked using a precision thermometer certified by the National Institute of Standards and Technology. For covered anaerobic lagoons, the average daily ambient temperature over the duration of the performance evaluation also should be measured and recorded or obtained from the nearest National Oceanic and Atmospheric Administration weather observation station.

8.7 Reporting

All reductions must be shown to be statistically significant at least at the $P<0.05$ level using the Student t test (Snedecor and Cochran, 1980.). Any suspected outliers in data sets should be tested at $P<0.05$ using Dixon’s method (Snedecor and Cochran, 1980). For covered lagoons, claims of TVS and COD reductions will have to be estimated based on observed biogas production. All densities of indicator organisms and pathogens should be reported and compared statistically on a $\log_{10}$ colony-forming units (CFU) per 100 ml basis. If a reduction is claimed, it also must be statistically significant at least at $P<0.05$. When differences are found to be statistically significant, 95 percent confidence interval estimates should be reported.

9.0 REPORT FORMAT

Reports presenting results of performance evaluations of anaerobic digestion systems for livestock manures should contain the following sections:

- Summary and Conclusions—A brief overview of the performance evaluation and presentation of the major findings.
- Introduction—Descriptions of the location of the performance evaluation and the biogas system evaluated followed by the objectives of the evaluation.
- Methods and Materials—A description of methods and materials employed in the performance evaluation.
- Results—Summaries of the results obtained.
- Discussion—A discussion of the results obtained, especially with respect to similarities to and differences from previously reported results.
- References—A list of literature cited following the format used in this document.

- Appendices—
    - A copy of the QA/QC plan for the laboratory that performed digester influent and effluent sample analyses,
    - A record of tests of the accuracies of meters and temperature measuring devices used,
    - All data collected in tabular form, and
    - Technical specifications (meta data) for the distributed generation/combined heat and power portion of the system.

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APPENDIX A

General Gas Law

To determine biogas production under digester operating conditions from COD destruction based on the stoichiometrically based estimate that 5.60 ft^3 of methane are produced per lb of COD destroyed (0.3496 m^3 per kg COD destroyed) under standard conditions (0°C and 1 atm) or correct non-temperature- or pressure-compensated biogas production measurements to standard conditions, the following relationship (the general gas law) should be used.

$$V_2 = V_1 * (T_2/T_1) * (P_1/P_2) \quad \text{(A-1)}$$

Where: V_1 = gas volume (m^3) at temperature T_1 (°K) and pressure P_1 (mm Hg)
V_2 = gas volume (m^3) at temperature T_2 (°K) and pressure P_2 (mm Hg)

APPENDIX B

U.S. Emission Equation Default Values

Table B-1. Maximum Methane Generation Potential

Animal Type	Maximum Methane Generation Potential, B_o (m^3 CH_4/kg VS added)
Dairy Cows	0.24
Dairy Heifers	0.17
Feedlot Steers	0.33
Feedlot Heifers	0.33
Not on Feed Bulls	0.17
Not on Feed Calves	0.17
Not on Feed Heifers	0.17
Market Swine.	0.48
Breeding Swine	0.48
Feedlot Sheep	0.36
Not on Feed Sheep	0.19
Goats	0.17
Horses	0.33
Layers	0.39
Other chickens	0.39
Ducks	0.36
Broilers	0.36
Turkeys	0.36

Source : U.S. EPA, 2010

Table B-2. Methane Conversion Factors

Manure Management System Component	MCFs by Average Annual Ambient Temperature (degrees C)																		
	Cool					Temperate											Warm		
	<10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	>28
Uncovered Anaerobic Lagoon	66%	68%	70%	71%	73%	74%	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%	80%	80%
Liquid/slurry (with crust cover)	10%	11%	13%	14%	15%	17%	18%	20%	22%	24%	26%	29%	31%	34%	37%	41%	44%	48%	50%
Liquid/slurry (w/o crust cover)	17%	19%	20%	22%	25%	27%	29%	32%	35%	39%	42%	46%	50%	55%	60%	65%	71%	78%	80%
Storage pits <1 month	3.0%					3.0%											30.0%		
Storage pits >1 month	17%	19%	20%	22%	25%	27%	29%	32%	35%	39%	42%	46%	50%	55%	60%	65%	71%	78%	80%
Solid manure storage	2.0%					4.0%											5.0%		
Dry lots (including feedlots)	1.0%					1.5%											2.0%		
High-rise houses for poultry production (without litter)	1.5%					1.5%											1.5%		
Poultry production with litter	1.5%					1.5%											1.5%		
Deep bedding systems for cattle and swine(<1 month)	3.0%					3.0%											30.0%		
Deep bedding systems for cattle and swine (>1 month)	17%	19%	20%	22%	25%	27%	29%	32%	35%	39%	42%	46%	50%	55%	60%	65%	71%	78%	80%
Manure Composting - In Vessel	0.5%					0.5%											0.5%		
Manure Composting - Static Pile	0.5%					0.5%											0.5%		
Manure Composting- Extensive/ Passive	0.5%					1.0%											1.5%		
Manure Composting- Intensive	0.5%					1.0%											1.5%		
Aerobic Treatment	0.0%					0.0%											0.0%		

Source : IPPC, 2006

APPENDIX C

Material Balances

A material balance (or inventory) is a simple accounting of any material in a system, which may be a single unit, a collection of units, or an entire system and generally may be stated as:

Input (enters through the system boundary) +
Generation (produced within the system) –
Output (leaves through the system boundary) – (C-1)
Consumption (consumed within the system) =
Accumulation (buildup within the system boundary)

If there is no generation or consumption within the system boundary, as is the case with fixed solids (FS) and total phosphorus (TP) in an anaerobic digestion reactor, Equation C-1 reduces to:

Input (enters through the system boundary) –
Output (leaves through the system boundary) = (C-2)
Accumulation (buildup within the system boundary)

In the analysis of the performance of livestock and other waste treatment or stabilization processes, it is generally assumed that no accumulation of any substance due to settling is occurring if the input of FS, and preferably also TP, is equal to the output. Therefore, any difference between input and output must be due to generation or consumption and Equation C-1 reduces to:

Input (enters through the system boundary) +
Generation (produced within the system) - (C-3)
Consumption (consumed within the system) =
Output (leaves through the system boundary)

If generation is zero or negligible in comparison to consumption, Equation C-3 reduces to:

Input (enters through the system boundary) –
Output (leaves through the system boundary) = (C-4)
Consumption (consumed within the system)

and treatment or stabilization efficiency is calculated as follows:

Treatment or stabilization efficiency, % = (C-5)
*(Consumption/Input) * 100*

The basis for material balances for continuous steady-state processes such as anaerobic digestion usually is mass flow rates (e.g., kg per hr). However, material balances to estimate treatment or stabilization efficiency can be constructed using concentrations (e.g., mg per L) when volumetric flow rates (e.g., L per hr) are equal. Although there is some reduction in volume during anaerobic digestion due to the saturation of the biogas leaving the reactor with water vapor, the reduction in volume is negligible and can be ignored.

For estimating chemical oxygen demand (COD) reduction in covered lagoons based on methane production under standard conditions, the relationship is:

$$COD_{reduction}\text{, lb/unit time} = (\text{Methane production, ft}^3\ CH_4\text{ /unit time})/(5.60\text{ ft}^3\ CH_4/\text{lb } COD_{destroyed}) \quad \text{(C-6a)}$$

or

$$COD_{reduction}\text{, kg/unit time} = (\text{Methane production, m}^3\ CH_4\text{ /unit time})/(0.3496\text{ m}^3\ CH_4/\text{kg } COD_{destroyed}) \quad \text{(C-6b)}$$

For non-standard conditions, the universal gas equation (see Appendix A) should be used to determine the volume occupied by one mole of methane and the methane equivalent of COD converted under anaerobic conditions assuming 64 g COD per mole of methane.