Module 2
Introduction to Anaerobic Digestion

2.1: The anaerobic digestion process

2.2: Applications of anaerobic digestion

2.3: Snapshot of anaerobic digestion in Vermont

2.4: Products from anaerobic digestion

2.5: Environmental benefits & concerns:
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This curriculum is adapted from: eXtension Course 3: AD, University of Wisconsin

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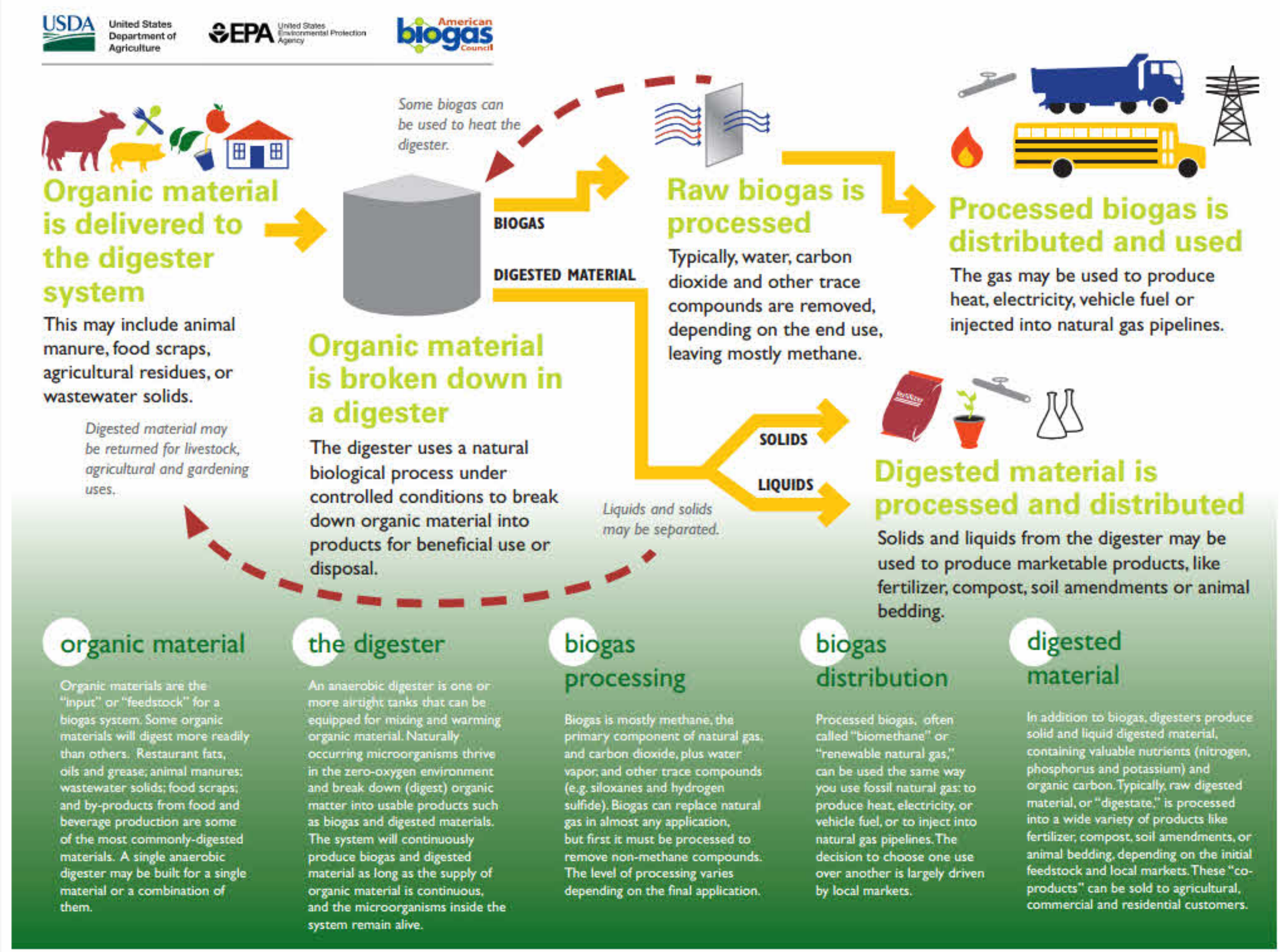
What is anaerobic digestion?

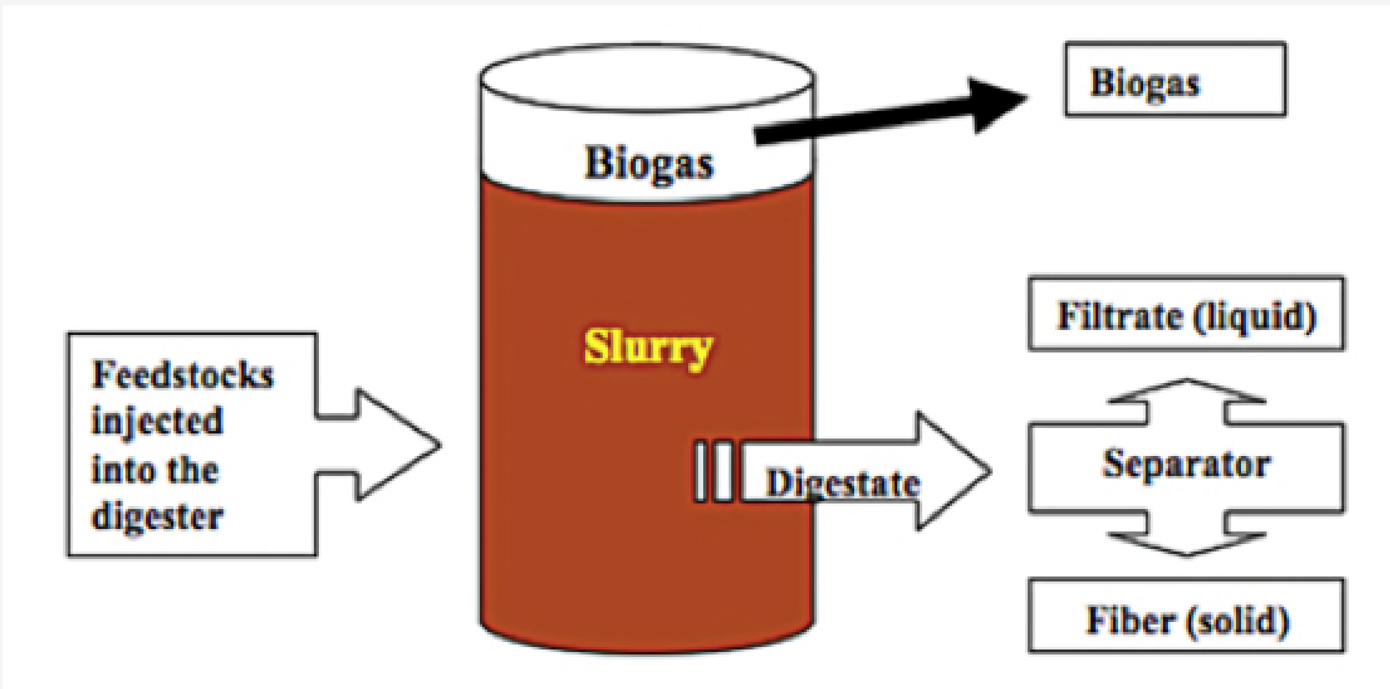
Overview cartoon



What is anaerobic digestion?

Anaerobic digestion: *a natural bacterial process of ruminant animals, like cattle and sheep, and of anaerobic environments, like lake bottoms, marshes and swamps.*

- In the absence of oxygen, the AD (anaerobic digestion) process degrades organic materials (often seen as waste) into methane-rich biogas and nutrient-rich digestate.



Basic AD terms

Aerobic: *process that occurs in the presence of freely available oxygen*

Anaerobic: *process that occurs in the absence of freely available & chemically bound oxygen*

Alkalinity: *acid-neutralizing capacity; sum of all bases*

BOD (biological oxygen demand): *amount of oxygen required to biologically oxidize & degrade organic material*

COD (chemical oxygen demand): *amount of oxygen required the chemically oxidize & degrade organic material; faster than BOD; values typically higher*

Feedstock: *manure & organic material 'fed' to the AD to produce biogas*

Slurry: (aka sludge) *the mixture of feedstock & microbes filling the AD*

Biogas: *combustible gas produced by AD: 60% CH_4, 40% CO_2, H_2, H_2S*

Digestate: (aka effluent or filtrate) *slurry after digestion; nutrient-rich*

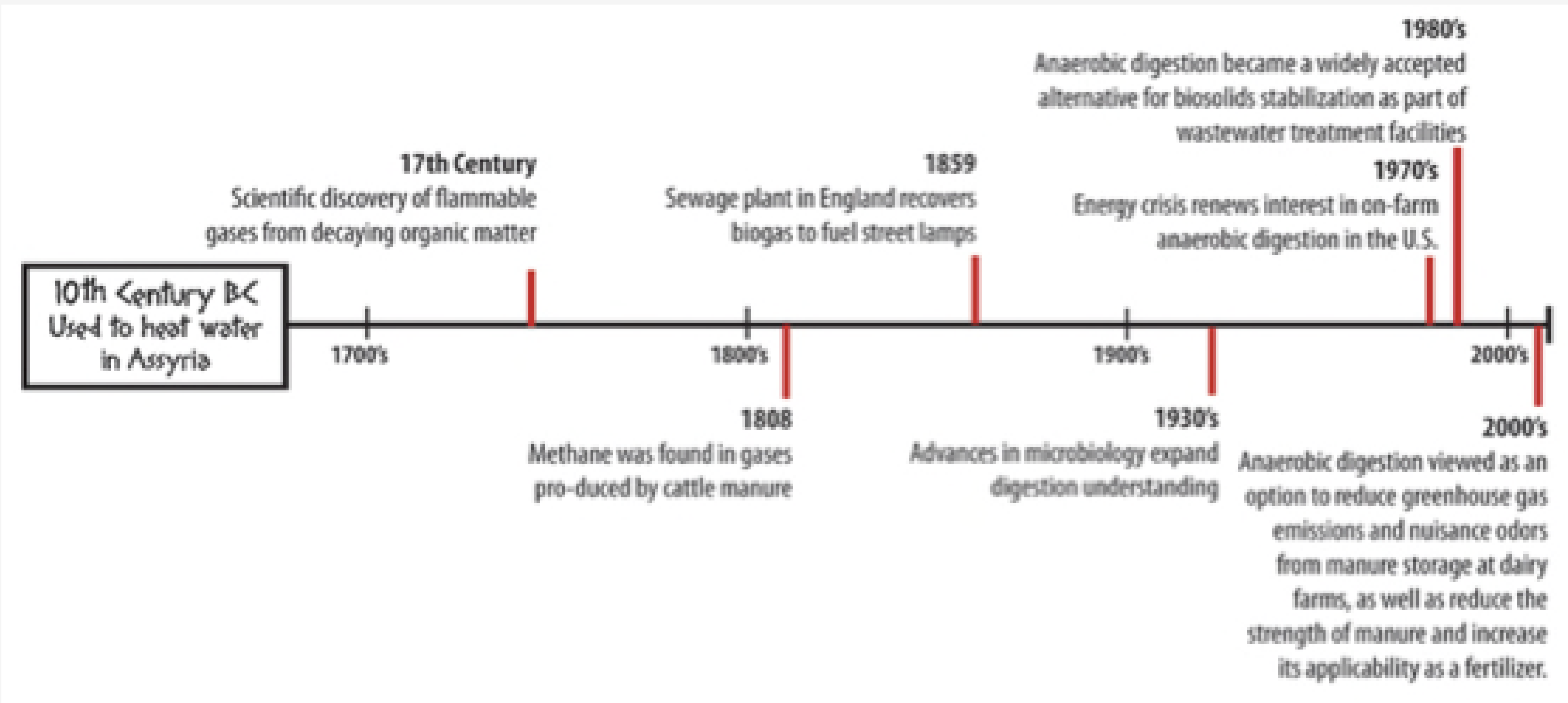
Fiber: (aka separated solids) *solid portion of digestate; used as fertilizer, bedding, compost*

Volatile solids: *the organic component of solid feedstock materials*

(Mackay & Rowlands, 20__)

An ancient, but evolving, technology

Used by man long before the modern era, modern AD is a **renewable energy technology** that produces heat and electricity, recycles society's organic wastes to produce nutrients for agriculture, and reduces odors and pathogens.



Global AD today

Today, **simple, small- to medium-scale AD** installations are used in the developing world to produce cooking and heating gas from organic wastes.

- 2005: 8 million small AD facilities in China
- 2011: 500 AD in Tanzania & 1000 AD in Lesotho

AD is widely applied in **Europe** as a combined heat & power technology.

- Germany: 6800 AD systems
- Austria: 511 AD systems

Manure is a secondary feedstock; crops & organic wastes dominate.

Why is AD **more widespread in Europe** than in the US?

- Fossil fuel energy is not (or is less) subsidized in Europe
- But European governments do support renewable energy technologies
- European farm subsidies favor diversification and AD
- Europe's resources are more limited so they focus on reuse & efficiency
- Europe is focused on mitigating climate change

Wellinger & Linberg (2000)

AD in the US today

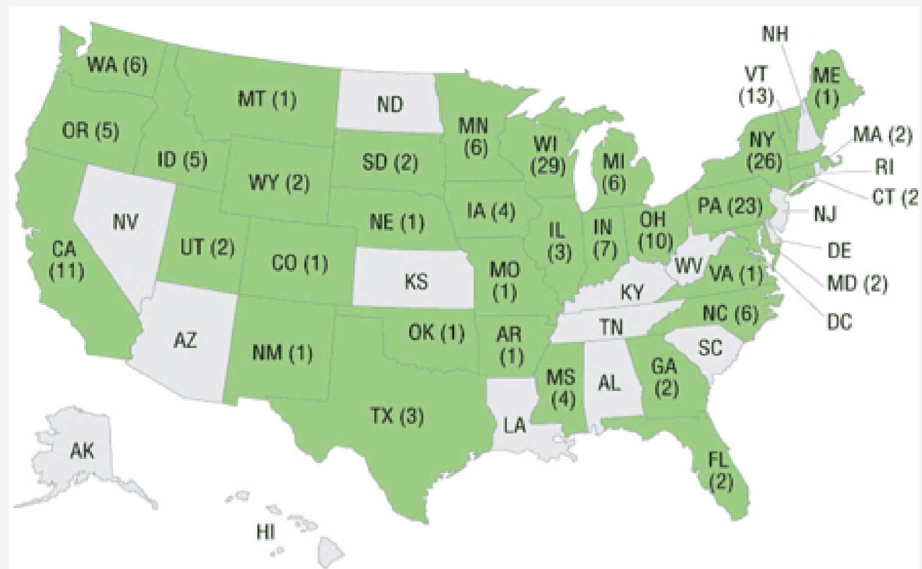
In the US, AD is mainly employed at **municipal wastewater treatment** plants to reduce volumes of sludge and levels of pathogens. Biogas is sometimes used to heat the plant, but just over 100 use biogas to produce energy. However, most wastewater plants rely mainly on aerobic processes.

- **2008:** only 1,351 of 3,171 wastewater plants used AD

US farms began using AD to produce energy during the energy crisis of the 1970s. This early effort was largely unsuccessful. However, farm AD has boomed since 2000.

- **2014:** 239 farm AD plants
  205 produce electricity
  586,000 MWh electricity
  55,000 MWh heat
  (1 MWh ~1000 households

- **Vermont:** 17 AD plants in 2013

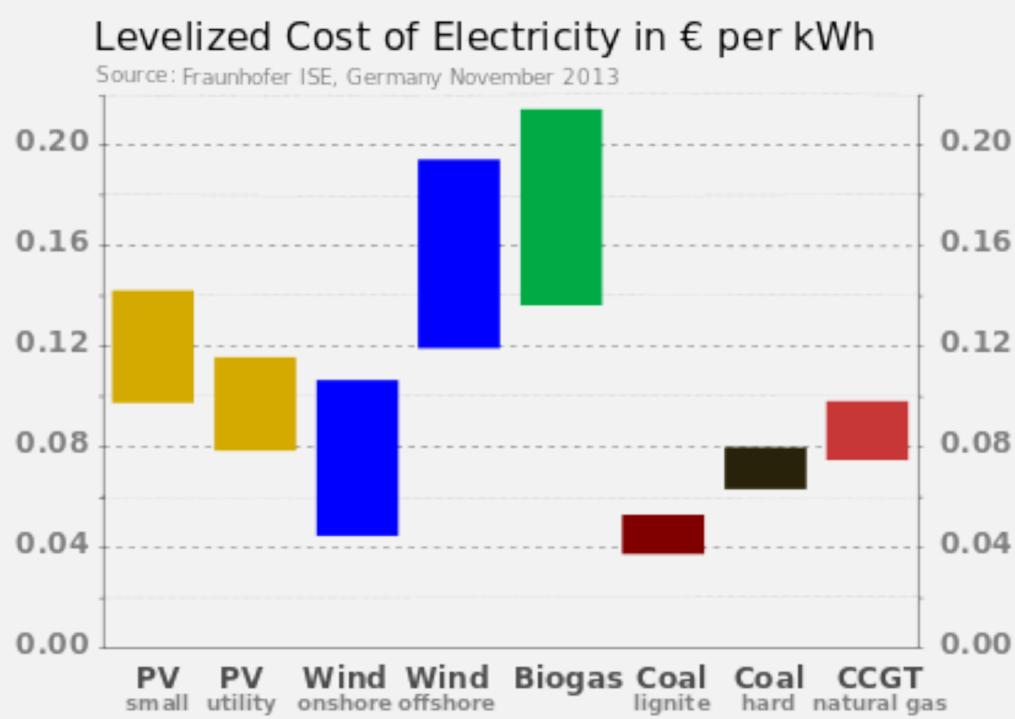


AD vs. other RE technologies?

AD is **more expensive to install** than solar or on-shore wind. However, AD produces energy 24 hours per day, 7 days per week, 365 days per year.

And, unlike other renewable energy technologies, AD **provides ecosystem services**: benefits provided by ecosystems that contribute to making human life both possible & worth living.

- Reduces the GHG potential of methane.
- Recycles society's wastes.
- Recovers & manages nutrients for use in agriculture.



Assessment!

Please answer the questions in **section 2.1** of the Module 2 Assessment.

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How & where is AD used?

AD for wastewater treatment

Wastewater treatment: *AD treats 'high-strength' organic wastes*

'High-strength' wastes (or feedstock materials) have high concentrations of decomposable organic material, or high biological oxygen demand (BOD). [NB: chemical oxygen demand (COD) is easier to measure than BOD and often used to gauge feedstock 'strength'.

<u>High-strength example</u>: fats, oils and grease (FOG)

Discharge of untreated high-strength organics into the environment causes high rates of microbial growth and release of excess nutrients, resulting in depletion of oxygen, and eutrophication of water.

Advantages of using AD for wastewater treatment:

1. AD uses less energy than aerobic treatment.
2. AD decreases the volume of biosolids produced.
3. AD produces biogas: renewable energy.

On-farm AD: motivation?

The main reasons for using on-farm AD in the US are not energy production!

- Reduction of manure odors
- Management of manure nutrients

Growing concerns about environmental quality, biosecurity, energy security, nutrient scarcity and climate change have also boosted on-farm AD.

- Algae growth in Lake Champlain is fueled by nutrient runoff.
- Peak phosphorous is upon us: we've used up half of global P supplies.
- AD provides some separation of N & P nutrients.
- AD converts N to a form more readily used by plants.
- AD drastically reduces that pathogens present in manures.
- Methane from farms & landfills is a GHG 27-times as potent as $CO_{2,}$ accounting for 9% of GHG emissions.

In 2009, the US Dairy Industry pledged to reduce methane emissions by 25% by 2020. In 2014 the USDA released its **Biogas Opportunities Roadmap** to guide us to this goal. It suggests installation of 11,000 additional AD plants, capable of powering 3 million homes.

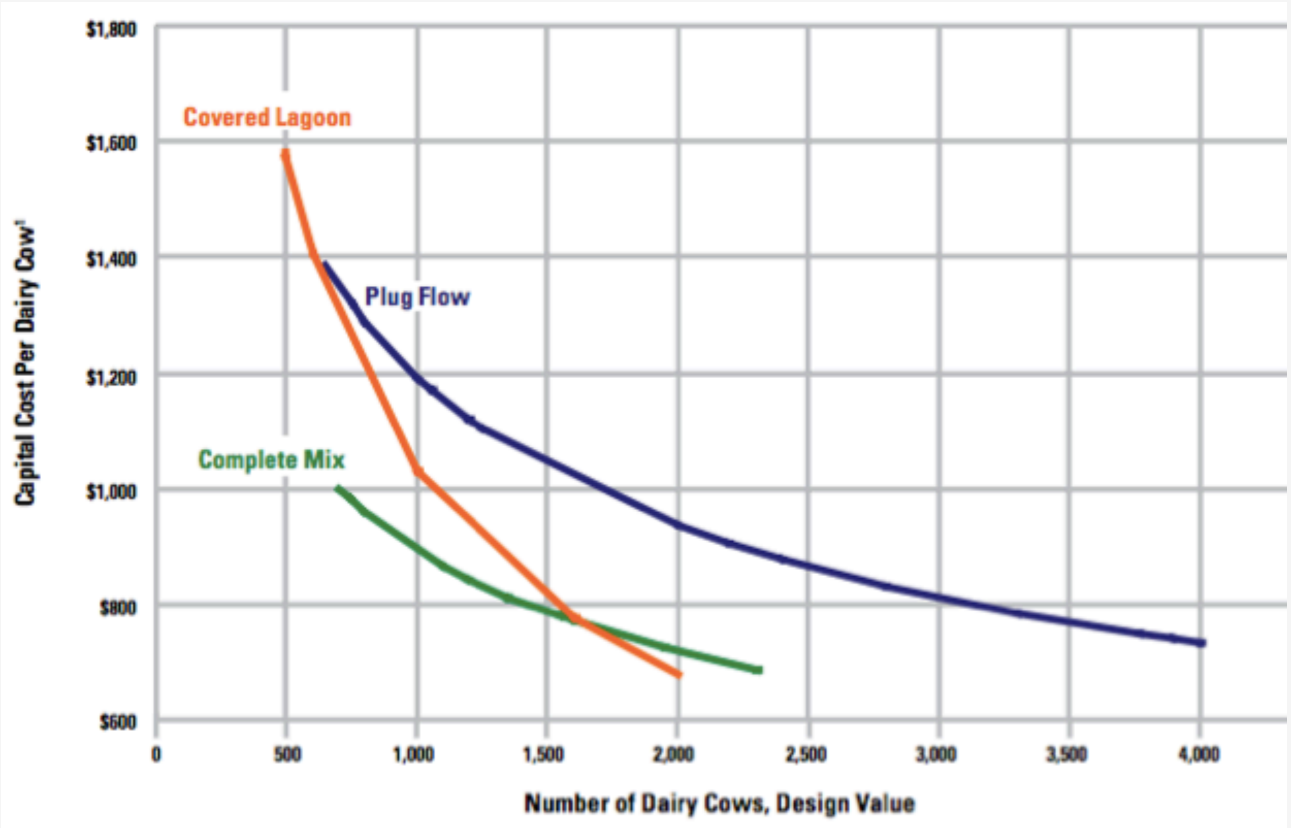
On-farm AD: challenges?

Installing efficient farm AD requires **capital & training investments.**

Costs vary with AD technology

- 2009: average per AD installation cost was $1.5 million

Operator training is critical, though daily work hours may be less than full time.



Small-farm AD?

Generally, it's thought that 1000 cows are needed to justify farm AD.

However, AD may soon pay for smaller **150 – 200 cow** farms because:

- **Off-farm feedstock** (organic wastes) effectively increase herd size.
- New **small-scale AD technologies** may be coming.
- USDA financing & **feed-in tariffs** for renewable energy helps.

Genset size of the 205 on-farm AD projects that produce electricity in the US ranges from 15 – 6450 kW.

- Average genset size is 750 kW
- Only two Vermont projects have gensets ≥ 500 kW

Herd size of the 239 on-farm AD projects in the US:

- Average herd size is 2100 head of cattle
- Only 67 are fed by less than 1000 head
- 7 of the small herds are in Vermont and range from 75 – 950 head
- Only five Vermont AD projects are based on less than 500 head

Commercial / biomass AD

The goals of **off-farm AD** are often to:

- Treat large amounts of organic waste (alternative to landfilling);
- To produce renewable energy; or
- To reduce emission of methane by combustion.

Commercial AD facilities are often **located** next to large food processing or production facilities.

- World's largest dry AD facility opened in San José, CA in 2013. It will process 90,000 tons of organic waste each year.

In **Vermont**, NEO hopes to open a commercial biomass AD facility in Brattleboro at an old landfill site.

http://zerowasteenergy.com/worlds-largest-dry-fermentation-anaerobic-digestion-facility-opens/

Assessment!

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A snapshot of AD in Vermont (2015)

Support for AD in Vermont

Vermont is very supportive of anaerobic digestion, particularly on-farm.

- Vermont has more on-farm AD, per capita, than any other US state.

Funding:

- USDA offers farmers grants through the REAP (Renewable Energy for America Program) program. http://www.rurdev.usda.gov/orreap_renew_grants.html
- The Vermont Agency of Agriculture Food and Markets (VAAFM) has worked with farms to provide technical support & secure USDA funding.
- Vermont's Clean Energy Development Fund has provided support to AD projects. http://publicservice.vermont.gov/topics/renewable_energy/cedf
- In 2005, Vermont's first-in-the-nation feed-in tariff for renewable energy (the **SPEED program**) guaranteed a premium price for AD electricity for 20 years, allowing investors to recoup their investment in a reasonable time. http://vermontspeed.com/
- In 2015, the Vermont Legislature replaced SPEED with **RESET.** [coming modules]

Cow Power

Green Mountain Power, Vermont's largest electric utility, sells renewable electricity to its customers at a 4¢ premium through its Cow Power program:
http://www.greenmountainpower.com/innovative/cow/
http://video.pbs.org/video/2225827234/

- On-farm anaerobic digestion provides most of that renewable electricity.
- GMP purchases renewable energy credits (RECs) from partner farms and sells them to GMP customers, providing partner farms with a reliable market for their RECs.
- GMP has also provided technical assistance to partner farms to keep their AD systems up and running.
- In many ways, GMP's Cow Power program has been a vocal & effective advocate for AD across the state.

AD technology in Vermont?

In Vermont, most on-farm AD plants have **plug flow** designs built by GHD, now DVO.

http://www.dvoinc.net/

There are at least four **complete-mix** on-farm AD facilities built by RCM or Bio-Methatech (using the technology of Lipp of Germany).

http://www.bio-methatech.com/

http://www.rcmdigesters.com/

Magic Hat brewery uses a unique design from PurposeEnergy.

http://www.sevendaysvt.com/vermont/magic-hat-produces-its-own-energy-with-beer/Content?oid=2142409

And there are a few other design in Vermont as well.

This course devotes a later module to AD technology and design in detail.

‘Extras’?

The majority of Vermont’s AD facilities do <u>not</u> include:

- Feedstock holding tanks;
- Feedstock mixing tanks;
- Hydrolysis tanks;
- Biogas treatment or scrubbing; or
- Nutrient separation technology.

However, newer facilities have incorporated some of these technologies, particularly larger facilities run by dedicated, full-time AD operators.

- Vermont Tech
- AD in northern Vermont (???)
- Planned GMP facility on St. Alban’s Bay

Assessment!

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Energy products & co-products of AD

AD produces energy & ‘co-products’

Anaerobic digestion produces energy and co-products. Revenue and benefits from co-products often surpasses that from biogas.

Biogas: *combusted to produce heat or co-generation of heat & electricity*

Digestate: *the biomass that remains after feedstock is processed by AD*

- Effluent (liquid filtrate) used as fertilizer; rich source of N, P, K.
  - Offsetting use of synthetic fertilizer lowers costs & carbon footprint.
- Separated solids (fiber) used as dairy herd bedding, fertilizer, compost base.
  - High bedding costs make this a valuable co-product.

CO_2 *(carbon dioxide)*: methane is converted to CO_2 during combustion

- Generally seen as a pollutant, CO_2 can be used to augment the growth of plants and algae.

Biogas

Biogas: *a mixture of 50-60% CH_4, 40ish% CO_2 with some H_2O, H_2S, H_2, N_2, etc.*

- Methane content varies with feedstock from 50 – 70%.
- Typical yields: 7 – 12 ft^3 / lb volatile solids in feedstock

Biogas **energy content**:

- 10 Btu / 1 ft^3 or
- 2.52 kcal / 0.028 m^3
- So, biogas with 65% methane produces 650 Btu / ft^3 or 5,857 kcal / m^3

Biogas combustion is improved by **conditioning or scrubbing:** drying off water and reducing the levels of CO_2 and H_2S.

Most systems pipe biogas underground to the generator. The cooler earth temperatures **condense the water vapor**, providing somewhat drier biogas for combustion.

Scrubbing biogas to biomethane

Biomethane: *methane produced by removing all other gases from biogas; maximum of 4% H_2S*

- Chemically equivalent to natural gas though biologically produced;
- Can be injected into natural gas pipelines;
- Can be used to vehicles equipped for natural gas;
- Increased energy density of 1000 Btu / ft^3; and
- Fiscally viable only when natural gas prices are high enough.

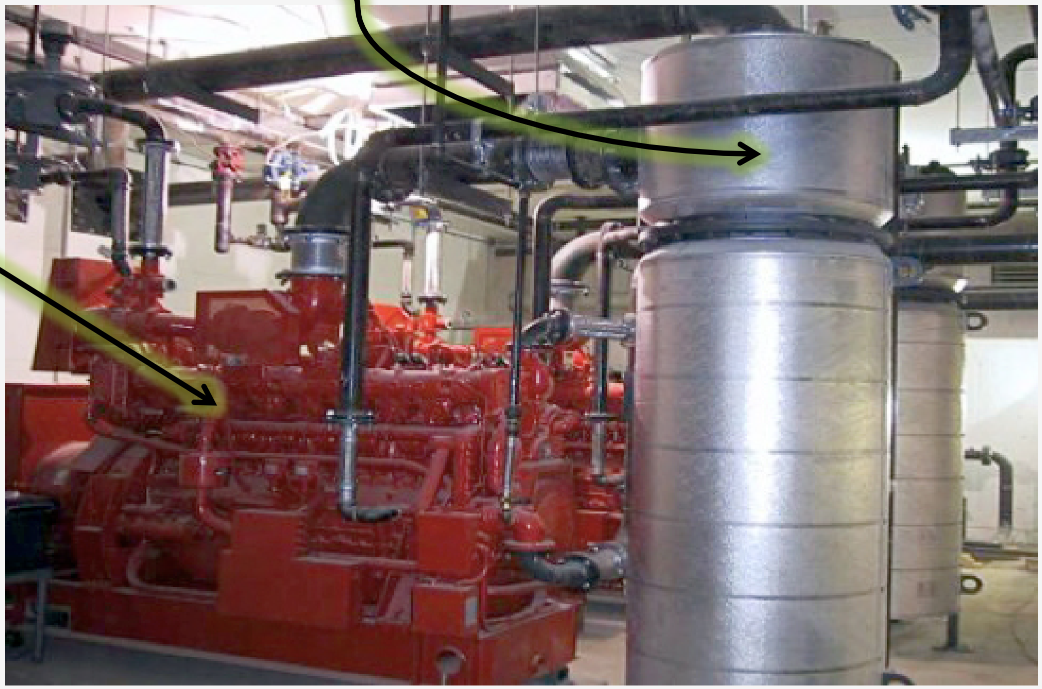
Biomethane from Scenic View Dairy in MD is injected into the natural gas grid

Biogas combustion & heat recovery

Biogas is burned in **internal combustion engines** that produce 30% electricity and 70% heat.

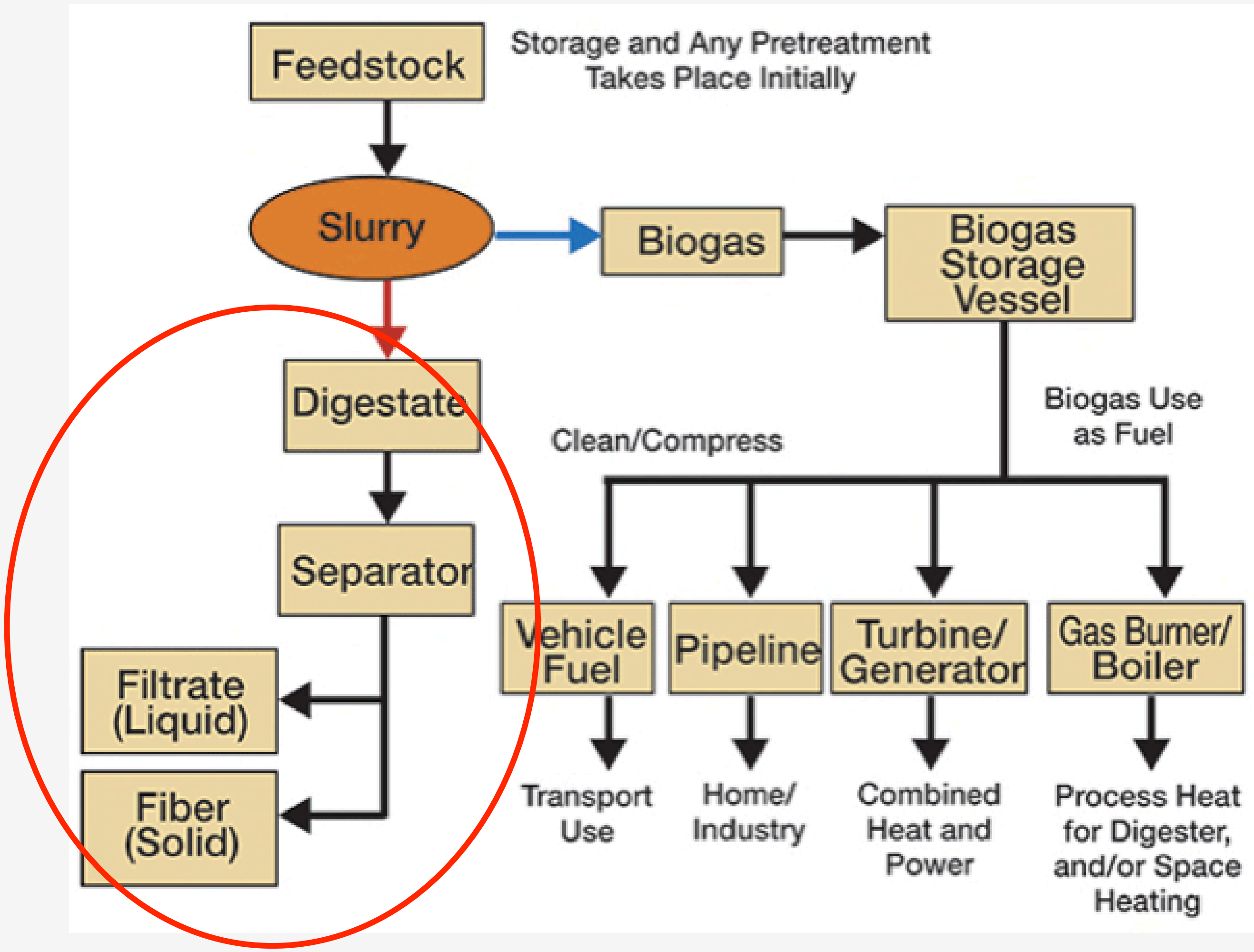
Heat can be recovered from:

- From exhaust gases
- Water jackets that surround the engine



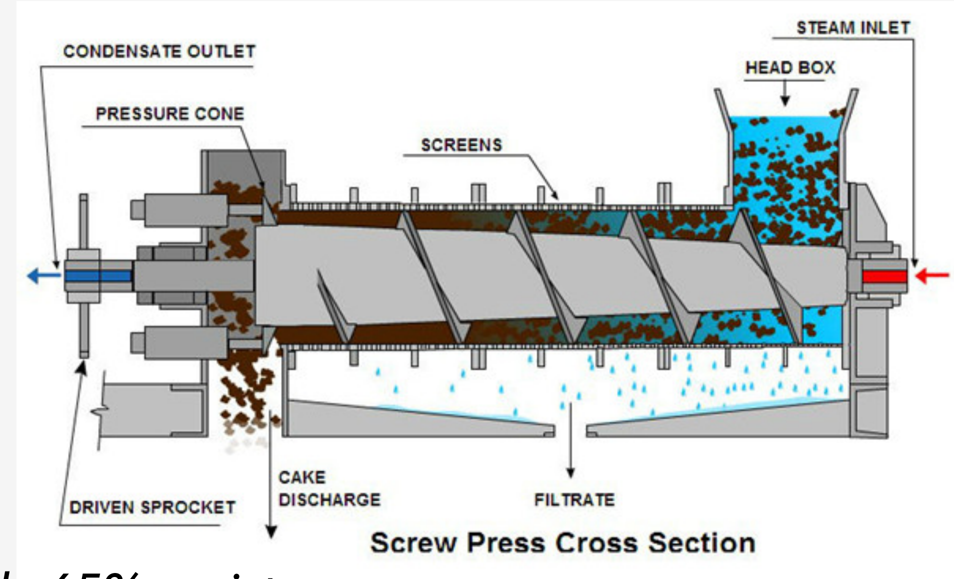
Digestate

Digestate: *nutrient-rich slurry remaining after removal of biogas*



Solids separation

Solids separation is accomplished using a screw-press separator; an auger pushes digestate against a perforated screen, squeezing out liquid effluent.



Separated solids:
the solid portion of digestate; roughly 65% moisture

- Enriched for phosphorous
- Animal bedding (often a source of both savings & profit)
- Field fertilizer
- Compost base
- Component of composite materials

Effluent: *the liquid portion of digestate, enriched for ammonia nitrogen*

- Used as field fertilizer; should be injected rather than broadcast

Solids as bedding

Animal bedding gives comfort to animals and absorbs moisture and urine. Traditional bedding materials include straw, sawdust, grain hulls, and sand. The increased energy demand for wood products has increased the cost of sawdust and shavings.

Sand bedding must be removed from manure before anaerobic digestion.

Separated solids reduce a farm's operational costs and are often sold for profit.

- Mastitis rates and somatic cell counts are not increased by solids bedding
  http://cwmi.css.cornell.edu/beddingfinalreport.pdf

This topic is covered in depth in another module.

Solids as compost base

Composting: *an aerobic process in which microbes decompose organic materials to CO_2, H_2O and soil-like and nutrient-rich soil-like material.*

Separated AD solids can be:

- Used as a composting base (an input).
- Combined with compost and nutrients to produce custom potting soils.
- Used to produce nursery pots.
  http://connecticut.cbslocal.com/2013/12/16/profile-a-connecticut-green-business-owner/

Making composite materials

Composite materials: materials created by blending a mixture of materials, often organics and inorganics

Michigan State University and the University of Wisconsin-Madison's Forest Products Laboratory have used AD fiber to produce novel products:

- Medium density fiberboard
- Decking material

Nutrients & NMPs

The AD process **'mineralizes'** nutrients, converting them to small molecules that are very bioavailable to plants. Digestate typically is a more effective fertilizer than the manure that it is created from.

- Potassium (K) levels are unchanged.
- Nitrogen (N) is converted to ammonia (NH_3) and enriched in filtrate.
- Phosphorous (P) binds to solids and is concentrated in the solids.

Following 2015 legislation, Vermont requires large ($\geq$700 cows), medium ($\geq$200 cows), and small farms to use **nutrient management plans** to ensure that nutrients benefit crops and do not enter the water supply.

The ability of AD to partially separate nutrients is helpful.

Nutrient management planning is addressed in detail in a later module.

Assessment!

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Environmental impacts of AD: benefits & concerns

Environmental benefits of AD

AD's **environmental benefits**:

- Decreases GHG emissions as methane is contained and converted to CO_2;
- Odor control;
- Capture and recycling of organic wastes and nutrients;
- Protection of water quality; and
- Pathogen reduction & destruction.

Greenhouse gas emissions

Greenhouse gases (GHGs): *gases that reflect and contain heat in earth's atmosphere and thus contribute to global climate change.*

Methane is a greenhouse gas with **21 – 27 times the GHG potential of CO_2**.

- AD captures nearly all of the methane potential of manure.
- Combustion of methane reduces its GHG potential 21 – 27 times.
- Moving organic waste from landfills to AD captures methane now leaking from landfills.
- Theoretically, the CO_2 emitted from the generating engine will be recycled to build the plants fed to cows or used for human food.
- Practically, the carbon in CO_2 can be recycled by passing it through greenhouses to enhance plant growth.
- Use of biogas to produce energy replaces fossil fuels, further reducing GHG emissions.

AD also reduces the emission of **nitrous oxides (NOx)**, another GHG, from manure and organic wastes.

Odor reduction

Manure and livestock odors are produced by **75 malodorous molecules** created by naturally ocurring anaerobic degradation of organics.

- Most malodorous molecules contain N or S:
  - Phenols & cresols;
  - Indole & skatole; and
  - VFAs.

The AD process **redirects metabolism of volatile solids** to produce methane, decreasing production of malodorous molecules.

- Odors are reduced by AD for 10 days at 35°C.
- Increasing retention (digestion) time increases odor reduction.
- Odors don’t return even with digestate is stored for 3 months.
- Odors are reduced by approximately 79%.

Water quality

Runoff of nutrients, particularly phosphorous (P) and nitrogen (N), into surface or ground waters cause overgrowth of algae and other aquatic plants. Algae growth uses dissolved oxygen, creating **hypoxic** or **anoxic** conditions that inhibit or kill other aquatic organism throughout the food web.

The **partial nutrient separation** effected by AD makes it easier to apply nutrients where needed in a targeted manner.

- The lower levels of P in liquid effluent allow farmers to slowly lower P levels in P-saturated fields.
- The captured P in solids can be exported to P-poor land.

There has been an environmental side-benefit from the regulatory requirement of **nutrient management plans** (NMPs) for farms using AD technology.

- In Vermont, regulations passed in 2015 require farms of all size to use nutrients responsibly and require NMP for farms previously seen as too small for regulation.

Pathogen reduction or destruction

Studies show that AD reduces levels of many pathogens by **90%** or more.

- *Coliform*
- *Streptococcus*

Of course, the degree of pathogen destruction is **dependent** on AD conditions:

- AD temperature
- AD retention time

The use of **post-consumer feedstock materials** has increased concerns about pathogens.

- Fear that pathogens present in feedstock could harm workers;
- Or contaminate separated solids and effluent; and
- Pass to animals on farms.

Indirect environmental benefits

- Reduction of transportation of high-strength organic wastes;
- Replaces land application of untreated high-strength organic wastes; and
- Reduction of soil compaction because fertilizer is more effective

Environmental concerns about AD

AD does create some **environmental concerns**:

- Air emissions;
- Biogas combustion;
- Aerated digestate;
- Human and animal health; and
- Do digesters encourage the development of CAFOs?

Air emissions

There is little data to prove that AD plants don't emit (or **leak**) any methane.

- The EPA estimates 10% leakage when evaluating AD efficiency.

Combustion of biogas, as opposed to biomethane, releases small amounts of **air pollutants** in addition to CO_2.

- NOx
- CO
- volatile organic compounds (VOCs)

Generation of these pollutants can be **reduced by**:

- Scrubbing CO_2, H_2S, NH_3 from biogas
- Reducing the amount of N & S in feedstock (reducing protein content)

AD plants use **flares** to burn of biogas that isn't combusted, decreasing release of uncombusted biogas. Flares should have reliable igniters and be protected from wind.

Aerated digestate

When digestate is aerated during transfer or land-application, **ammonia** is released into the air and is an air pollutant.

Release of ammonia can be **decreased by**:

- Incorporating digestate into soil: dragging or injecting
- Lowering the pH of the digestate

Effects on human and animal health

Ammonia is **toxic** to animals and humans.

- Ammonia is caustic or corrosive to the airways.
- When ammonia combines with nitrous oxide it forms aerosol nitrate, a fine particulate pollutant.
- Livestock are the greatest source of ammonia emissions.

Hydrogen sulfide (H_2S; hydrosulfuric acid) is **acutely toxic** to animals and humans and **corrodes** metals and machinery

- Safety precautions are essential!

Does AD encourage CAFOs?

AD systems are most economical for very large farms with over 500 head of cattle or 2000 pigs or more chickens. These large operations confine rather than pasture the animals and are called Concentrated Animal Feeding Operations (**CAFOs**).

AD will reduce odors and make land application of effluent easier, but doesn't reduce the threat of the huge volume and concentration of manure, nutrients and pathogens to water and land immediately surrounding the CAFO. Currently, most farm AD is on CAFOs.

If **interconnection costs** were covered by the cost paid for AD electricity, AD could be installed as easily on small farms as on CAFOs.

Opportunity costs?

Opportunity cost: *the loss of potential gain from other alternatives when one alternative is chosen.*

- Does the use of AD prevent investigation or use of other methods of managing manure and nutrients?

Development and implementation of NMPs and best management practices (BMPs) are much less expensive than AD, and can be used on farms of any size.

BMPs include:

- Better manure containment and storage;
- Use of NMPs;
- Buffer strips;
- Rotational grazing; and
- Composting.

Sources & resources

This curriculum is a modification of the wonderful:

- eXtension Course 3: AD, University of Wisconsin

http://fyi.uwex.edu/biotrainingcenter/online-modules/series-three-anaerobic-digestion/

Additional sources & resources:

- AgSTAR
- US EPA
- International Energy Agency
- Kramer (2011)
- Wilkie (2000)
- Odgers & Struss (2009)
  Grande (2010)
- Pinder (2003)
- Lake Michigan Air Directors Consortium (2007)
- Biogas Opportunities Roadmap, USDA, Aug 2014
- Wellinger, A. & Linberg, A 2000) Biogas upgrading & utilization – IEA Bioenergy Task 24, International Energy Association, Paris, France: p.20

Assessment!

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