**MEC3040: Guide to modeling AD diets and energy outputs**

The simplest way to model the energy outputs of anaerobic digesters is to create a spreadsheet that turns inputs of volumes of a variety of feedstock materials into outputs that predict the AD facility’s energy output and compliance with local regulations. Some of the important inputs and parameters needed to create a simple spreadsheet model are presented and explained in this guide along with a description of units, conversions and simple equations where they apply. Each section also presents a few problems to exercise this knowledge.

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Note that a **small spreadsheet database** showing %TS, %VS, C:N ratio, biogas potential and percent methane for a number of on-farm and off-farm feedstock materials is posted on the AD feedstock module page.

English-metric and metric-metric conversion factors are available on the web.

*First assignment:*

*Complete the conversion problems presented in each section and show all work on green engineering graph paper or quad-ruled paper.*

# **Feedstock volume and density**

Most digesters have maximal daily feeding volumes and feedstock volume are used in calculated predicted energy output. Operators may also need to store feedstocks and storage space is determined by the volume of feedstock needed at any one time.

Feedstock volumes (and amounts) can be measured and expressed in many units: cubic yards, cubic feet, cubic meters, liters, gallons, lb, kg and English and metric tons. Energy-rich off-farm materials are often delivered by tanker trucks and thus measured in gallons. It’s easy to convert cubed lengths to volumes but converting gallons (and other volumes) to metric tonnes (mt) isn’t as straightforward. Why do it? Feedstock biogas yields are expressed as volume of biogas per mass of feedstock.

Converting gallons to mass requires some knowledge of material density. Some material densities are available on the web and others may have to be estimated on the basis of water content or similarity to feedstock of known density.

* **Water has a density of 8.34 lb/gallon or 264.17 gallons/metric tonne.**

Beer slurry, milk, glycerol, FOG, and ice-cream waste are very liquid, so and we can assume that their density is approximately that of water.

* Most **other organics** are ‘drier’ and thus less dense than water. Some known densities are shown here relative to water for comparison. In a very general sense, as feedstock gets ‘fluffier’ or less well packed it become less dense.

|  |  |
| --- | --- |
| **feedstock** | **gallons/metric tonne** |
| water | 264 |
| food waste | 294 |
| packed silage (chopped hay or corn) | 464 |
| hay, loose | 2992 |
| hay, packed | 2057 |

Problems:

(1) You are a digester operator and can get a wide variety of feedstock materials delivered to you. You want to create a spreadsheet that records all of your inputs and calculates a bunch of important stuff, including percent total solids and percentages of on-farm and off-farm. You have a rudimentary lab facility at the digester. What’s the easiest way to determine the density of your feedstock? Keep it simple!

(2) Create conversions using ‘railroad track math’ or a spreadsheet shows math clearly to convert each of these values into gallons per metric tonne. Assume densities are very similar to water.

(a) 500 kg/m3

(b) 500 lb/yd3

(c) 500 lb/ft3

(d) 500 English ton/m3

*(a) 528 gallons/mt*

*(b) 891 gallons/mt*

*(c) 33 gallons/mt*

*(d) 0.489 gallons/mt*

# **Percent on- and off-farm feedstock**

In Vermont, on-farm digesters must source 51% of their feedstock from the farm (or from nearby farms) on a monthly or quarterly basis. And on-farm feedstock cannot include water and must be produced on farms. The calculations are simple, so it’s categorizing material that’s important.

Problem:

(3) An operator combines these feedstocks: 8,000 gallons of manure; 500 gallons of silage; 5,000 gallons of beer yeast slurry; 300 gallons of past-date milk; 3,000 gallons of ice-cream waste; and 2,500 gallons of glycerol. What percent of this feedstock mixture is on-farm?

*44.0%*

# **Percent total solids**

Most AD feedstock materials have very high moisture contents. Generally, the more water the higher the density. Since water doesn’t produce energy but does require all sorts of handling, it’s useful to know how much of a load of feedstock is water. Percent total solids is determined by heating feedstock overnight at a temperature that is too low to cause combustion but high enough to evaporate water, generally between 100 and 400°C. Initial sample volume is recorded and mass is measured before and after heating.

%TS = (final dry mass/initial wet mass)(100)

How is %TS practically useful? First, most AD systems are designed with minimum and maximum percent total solids (%TS) for their overall diets or feedstocks. So, the %TS of each feedstock can be used to calculate the weighted average %TS of any feedstock mixture to be sure it meets these standards. Second, feedstock energy content is sometimes expressed as cubic meters of methane or biogas per mass of volatile solids. Volatile solids are a fraction of total solids, so that calculation begins by determining the mass of total solids in a given volume of feedstock.

Problems:

(4) A dry and empty crucible weighs 20.0 g. 100.0 mL of sample is added, and the initial mass of the crucible with wet sample is 130.0 g. The sample is placed in a drying oven for 24 hours and its dry mass is 30.0 g. Calculate the sample’s percent TS.

*9.09%*

(5) You feed 3000 gallons of a feedstock that appears to be nearly as liquid as water and flows well. Its %TS is 9.09. Calculate its solids content in:

(a) kg

(b) metric tonnes

*(a) 1.03 mt of TS*

*(b) 1.03 E3 kg of TS*

# **Percent volatile solids**

Volatile solids are that fraction of total solids that are organic material that can be converted into biogas by anaerobic digestion. (Total solids also include inorganic materials that cannot be digested.) The best feedstocks have high volatile solids (>90%) and produce the most biogas. In the lab, total solids are ignited with a torch and heated for 8 hours at 550C resulting in combustion (or volatilization) of organic material, releasing volatile organic compounds (VOCs) as gases and leaving ash behind. Mass of the ash is determined and compared to the mass of total solids; volatile solids are the difference and are lost during combustion.

%VS = (mass total solids – mass of ash)(100)

Note that volatile solids are expressed as a percent of total solids. So, VS calculations are actually a percentage (%VS) of a percentage (% TS).

Problems:

(6) The crucible of dried solids in the previous problem (total dry mass of 30.0 g) is ignited and placed in a 550C muffle furnace overnight. After cooling, its total mass is 21.0 g. Calculate the sample’s %VS.

*90.0%*

(7) You feed 3000 gallons of a feedstock that appears to be nearly as liquid as water and flows well. Its total solids content is 9.09% and its volatile solids content is 90%. Calculate this feedstock’s volatile solids content in:

(a) kg

(b) metric tonnes

*(a) 0.93 mt of TS*

*(b) 9.3 E2 kg of TS*

# **C:N ratio**

Even the best feedstock won’t be converted to biogas efficiently unless its ratio of carbon to nitrogen is optimal, between 20:1 and 30:1 C:N. It’s the carbon that forms methane, so without enough carbon energy can’t be converted to methane (CH4). Nitrogen is needed to make the enzymes (proteins) that bacteria need to do work. But too much nitrogen forms ammonia which inhibits the process of digestion. High carbon feedstock is rare, so diets need to be designed with C:N ratios in mind. While AD data is often tough to find, C:N ratios are particularly obscure.

One way to make ratios a bit more approachable is to convert them to percentages. Manure has a C:N ratio of 20:1, so it has a total of 21 parts: 20 parts are carbon and just 1 part is nitrogen. Those ‘parts’ and ‘whole’ can be used to create percentages.

When determining the overall C:N ratio of daily or monthly feedstock we have to use weighted averages of all feedstock materials. This can be done by calculating volumes or mass of carbon and nitrogen in each feedstock, summing all carbon and all nitrogen, and then calculating the ratio of the summed carbon to nitrogen. Note that calculation of volume (without taking %TS into account) and calculation of mass (using %TS) work equally well.

Problems:

(8) Convert these C:N ratios to percentages of carbon and nitrogen.

(a) 20:1

(b) 100:1

*(a) 4.8%*

*(b) 1.0%*

(9) 5000 gallons of manure (C:N = 20:1) are mixed with 1000 gallons of glycerol (C:N = 100:1). What is the overall C:N ratio of this feedstock mixture?

*23:1*

# **Biogas potential and yield**

Biogas potential (aka energy content) allows us to predict the biogas and energy output of any feedstock mixture. Unfortunately, units for biogas potential values vary greatly depending on the source. These units are not uncommon: m3 biogas/fresh metric tonne; m3 CH4/kg VS; L biogas/metric tonne of organic matter (OM). It’s best to convert all values to the same units before creating a spreadsheet. And for operators, the most convenient measurement is probably the first, m3 biogas/fresh metric tonne, because operators feed volumes of fresh material rather than dry matter (DM or TS) or organic matter (OM or VS).

* Biogas vs. methane: Biogas contains between 50 and 75% methane but it’s the methane that is burned to produce energy. Under good operating conditions biogas is generally between 60 – 70% methane, and 60% is a good conservative value. More power would be a pleasant surprise! Of course, operators can use their system’s average methane percentage when doing these calculations, but methane output varies between feedstock materials.
* Fresh vs. VS (OM):

Again, fresh metric tonnes is very convenient for the operator! To convert values from volume of biogas or methane per mass of VS (or OM) one must also know TS values. Start with VS, convert to TS and then to fresh volume or mass.

* COD (chemical oxygen demand):  
  Some labs, and many wastewater systems, measure feedstock energy as chemical oxygen demand (COD): the amount of oxygen required to completely degrade a feedstock using chemicals. This method of predicting biogas yield is based the stoichiometric relationship between the COD destroyed during AD and the amount of methane produced:   
   CH4 + 2O2 🡪 CO2 + 2H2O   
  Using this stoichiometry and the facts that 1 mole of ideal gas occupies a volume of 22.4 L at STP, and that 2 moles of oxygen gas have a mass of 64 g, 1 gram of COD produces 350 mL of methane.

22.4 L = 0.350 L/g oxygen gas consumed

64 g

Once your units are aligned, biogas produced from each feedstock material can be calculate by multiplying mass (or volume) by biogas potential.

Problems:

(10) Assume that biogas is 60% methane. Convert food waste’s biogas potential of 6.60 E4 L of methane per fresh metric tonne to cubic meters of biogas per fresh metric tonne.

*110 m3 biogas*

*1 fresh mt*

(11) Convert a biogas potential of 110 m3 biogas / fresh mt to m3 biogas per kg of VS. The feedstock is food waste: 20% TS, 95% VS.

*0.579 m3 biogas*

*1 kg VS*

(12) A feedstock supplier tells you that the load of feedstock he’s sending you has a COD of 1000 g per gallon. Calculate a per gallon biogas potential for this feedstock.

*154 m3 biogas*

*1 mt*

# **Calculating electric output from biogas production**

The amount of electricity that can be generated by combustion of biogas depends on a few factors: (1) the methane content of the biogas; (2) the energy content of methane; and (3) the efficiency of the generator. The energy content of methane is a constant: 10 kWh per cubic meter. The biogas content of methane varies from 50 – 75% and the efficiency of AD generating engines is around 30%

kWh = (m3 methane)(10 kWh/m3)(generator efficiency)

There is a simple, quick and dirty way to estimate electricity output without a calculator. One cubic meter of biogas contains 6.7 kWh of electricity, but the efficiency of generating engines reduces that to a practical value of 2 kWh/m3 of biogas.

Problems:

(13) An operator creates an AD diet that produces 5,000 m3 of biogas each day with a methane content of 65%. The generating engine of her AD facility has a capacity of 350 kW and an efficiency of 35%.

(a) Calculate the potential electric output with this diet.

(b) Will the generator 100% of the time on this diet? Will the flare need to run?

*(a) 11,375 kWh/day*

*(b) 8400 kWh/day*

(14) Use the quick and dirty method to answer 1(a).

*10,000 kWh*

# **AD system efficiency: VS destruction**

All of the work above assumes a 100% conversion of biogas potential to biogas. That’s very rosy and pretty unrealistic. While the problems posed here didn’t factor digester efficiency in, a wise operator considers the efficiency of his AD system. AD system efficiency is often expressed as percent destruction of VS. A figure of 70% VS destruction is realistic. Our data suggests that VTCAD can operate with an efficiency of 77%.

Problem:

(15) Look back at problem (13). The operator decides that her calculation of energy output should be very conservative so that her performance will tally with her predictions and perhaps be a pleasant surprise. Her data shows that her AD system destroys 70% of VS in its feedstock. Repeat calculations for (13a) and (13b) including factoring in this efficiency.

*(a) 7,963 kWh/day*

*(b) 8400 kWh/day*