Biogas from Manure

An anaerobic digester will partially convert manure to energy in the form of biogas which contains methane.

Updated: March 9, 2023

Biogas Generation Terminology

Anaerobic: life of activity in an airless environment.

Anaerobic Bacteria: microbes whose metabolisms require the absence of free oxygen.

Anaerobic Digestion: the bacterial digestion of organic material in the absence of free ozygen.

Biogas: a gaseous product of anaerobic digestion that primarily consists of methane and carbon dioxide.

British Thermal Unit (Btu): a unit of energy defined as the amount of heat required to raise the temperature of 1 pound of water 1°F.

Carbon-to-Nitrogen Ratio (C/N): the ratio of carbon to nitrogen in organic materials. Anaerobic bacteria produce the most biogas when fed organic materials with a C/N ratio compatible with their metabolic requirements.

Digester: the sealed tank or container in which the biological requirements of anaerobic digestion are controlled to hasten digestion and optimize biogas production.

Effluent: the partially digested liquid manure or slurry which exits the digester.

Joule (J): the metric unit of energy. One Btu equals 1055 joules. Since the joule is a very small unit, it is also referred to in kilojoules (kj), a thousand joules, or in megajoules (MJ), a million joules.

Loading Rate: the amount of volatile solids fed to the digester daily.

Manure: animal feces and urine, wasted feed, bedding, and anti-slip material form the barn and yard.

Mesophilic: bacteria which thrive in a temperature range around 95°F (35°C).

Methane: a combustible gas produced by anaerobic digestion, also the principal component of natural gas.

Retention Time: the average time that the slurry remains in the digester.

Sludge: the separated manure solids which settle to the bottom of the digester.

Slurry: the mixture of manure and water processed in the digester.

Thermophilic: bacteria that are most active in a temperature range of 120°F to 140°F (49°C-60°C).

Volatile Acids: the intermediate material produced in the digester by acid-forming bacteria and used by methane-forming bacteria.

Volatile Solids: the organic constituents of manure.

Introduction

Manure can be an alternative energy source for livestock farmers. An anaerobic digester will partially convert manure to energy in the form of biogas which contains methane.

In 1974, in response to public interest in biogas production as an energy alternative, the Pennsylvania Department of Agriculture funded a project at Penn State to design an anaerobic digester for farm use. The purpose of the study was to determine the technical requirements and economic feasibility of biogas production on the farm. The Agricultural Engineering Department in cooperation with the Dairy Science and Sanitary Engineering Departments built and tested a 3,500-cubic-foot (100-m^3) anaerobic digester at one of the university's dairy barns. Penn State chose to study biogas production on dairy farms because:

- manure is easily collected on dairy farms where cows are routinely confined
- biogas is most efficient when used directly for heating, and
- dairy farms have a year-round demand for hot water.

Organic materials decomposing in a warm, airless environment release biogas. This process occurs spontaneously in nature; marsh gas and biogas are virtually the same. Biogas production can be hastened by sealing the organic material inside a heated, airtight tank called a digester.

Humphrey Davy conducted the first laboratory experiments on the anaerobic digestion of manure to produce methane in 1808. Since then, anaerobic digestion has been used mainly for municipal waste treatment. In 1895, the biogas from a waste treatment plant in Exeter, England, was collected and used to light nearby streets. During World War II, fuel-starved Germans built about 30 digesters, using some of the biogas to fuel farm tractors. In recent years, small, inexpensive digesters in India and China have been producing biogas for cooking and driving electric generators. Pioneers, such as R.B. Singh in India, have popularized anaerobic digestion and have persuaded others to recognize the potential of biogas production and the applications of biogas as fuel.

Under certain conditions, biogas production is economical now. It will become even more attractive to livestock farmers as the price of conventional fuel rises, and when mass production lowers the cost of digester system components.

In Pennsylvania, dairy cows produce an estimated 5.5 million tons of reclaimable manure each year. Given the gas production rate of the Penn State digester, a net daily biogas output of 40 cubic feet (1.2 m^3) per cow, Pennsylvania dairy farmers could produce 5 billion cubic feet (143 million m^3) of biogas per year. That is enough "manure power" to provide about 20 percent of all energy used on Pennsylvania diary farms.

We must learn more about the biology of anaerobic digestion in order to understand the dynamics of the Penn State digester system.

The Anaerobic Digestion Process

In the digester, bacteria decompose organic materials in the absence of air with the release of methane and carbon dioxide. This process is shown in Figure 1. Acid-forming bacteria break down or liquefy the volatile solids, changing them in to simple fatty acids. The methane-forming bacteria then convert these volatile acids to methane and carbon dioxide. These bacteria are sensitive to changes in their environment. Rapid digestion and efficient biogas production occur within limited ranges of temperature and are influenced by the composition of the raw material.

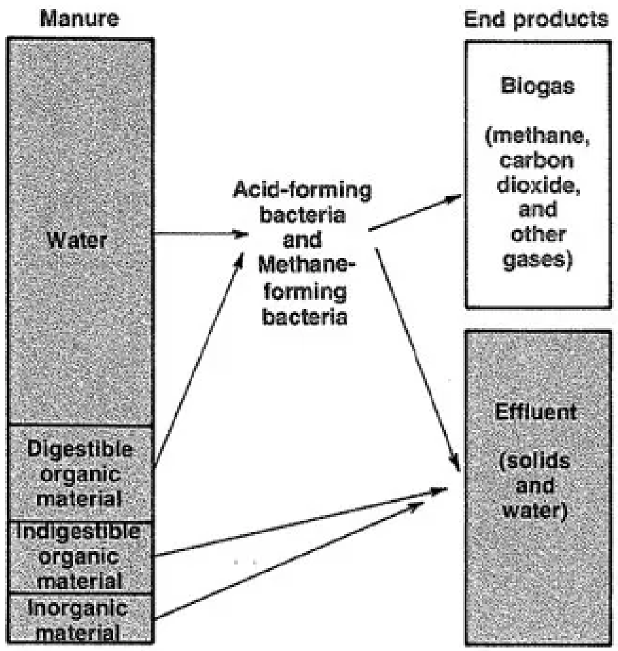

Figure 1. The breakdown of manure in an anaerobic digester.

Temperature

Optimum gas production occurs in two temperature ranges. Mesophilic bacteria thrive in temperatures around 95°F (35°C), and thermophilic bacteria in the 120°F to 140°F (49°C-60°C) range. Figure 2 shows that gas production decreases when the bacteria are subjected to temperatures outside of these ranges. While thermophilic bacteria produce somewhat more gas, often the gas is not worth the energy needed to raise the digester temperature from 95°F (35°C) to 120°F (49°C).

Raw Material

The composition of manure varies according to feed rations and different farm management practices. The amount of manure that can be collected will also vary. This depends on the type, weight, and number of animals, the feed ration, and the degree of confinement. For example, if all the manure could be collected from a 1,500-pound (680-kg) dairy cow, a farmer could collect about 125 pounds (57 kg) daily.

A digester can process other farm wastes, such as milk room waste water, straw, corn husks, grass, and leaves, with or instead of dairy cow manure. Beef, hog, and poultry manure are being used in digesters, although poultry manure digesters require further research. Regardless of the material used, gas production proceeds most efficiently when the raw materials fed to the digester have a certain pH and carbon-to-nitrogen ratio (C/N).

Bacteria thrive in a slurry with a pH around 7.0. Consequently, if the incoming slurry has a pH in this range, digestion should proceed smoothly. Under normal conditions, the digestion process balances excess acidity or alkalinity on its own.

Carbon is the major chemical element in manure, and the bacteria digest the carbon with the release of biogas. However, in order to derive their energy from carbon, the bacteria require that nitrogen be available in the raw material. The ratio of carbon to nitrogen in the raw material is crucial to efficient digestion. A high C/N ratio means that the nitrogen will be exhausted before the carbon is digested. Conversely, a low C/N ratio or too much nitrogen in relation to carbon results in high ammonium concentrations that may become toxic to the anaerobic bacteria.

It is possible to adjust the C/N ratio of a digester by adding material to complement the material already in the digester. For instance, sawdust which has a high C/N ratio could be added to poultry manure which has a low C/N ratio. Dairy cow manure has a C/N ratio just slightly below that required by the bacteria.

The Anaerobic Digester System

The design of a digester system will vary with the individual farm's needs; it should be adjusted to the topography of the farm, existing farm equipment, and housing and management systems. However, some aspects of digester system design should be considered in every case.

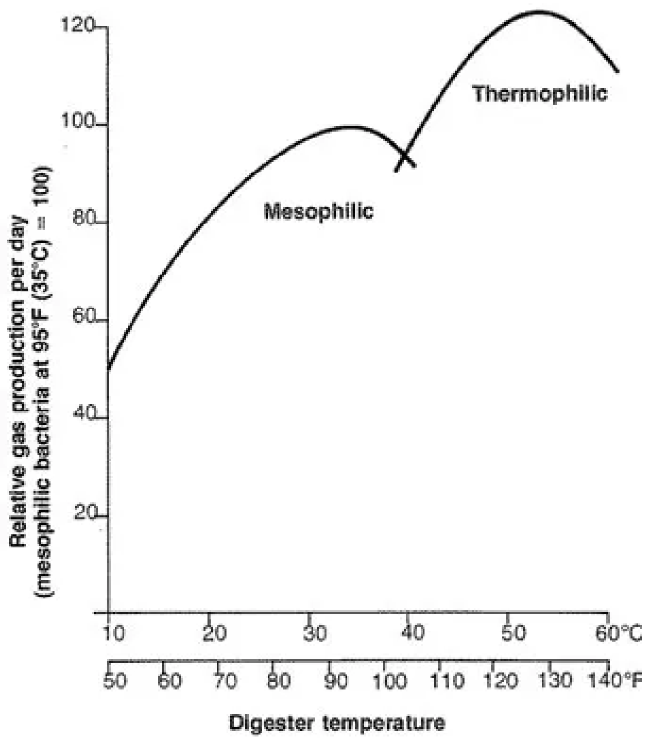

Figure 2. Effect of temperature on gas production rate. (Roediger, H. Die anaerobe alkalische Schlammfaulung. *Wasser-Abwasser*, H.1, Verlag R. Oldenbourg, Muchen u. Wien. 1967.)

Digester system design

The main components of a farm-size digester system are a slurry handling system, including slurry preparation area, manure pump or other loading method, and effluent tank; one or more digester chambers; and housing for the heating, agitation, and hydraulic equipment. For the best performance, these components should:

- be arranged to minimize heat loss,
- provide a simple flow path for material through the system,
- be as automated as possible, and
- be accessible for maintenance and repairs.

It is important to comply with state and local safety ordinances when designing a digester system. Biogas is combustible and, therefore, dangerous. It has the potential to suffocate, and when mixed with air in a concentration of 6 to 15 percent, the gas becomes explosive.

All materials in contact with the manure or biogas should be corrosion resistant. For instance, PVC plastic was used for the slurry handling pipes in the Penn State digester. The design should incorporate alternative methods of moving slurry or biogas through the system. A blocked pipe could result in backed up slurry spilling from the digester. All pipes and gas lines should be made large enough to provide access for cleaning devices.

Digester system costs

Table 1 lists the major components and estimated costs of the Penn State digester system. These costs reflect 1975 price levels and the use of agricultural construction methods.

Table 1. Cost estimate for the principle components of the Penn State 100-cubic-meter anaerobic digester.

Principle Components	Cost
Foundation (including sludge auger housing)	$2,500
Digester (including insulation)	$ 4,600
Effluent storage	$ 1,900
Roof (including insulation)	$ 1,500
Gas pump	$ 700
Boiler	$ 600

Hydra-ram manure pump (including hydraulic unit)	$ 4,900
Supplies and labor (estimated)	$ 3,300
Total initial cost	$ 20,000

The Penn State digester system is a prototype that was constructed with test equipment a farmer would not need. A farmer considering the construction of a digester of this size can expect to invest from $18,000 to $30,000, depending on local prices, the labor the farmer contributes, and the choice of components included in the system.

The Digester

Types of digesters

Digesters can be loaded with slurry continuously or by the batch. A batch-load digester is filled to capacity, sealed until it has produced all the biogas it can, emptied, and filled again. Gas production is uneven because bacterial digestion starts slowly, peaks, and then tapers off as the volatile solids are consumed. This problem can be solved by connecting a series of batch-load digesters that have been loaded at different times so that a dependable amount of biogas is available daily. This method uses manure efficiently but is less efficient in terms of digester space.

The Penn State digester is loaded continuously; that is, fresh slurry is added to the digester daily. Gas production is consistent because the bacteria always have a fresh supply of volatile solids to digest. The continuous-load digester uses expensive digester space efficiently, although it may not produce quite as much gas per pound (kilogram) of manure.

Digester design

The two basic designs for continuous-load digesters are shown in Figure 3. The plug-flow digester is a horizontal cylinder seated in a trench. The slurry flows in a straight path through the system; incoming slurry pushes the material through the digester. This design is usually constructed of flexible materials which are inexpensive, but not durable unless protected from the weather.

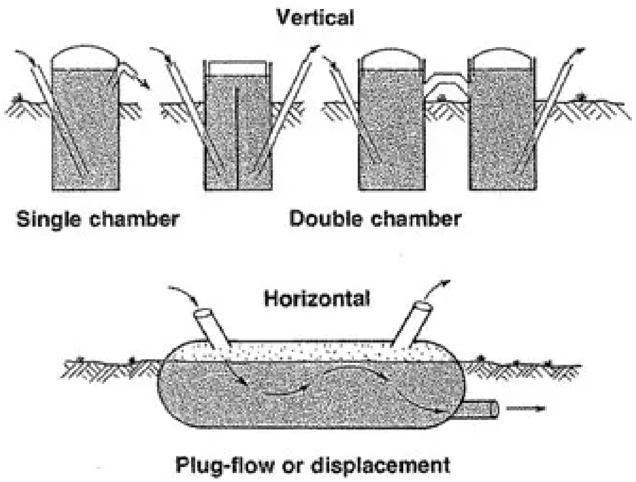

Figure 3. Designs of continuous-load digesters. (Stoner, *Producing Your Own Power*, pp. 163.)

The Penn State digester is the vertical double chamber type shown in Figure 4. The digester has rigid walls, agitation equipment, and minimum area for heat loss.

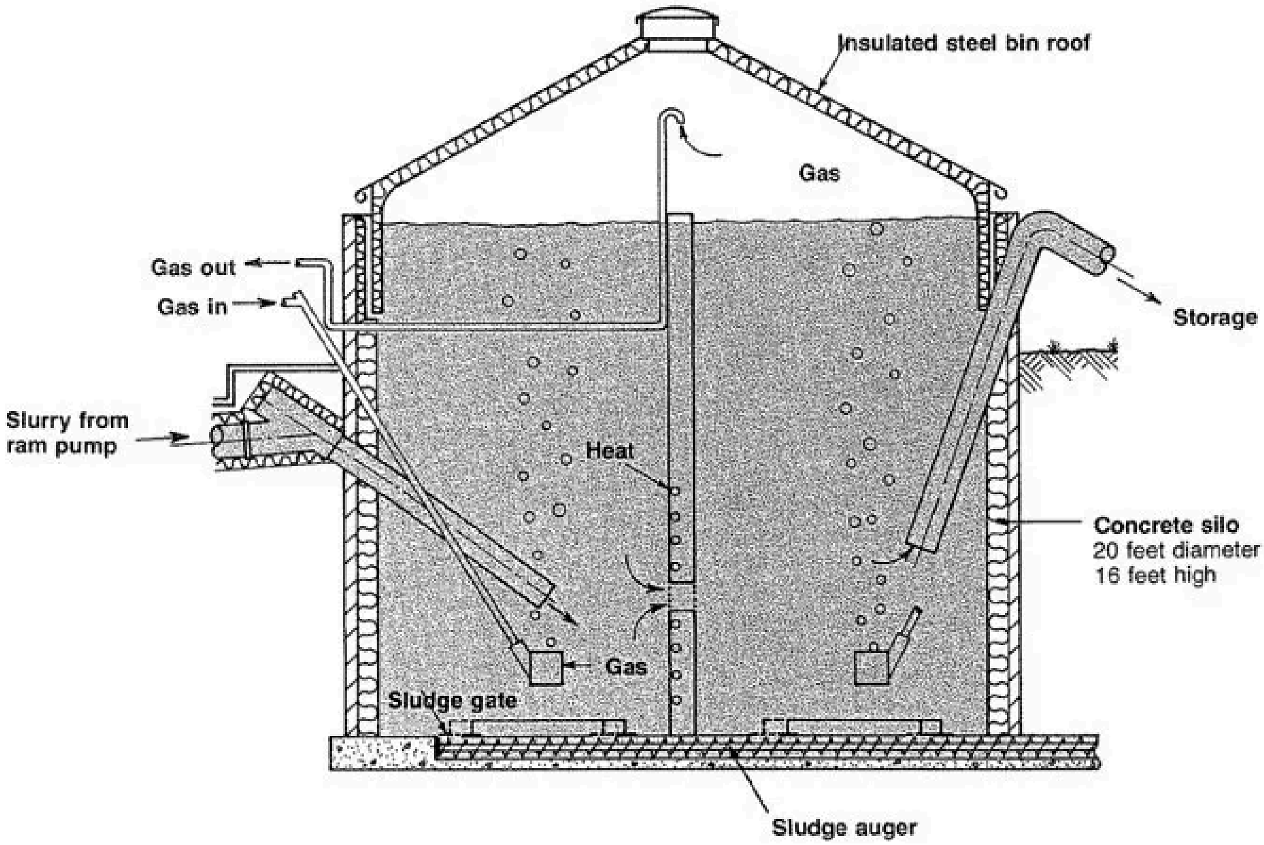

Figure 4. Cross section of the Penn State digester.

Digester construction

The Penn State digester was constructed with concrete silo panels to form a 16-foot (4.8-m) high tank with a diameter of 20 feet (6m). Steel reinforcement hoops were secured around the outside of the digester. A sludge removal auger was built into the reinforced concrete foundation and floor. For the heating system, 188 feet (57m) of ¾-inch (2-cm) steel pipe was cast into the panels composing the middle wall to provide 72 square feet (6.5 m^3) of heat exchange surface.

The digester roof serves as the gas collection and storage area and can store the biogas produced in 6 hours. The floating roof is independent of the tank; its bottom edge is submerged in the slurry, and its weight is supported by the pressure of the gas inside. This preserves anaerobic conditions in the digester while allowing the roof to rise and fall according to gas production and use. The floating roof was constructed from an 18-foot (5.4-m) diameter galvanized steel grain bin roof assembly and a 40-inch (1-m) high wall section.

To reduce heat loss, two-thirds of the digester was built below ground. The digester was insulated on the inside with 4 inches (10 cm) of polystyrene foam plastered with about 1 inch (2.5 cm) of gunite. The roof was insulated with 3 inches (7.5 cm) of urethane foam, and nylon-reinforced Hypalon sheet provided the gas seal.

Digester size

A farmer planning to build a digester system similar to the Penn State system, which has a 14-day retention time, should provide 30 cubic feet (0.9 m^3) of digester volume for each 1,500-pound (680-kg) lactating dairy cow. If the farmer is collecting the manure from dry cows and replacement stock, 15 cubic feet (0.45 m^3) should be added for every 1,000 pounds (455 kg) of animal weight.

The Slurry Supply System

An efficient slurry supply system is crucial to the smooth operation of the digester system. Manure is a difficult substance to handle, and the 100-cow digester processes 6.25 tons (5.6 Mg) of manure every day. The slurry flow path through the Penn State digester is shown in Figure 5.

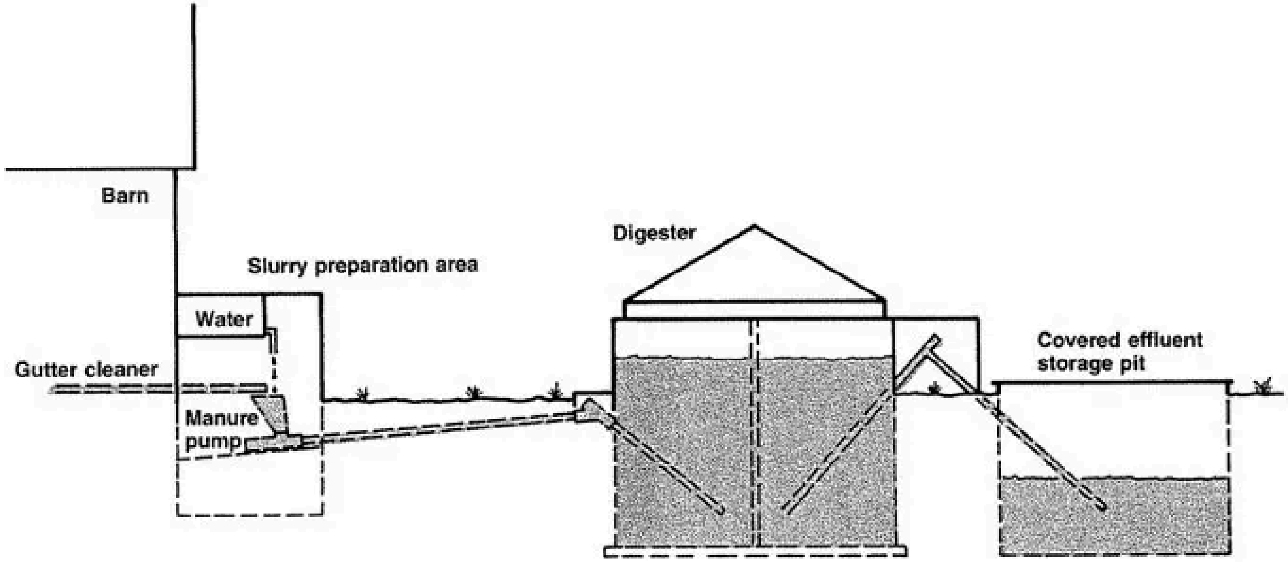

Figure 5. Slurry path through the Penn State digester.

Slurry loading system

The gutter cleaners deliver the manure from the barn to the slurry preparation area. The manure drops into the pump hopper with enough water to reduce the solids content from about 15 percent to 13 percent. The manure must be diluted to prevent clogging in pipes and pumps, and to ease mixing within the digester. However, the best system is the one that requires the least dilution; the added water wastes digester space and heat.

In 1975, the slurry loading system consisted of an electrically-driven centrifugal manure pump which pumped the slurry to an elevated tank where it was discharged by gravity into the digester. This system was replaced by a hydraulic ram pump which pushes the manure directly into the digester. It was capable of handling more than 13 percent solids and large particles and long fibers without clogging. Tests will be conducted on a direct gravity feed method which will not require a pump.

Loading rate

The loading rate is the weight of volatile solids fed to the digester daily. The volatile solids concentration in the digester determines the rate of gas production. For instance, a digester loaded with 4 units by weight of volatile solids will produce twice the gas as the same digester loaded with only 2 units.

The results of tests with three different loading rates are shown in Table 2. These results indicate that high loading rates are accompanied by high daily gas output per unit digester volume. This results in a greater rate of return on the capital outlay for construction. With the capital cost related to size, a high loading rate will permit the use of a smaller digester and lower operating costs, for a given size herd. A high loading rate means a low volatile solids reduction which results in low gas production per unit of volatile solids. The loading rates and related retention times shown allow sufficient digestion time to stabilize the effluent.

Table 2. Summary of capacity tests of the Penn State 100-cubic-meter digester showing total gas production

Volatile solids fed to digester lbs/day	Volatile solids fed to digester kg/day	Retention time (days)	Equivalent # of cows	ft^3 gas/cow-day	m^3 gas/cow-day	ft^3 gas/ft^3 digester/day	m^3 gas/m^3 digester/day	ft^3/day	m^3/day	ft^3 gas/lb. VS/day	m^3 gas/kg VS/day
763	346	35	50	47.3	1.34	0.7	0.67	2,365	67	3.1	0.19
1,221	554	21	80	57	1.61	1.3	1.29	4,560	129	3.7	0.23
2,270	1030	11	150	47.5	1.35	2.0	2.02	7,130	202	3.1	0.20

Retention time

The volume of slurry in the digester remains constant; the incoming slurry displaces an equal amount of processed slurry from the digester each time the digester is loaded. Since the volume is constant, the fraction of the digester's liquid volume replaced each day determines the retention time. For example, if slurry equaling one-tenth of the digester's liquid volume is added daily, the digester slurry has an average retention time of 10 days.

A brief retention time does not allow the bacteria enough time to digest the manure, and a long retention time does not furnish enough fresh slurry to promote bacterial growth and a high gas production rate. Retention times of 20-24 days are more common for dairy manure digesters.

The effluent

The effluent flows through an overflow pipe into a covered manure pit. The organic content of the processed manure is reduced and stabilized so that the effluent is an almost odorless, homogenized liquid that does not attract rodents or flies.

Only a small percentage of the manure is actually converted to biogas. Dairy cow manure is about 85 percent water and 15 percent solids. Of these solids, about 91 percent are volatile, and the Penn State digester converts from 20 to 30 percent of the volatile solids to biogas. A dairy cow produces around 17 pounds (7.7 kg) of volatile solids a day, of which one-fourth is converted to biogas. Consequently, an anaerobic digester is a system for manure treatment, not manure disposal.

The digester effluent is a resource; it contains almost all of the nitrogen that was in the raw manure. The effluent is an excellent fertilizer because the nitrogen in the effluent is more readily absorbed by plants than the nitrogen in raw manure. The daily effluent from a 100-cow digester contains about 55 pounds (24 kg) of nitrogen.

The effluent is most compatible with a liquid manure handling system. However, the water can be removed from the effluent and recycled through the digester as dilution water. The sludge can be used for bedding or mulch; it is being tested for stock feeding.

Sludge removal

The sludge that collects at the bottom of a digester tank must be removed regularly because the accumulation of sludge reduces active digester space. The sludge is removed from the Penn State digester through the sludge gates built into the bottom of the digester. These gates, located in both stages of the digester, are operated by hydraulic valves. When the gates are opened, the sludge flows into the auger channel, and the auger conveys the sludge to the storage pit.

Slurry heating system

The heating system should be designed to handle the coldest weather expected in a given area. A standard gas-fired boiler, fueled with biogas, maintained the Penn State digester's temperature of 95°F (35°C) all year. An electric pump circulates hot water through pipes located just below the surface of the middle wall in the first stage of the digester. This method of heating proved satisfactory. If the temperature of the heating surface is too high, over 150°F (77°C), the slurry will bake onto the heating surface. There was no evidence of this in the Penn State digester. Except for starting up, the digester uses the biogas it produces to fuel its heating system, which consumes approximately 30 percent of the biogas produced on a yearly basis.

Slurry agitation system

Mixing the slurry within the digester aids the digestion process by maintaining uniform temperature and bacteria and volatile solids distribution throughout the slurry. It also minimizes sludge formation, and it prevents a crust from forming on top of the slurry which interferes with the release of biogas. An electrically-driven vacuum pump, such as those used for milking machines, draws the biogas from storage under the roof and injects it at the bottom of both stages of the digester. Thus, biogas recirculation provides agitation.

Other methods of agitation include slurry recirculation pumps and mechanical paddles. However, mechanical components exposed to the slurry can corrode, and they are difficult to service or repair without disrupting digestion by opening the digester.

Biogas

The biogas produced by the Penn State digester is approximately 60 percent methane and 40 percent carbon dioxide. This means that the gas has 60 percent of the energy in natural gas or about 600 Btu per cubic foot (22 MJ/m^3). The methane content of the biogas will fluctuate according to digester conditions. Biogas contains traces of hydrogen sulfide which is highly corrosive but which can be removed by filtering the gas through steel wool or iron filings. Since the biogas is warm when it leaves the digester, it contains water vapor which will condense when exposed to the colder temperatures outside. Condensation traps in the gas lines are necessary to prevent water from blocking the low points in the lines. After condensing any water vapor in the biogas, the gas can be used as fuel in stoves, water heaters, and boilers. However, the gas burner nozzle must be enlarged to compensate for the low-Btu gas.

Tests using biogas as the only fuel in a gasoline engine showed that the energy in 200 cubic feet (5.7 m^3) of biogas equaled the energy in 1 gallon of gasoline. The Penn State digester produced the energy equivalent of 20 gallons (76 L) of gasoline per day. In diesel engines, biogas replaced most of the liquid fuel; some diesel was needed for ignition. Engine adjustments and a biogas conversion kit were necessary.

Biogas is difficult to store, compress, or liquefy. To be liquefied, methane requires a temperature of −117°F (−83°C) at a pressure of 5,000 psi (35MPa). A temperature of −260°F (−162°C) is needed to liquefy methane at atmospheric pressure. If biogas is used to fuel an engine, the engine should be stationary, close to the digester, and working frequently. In this way, the engine's cooling water can be used to heat the digester, thereby increasing the system's efficiency.

Biogas has been suggested as a fuel for cooking, space and water heating, crop drying, refrigeration, irrigation, and generation of electricity.

The Value of Biogas

Beyond the advantages, disadvantages, and technology involved, it is necessary to evaluate the feasibility of biogas production on the farm in purely economic terms. The estimated annual cost of biogas production at Penn State is shown in Table 3.

Table 3. Total annual cost of the Penn State digester system.

Costs	Amount
Capital Cost	$20,000
Fixed Costs	
Interest	$1,200
Depreciation: Structure ($12,000 @ 20 yrs)	$600
Depreciation: Equipment ($8,000 @ 8 hrs)	$1,000
Repairs and maintenance	$600
Total fixed costs	$3,400
Operating Costs	
Electricity (@ 4¢/kWh, 25 kWh/day)	$365
Supplies (oil and L.P. gas)	$150
Total operating costs	$515

Total cost - fixed+operating (excluding labor)	$3,915
Labor (1.5 hrs/day @ $3.00/hr)	$1,642
Total annual cost	$5,557

Considering the capital and operating costs of the Penn State digester, the cost of the energy in biogas is equivalent to conventional fuels at the prices shown in Table 4.

The comparisons in Table 4 give some idea of the relative energy cost of various fuels compared to the cost of biogas. They indicate that biogas may be feasible when:

- it can actually replace conventional fuel,
- the conventional fuel price is higher than the biogas, and
- all the biogas is used.

Table 4. Biogas energy cost equivalency to conventional fuels

The Penn State digester's annual cost of $5,557 produces a net amount of: 1,460,000 cubic feet (42,000 m^3 of biogas from the manure of 100 cows. This biogas has the energy value of 876,000,000 Btu (924,000 MJ).

If we know the energy value of conventional fuels, we can figure the equivalent price of conventional fuels to biogas by dividing the annual costs by the amount of fuel equivalent to the energy in the biogas produced:

Fuel	Energy per unit	Fuel equivalent to 876,000,000 Btu (924,000 MJ)	Equivalent price
Biogas	600,000 Btu/1000ft^3	1,460/1000ft^3	$3.80/1000ft^3
	22.2 MJ/m^3	42,000 m^3	$.13/m^3
Natural gas	1,000,000 Btu/1000ft^3	876/1000ft^3	$6.34/1000ft^3
	37 MJ/m^3	25,000 m^3	$.22/m^3
Fuel oil	140,000 Btu/gal	6,257 gal	$.89/gal
	39 MJ/L	23,700 L	$.23/L
Gasoline	124,000 Btu/gal	7,065 gal	$.79/gal
	34.5 MJ/L	26,700 L	$.21/L
Diesel	135,000 Btu/gal	6,489 gal	$.86/gal
	37.6 MJ/L	24,600 L	$.23/L
L.P. gas	92,000 Btu/gal	9,522 gal	$.58/gal
	25.5 MJ/L	36,000 L	$.15/L
Electricity	3,413 Btu/kWh	257,000 kWh	$.022/kWh

Fuel	Energy per unit	Fuel equivalent to 876,000,000 Btu (924,000 MJ)	Equivalent price
	3.6 MJ/kWh	257,000 kWh	$.022/kWh
Coal	25,000,000 Btu/ton	35 ton	$158.00/ton
	29 MJ/Mg	32 Mg	$173.00/Mg

Example: Assuming that a biogas water heater operates at 70 percent efficiency, it will be cheaper to heat the water with biogas instead of electricity whenever the cost of electricity is more than 3.2¢ per kWh. This is assuming that water heating consumes all of the biogas.

Selected Bibliography

- Jewell, William J., ed. *Energy, Agriculture and Waste Management*. Proceedings of the 1975 Cornell Agricultural Waste Management Conference. Ann Arbor: Ann Arbor Science Publishers, Inc., 1975.
- *The Mother Earth News Handbook of Homemade Power*. New York: Bantam Books, Inc., 1974, pp. 278-355.
- Persson, S.P.E., and H.D. Bartlett. *Agricultural Anaerobic Digesters: Design and Operation*. University Park, PA.: The Pennsylvania State University, College of Agriculture, Agricultural Experiment Station, Bulletin 827, 1979.
- Stoner, Carol H., ed. *Producing Your Own Power*. Emmaus, PA: Rodale Press, Inc., 1974, pp. 137-190.

Prepared by Eve Homan, in consultation with Mark D. Shaw, Agricultural Engineering, Howard Bartlett, Agricultural Engineering, and Sverker Persson, Agricultural Engineering.

This publication supported in part by a contract with the Pennsylvania Department of Agriculture, the Governor's Energy Council, and the Department of Energy.