07-Off-Grid Biomass Systems

Off-Grid Electrical Systems in Developing Countries, 2nd Edition

Chapter 7

Preface

- These lectures slides are intended to accompany the textbook *Off-Grid Electrical Systems in Developing Countries, 2nd Edition, 2025* written by Dr. Henry Louie and published by SpringerNature
- Additional content, explanations, derivations, examples, problems, errata, and other materials are found in the book and on www.drhenrylouie.com
- To request solutions, explanations, permissions to use author-supplied images, or if you notice an error, please email the author at hlouie@ieee.org
- Inquiries about guest lectures, seminars, or trainings can be made to hlouie@ieee.org
- If you want to support work in electricity access, consider donating to KiloWatts for Humanity or IEEE Smart Village

Learning Outcomes

At the end of this lecture, you will be able to:

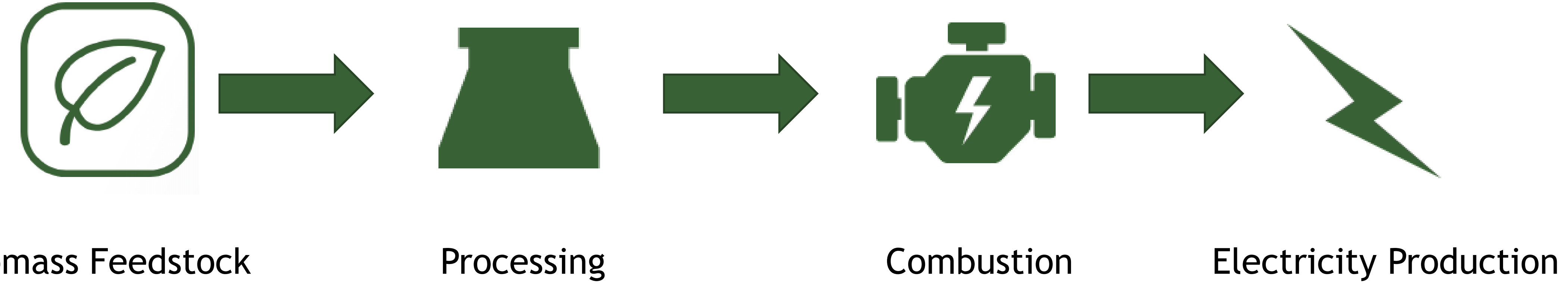
- ✓ Describe the use of biogas, syngas, and direct biomass combustion in offgrid electrification, emphasizing the key technical, economic, environmental, and social considerations
- ✓ Explain the fundamental processes involved in the production of biogas and syngas from biomass
- ✓ Produce a preliminary design of a small-scale biogas system for off-grid electrification
- ✓ Calculate the efficiency and feedstock requirements for biomass systems in off-grid applications

Introduction

- Majority of areas without electricity access are rural, farming-based communities
- Biomass from crop waste and animal byproducts can be used to generate gaseous fuel for internal combustion engine (ICE) gen sets
  - often the biomass fuel is used with diesel in a dual-fuel ICE
- Biomass has been successfully used in China and India but is underutilized in Sub-Saharan Africa (SSA)

Biomass

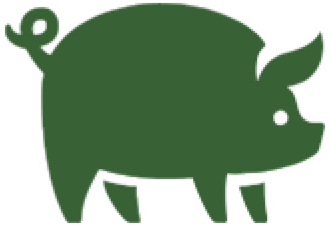
- Organic material from recently alive organisms
- Feedstock biomass is processed into a more convenient form before use in a gen set or steam turbine



Biomass Feedstocks

Forest waste

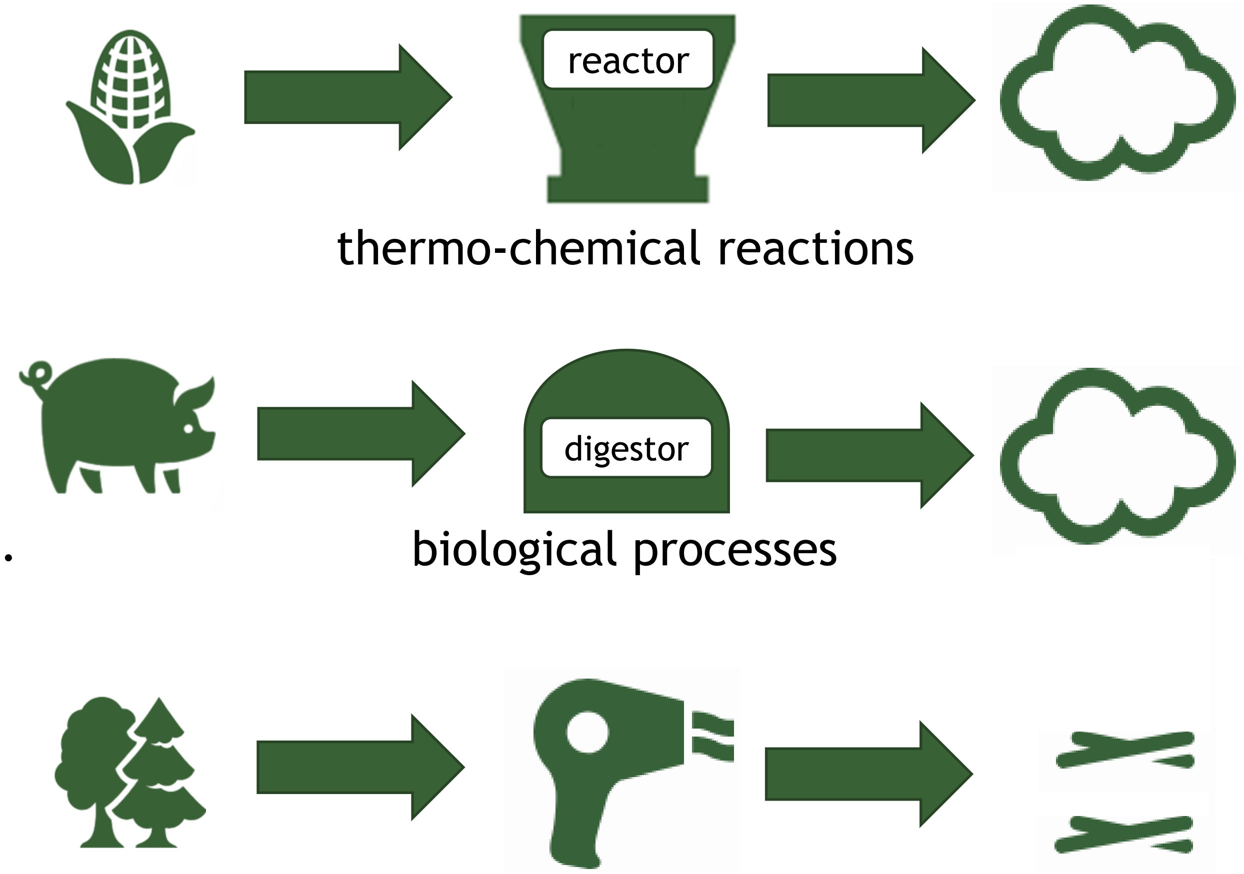
Crop residue



Animal waste

Food waste

Biomass Processing



Feedstock		Output
bagasse, bamboo, nut shells, cotton stalks, forest pruning, rice husk, wood pulp, etc.	thermo-chemical reactions	Syngas (hydrogen, carbon monoxide)
pig/cattle manure, chicken litter, food waste, slaughterhouse waste, stalks, straw, etc.	biological processes	Biogas (methane, carbon dioxide)
forest waste, manufacturing waste, etc.	cutting, drying	Dried Biomass

Principles of Operation

- Energy in biomass is stored via photosynthesis

$$6CO_2 + 6H_2O + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2$$

chemical energy in glucose is from solar radiation

- Decay or combustion can release the stored energy

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

Biomass Resource

Specific energy of biomass depends on type of biomass and its moisture content

- fresh wood: 8 MJ/kg
- dry wood: 15 MJ/kg
- sugarcane, maize approx. 18 MJ/kg

Methane is approx. 56 MJ/kg

- Relatively low specific energy is a challenge to biomass as it often needs to be collected and transported before processing
- Crop yields range from 0.5 to 20 tonnes per hectare (10,000 m^2)

Manure Production

- Biogas production often uses manure
- Wide variety of manure production rates
- “wet” and “fresh” manure refers to the excreted manure and includes moisture content
- Not all manure can practically be recovered

Animal	Total Production (wet) (kg/day)
Buffalo	14
Cow	10
Calf	5
Sheep/goat	2
Pig	5
Hen	0.075

Biogas

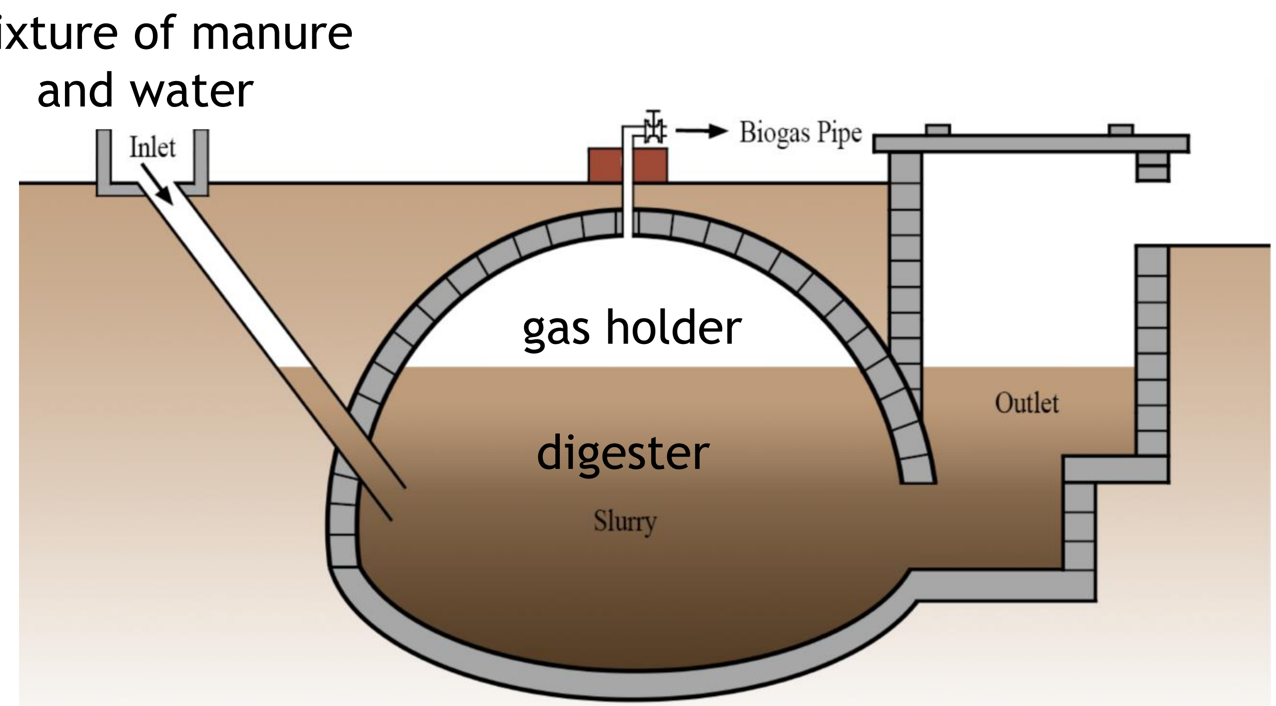
- Microorganisms convert biomass to biogas (methane and carbon dioxide)
- Requires biomass and water (or wet biomass such as manure)
- Process takes 10-60 days
- High efficiency (up to 85%, but <40% is more typical)
- Reactor is simple to construct
- Millions of digestors implemented, very few used for electricity generation
- Gas used in modified ICE gen set to produce electricity

Biogas

- Biogas is generated in a “reactor”
- Various types
  - fixed dome
  - bag
  - floating
  - others

Flexible (bag) Biogas Plant, Designed by Waste Bangladesh and supported by Sustainable and Renewable Energy Development Authority (SREDA), Bangladesh https://energypedia.info/index.php?curid=136399 licensed under CC BY-SA 4.0

Fixed Dome Biogas Reactor: Initial state



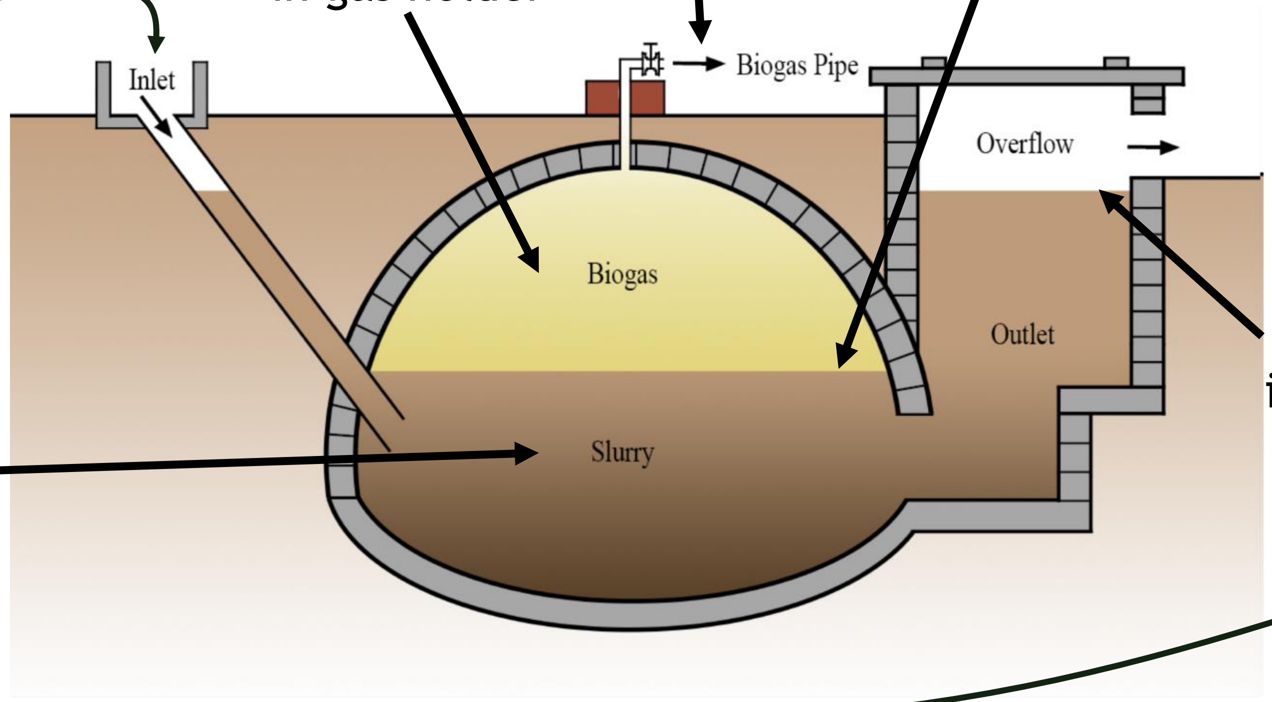
reactor volume = gas holder volume + digester volume

Biogas Reactor

biogas
removed

pressure from biogas
presses down on slurry in reactor

biogas accumulates
in gas holder



“used” slurry is pushed up
into the outlet and is removed

anaerobic digestion
produces biogas

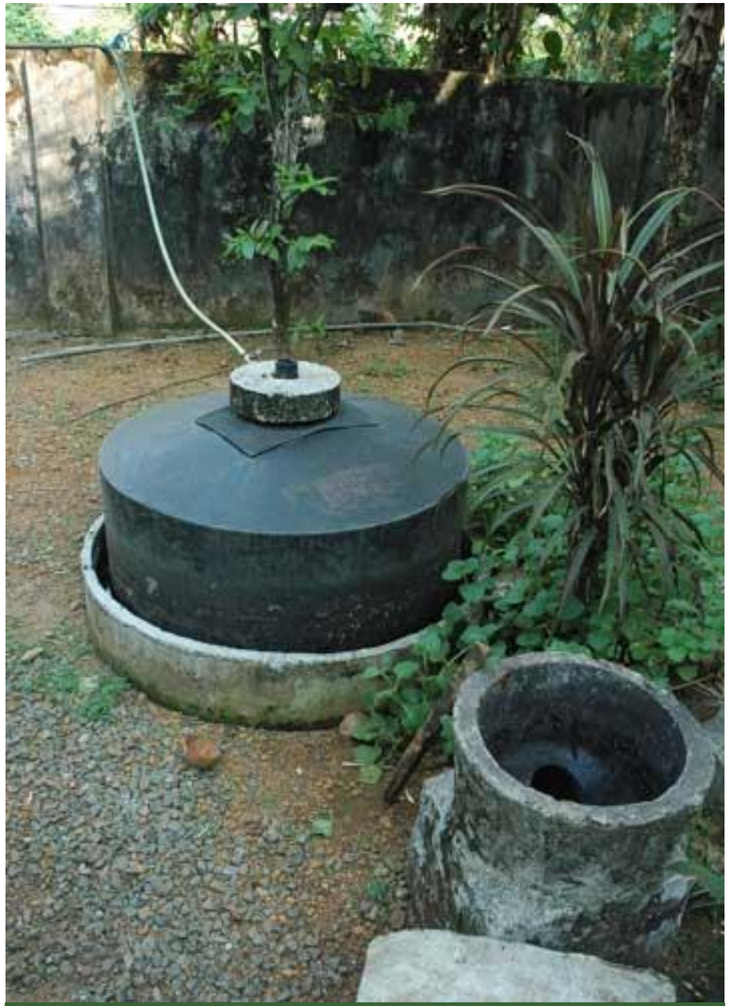
more manure and
water are added

Biogas Digestion

- Manure and water are often added on a continuous (daily) basis
- Residue from digestion is called "digestate"
- Digestate is a valuable fertilizer
  - must be treated before used or discharged into surface water (see WHO guidelines)

Biogas Digestor

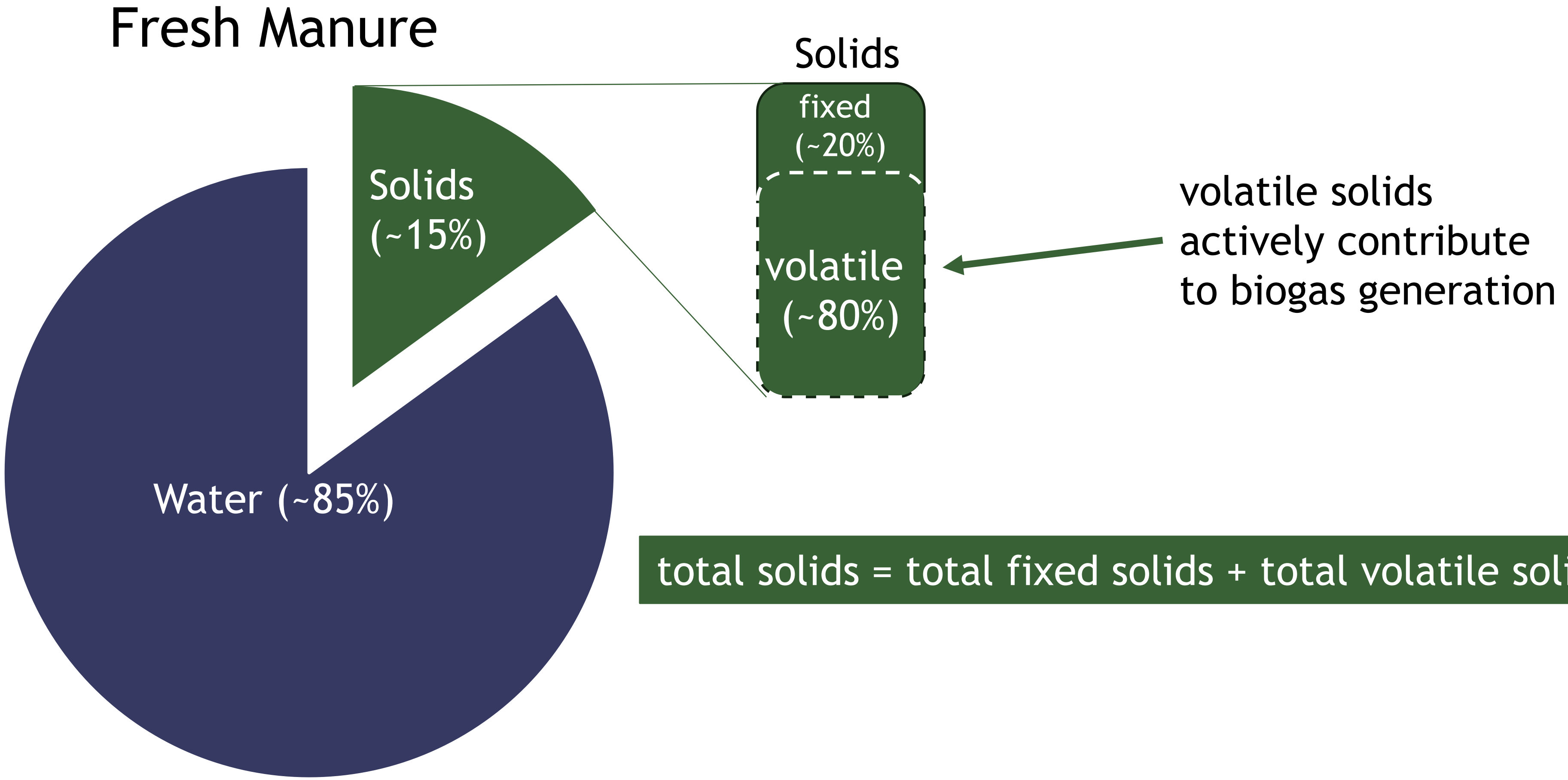
Biogas digestor under construction in Malawi
(courtesy P. Dauenhauer)



Biogas Yield

- Volume (yield) of biogas depends on many factors
  - volume of reactor and feedstock
  - type of feedstock
  - temperature, digestion time, pH level
  - etc.
- Simplified estimation procedure presented in the following

Solids



total solids = total fixed solids + total volatile solids

Volatile Solids

Animal	Total Production (wet) (kg/day)	Volatile Solids (kg/day)
Buffalo	14	1.94
Cow	10	1.42
Calf	5	0.5
Sheep/goat	2	0.44
Pig	5	1
Hen	0.075	0.028

Feedstock	Volatile Solids (% of raw waste)
Cereals/grains	81
Rice straw	36
Wheat straw	39
Grass	51
Corn stalk	43
Fruit waste	14
Vegetable waste	16

Exercise

Compute the percentage of volatile solids in (fresh) sheep manure

Animal	Total Production (wet) (kg/day)	Volatile Solids (kg/day)
Buffalo	14	1.94
Cow	10	1.42
Calf	5	0.5
Sheep/goat	2	0.44
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Hen	0.075	0.028

Exercise

Compute the percentage of volatile solids in (fresh) sheep manure

Volatile solids: 0.44/2 = 22%

This is higher than most other animals

Animal	Total Production (wet) (kg/day)	Volatile Solids (kg/day)
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Feedstock

- Total feedstock: biomass + water
  - manure: 1:1 biomass to water
  - plant: 1:2 biomass to water
- Daily total feedstock is sum of volume of feedstock (biomass) and water input to reactor expressed in liters/day

$$\dot{V}_{\mathrm{tf}} = \dot{V}_{\mathrm{feed}} + \dot{V}_{\mathrm{wa}}$$

Approximate: 1 liter of water, manure, or plant biomass weighs 1 kg, so we can substitute mass/day for volume/day

Initial Concentration

- Initial Concentration: mass of volatile solids per <u>cubic meter</u> of input

$$C_{\text{vs}}(\text{kg/m}^3) = \frac{\dot{m}_{\text{vs}}\ (\text{kg/day})}{\dot{v}_{\text{tf}}\ (\text{liter/day})} \times 1000\left(\text{liter/m}^3\right)$$

this is numerically equivalent to

$$C_{\text{vs}} = \frac{\dot{v}_{\text{vs}}}{\dot{v}_{\text{tf}}} \times 1000$$

Retention Time

- Retention time: the average time, in days, a quantity of feedstock is in the reactor before it is removed
- Longer retention time allows more biogas to be produced from feedstock, but requires a larger reactor

$$T_{\mathrm{dig}}\ \text{(day)} = \frac{V_{\mathrm{dig}}\ (\mathrm{m}^3)}{\dot{V}_{\mathrm{tf}}\ \text{(liter/day)}} \times 1000\left(\text{liter/m}^3\right)$$

V_{dig}: digester volume

Example 7.1

The feedstock for a biogas system is manure from 10 cows. The manure is mixed with water in a 1:1 ratio. Compute the daily feedstock input volume, retention time, and initial concentration based on a digester volume of 8 m^3.

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We assume that each cow excretes 10 kg of fresh (wet) manure per day, of which 1.42 kg are volatile solids.

The volume of total feedstock input to the digester each day is:

$$\dot{V}_{tf} = \dot{V}_{feed} + \dot{V}_{wa} = \underbrace{10}_{\text{10 cows}} \times (10 + 10) = 200 \text{ liters}$$

Animal	Total Production (wet) (kg/day)	Volatile Solids (kg/day)
Buffalo	14	1.94
Cow	10	1.42
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Retention time

$$T_{\text{dig}} = \frac{V_{\text{dig}}}{\dot{V}_{\text{tf}}} \times 1000 = \frac{8}{200} \times 1000 = 40 \text{ days}$$

Initial concentration

$$C_{\text{vs}} = \frac{\dot{m}_{\text{vs}}}{\dot{V}_{\text{tf}}} \times 1000 = \frac{10 \times 1.42}{200} \times 1000 = 71 \text{ kg/m}^3$$

For every cubic meter of total feedstock input, there are 71 kg of volatile solids

Yield Factor

- Yield factor: liters of biogas produced per kilogram of volatile solids per day
- Use simplified look-up table
  - depends on retention time and digester temperature

Yield Factor Table

Retention Time	Temperature (°C)					
Days	19-21	22-24	25-27	28-30	31-33	34-36
16-20	4.21	5.9	7.68	9.37	10.82	12.32
21-25	3.79	5.22	6.7	8.11	9.33	10.59
26-30	3.44	4.69	5.95	7.15	8.2	9.28
31-35	3.16	4.25	5.35	6.39	7.32	8.26
36-40	2.91	3.88	4.86	5.78	6.6	7.44
41-45	2.71	3.58	4.45	5.27	6.02	6.77
46-50	2.53	3.32	4.1	4.85	5.53	6.21
51-55	2.37	3.09	3.81	4.49	5.11	5.74
56-60	2.23	2.89	3.55	4.18	4.75	5.33
61-65	2.10	2.72	3.33	3.91	4.44	4.98
66-70	1.99	2.57	3.13	3.67	4.17	4.67
71-75	1.89	2.43	2.95	3.46	3.93	4.40
76-80	1.80	2.30	2.8	3.27	3.71	4.15

Yield Factor

Yield Factor Table

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36-40	2.91	3.88	4.86	5.78	6.6	7.44
41-45	2.71	3.58	4.45	5.27	6.02	6.77
46-50	2.53	3.32	4.1	4.85	5.53	6.21
51-55	2.37	3.09	3.81	4.49	5.11	5.74
56-60	2.23	2.89	3.55	4.18	4.75	5.33
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Long retention times mean that less fresh volatile solids are being added each day for a given digester volume

Higher temperatures within
this range increases biogas production
(but too high and it harms the microorganisms)

Biogas Production

- The biogas produced each day is found from:

$$\dot{v}_{\text{biogas}}\ (\text{m}^3/\text{day}) = \frac{Y_{\text{dig}}\ (\text{liter/kg/day}) \times v_{\text{dig}}\ (\text{m}^3) \times C_{\text{vs}}\ (\text{kg/m}^3)}{1000\ (\text{liter/m}^3)}$$

- Each kg of wet manure typically yields 10-40 liters of biogas with energy content of 20 to 23 MJ/m^3
- Off-grid homes typically need a few cubic meters per day for electricity use

Example 7.2

A digester in a biogas reactor has a volume of 5.0 m^3. The feedstock is manure from three buffalo. The manure is mixed with water in a 1:1 ratio. Estimate the daily biogas production from the digester, assuming the temperature of the digester is 25 °C.

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A digester in a biogas reactor has a volume of 5.0 m^3. The feedstock is manure from three buffalo. The manure is mixed with water in a 1:1 ratio. Estimate the daily biogas production from the digester, assuming the temperature of the digester is 25 °C.

Each buffalo excretes 14 kg of wet manure per day, of which 1.94 kg are volatile solids. The total feedstock volume input to the digester each day is found from

$$\dot{V}_{\mathrm{tf}} = \dot{V}_{\mathrm{feed}} + \dot{V}_{\mathrm{wa}} = 3\times(14+14) = 84 \text{ liters}$$

equivalent to 84 kg

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The initial concentration is

$$C_{vs} = \frac{\dot{m}_{vs}}{\dot{V}_{tf}} \times 1000 = \frac{3 \times 1.94}{84} \times 1000 = 69.3 \text{kg/m}^3$$

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Based on the size of the digester, the retention time is

$$T_{\text{dig}} = \frac{V_{\text{dig}}}{\dot{V}_{\text{tf}}} = \frac{5}{84} \times 1000 = 59.5 \text{ days}$$

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The yield factor is 3.55 liter/kg/day

Retention Time	Temperature (°C)					
Days	19-21	22-24	25-27	28-30	31-33	34-36
16-20	4.21	5.9	7.68	9.37	10.82	12.32
21-25	3.79	5.22	6.7	8.11	9.33	10.59
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The volume of biogas produced per day is

$$\dot{V}_{\text{biogas}} = \frac{Y_{\text{dig}} \times V_{\text{dig}} \times C_{\text{vs}}}{1000} = \frac{3.55 \times 5 \times 69.3}{1000} = 1.23\,\text{m}^3/\text{day}.$$

Each kg of wet manure produced 29 liters of biogas

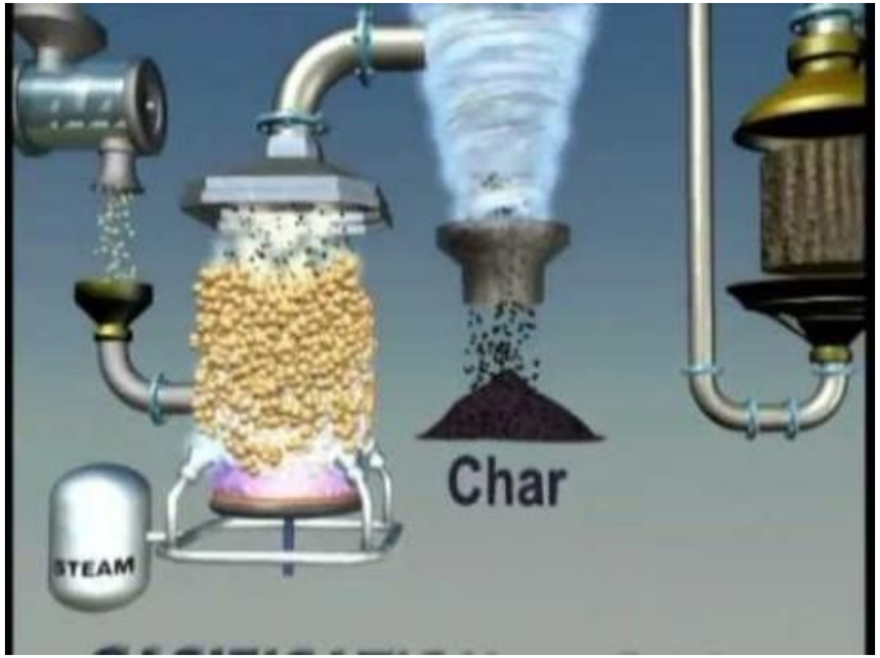
Syngas

- Thermo-chemical reactions convert dry biomass to syngas (gasification) inside a reactor vessel
- Dried woody biomass or crop residue often used
- High-temperature process, gas must be cooled and filtered before use
- Gas used in modified ICE gen set to produce electricity

Example for Glucose

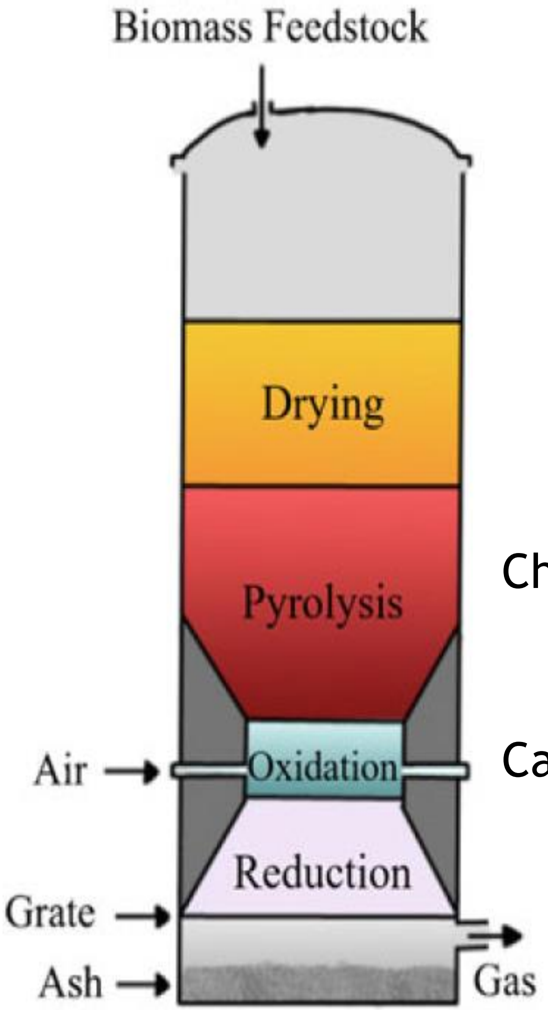
$$C_6H_{12}O_6 + O_2 + H_2O \longrightarrow xCO + yCO_2 + zH_2 + \text{other species}$$

Syngas Production



https://www.youtube.com/watch?v=kI7s6IRpOHA

Syngas Reactor



Char produced

C

$$C + O_2 \longrightarrow CO_2$$

Carbon dioxide, heat

$$C + H_2O \longrightarrow H_2 + CO$$

Syngas (hydrogen, carbon monoxide) 1.5 m^3 (3 to 6 MJ) per kilogram of dry input

Example 7.4

Consider a biomass gasification system serving 400 houses. Each house consumes 300 Wh of electricity per day. The gasification system is 60% efficient, and the combined efficiency of the engine and generator is 33.3%. The energy content of the dry husk feedstock is 12.6 MJ/kg, which costs US$25 per metric ton. Compute the mass of husk required each day and cost of fuel per kilowatthour of electricity consumption.

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The daily electrical demand, expressed in megajoules, is

$$E_{\mathrm{e,MJ}} = (0.300 \times 400)\frac{3.6\ \mathrm{MJ}}{1\ \mathrm{kWh}} = 432\ \mathrm{MJ}$$

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The required energy content of the input husks is found by accounting for the efficiency of the gasification and the engine/generator:

$$E_{\text{bio,MJ}} = 432 \times \frac{1}{0.6 \times 0.333} = 2162 \text{ MJ}$$

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The total mass of husk required each day is therefore

$$E_{\text{bio,kg}} = 2162 \times \frac{1}{12.6} = 171.6 \text{ kg}$$

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The cost per day is

$$171.6\ \text{kg} \times \text{US\$}0.025/\text{kg} = \text{US\$}4.29/\text{day}$$

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The cost per kilowatthour is

$$\frac{\text{US\$}4.29}{0.30\,\text{kWh/house} \times 400\,\text{houses}} = \text{US\$}0.0358/\text{kWh}$$

Direct Combustion

- Dry, processed (chopped or pelletized) biomass (often from forestry waste) can be directly combusted to generate steam for use in a steam turbine
- Usually associated with an industrial facility
- Heat generated may also be used in the industrial processing, increasing the overall efficiency
- Only practical at large scale

Economic Considerations

- Wide range of costs reported
  - Biogas reactor +US$6100/kW
  - Syngas reactor +US$5700/kW
  - Boiler +US$4300/kW

Costs likely greater for small-scale systems

- Free/low fuel costs, but feedstock prices can be volatile
- Operation and maintenance costs: 5-20% of the energy costs
- Energy cost: usually lower than gen sets and can be comparable to PV-based systems (but usually greater)

Environmental Considerations

- Crop residue and manure often available, but must be concentrated
- Net zero carbon dioxide emissions if fast growing crops are used. Other emissions result from combusting biomass
- Biogas and syngas require water supplies, which can limit there use in water scarce areas
- Gathering, storing, and drying biomass can take considerable space, smell bad, and attract pests

Social Considerations

- Collection, transportation, and processing of biomass can create local jobs
- Farmers may benefit from selling or having waste removed from their fields
- Many cultures have taboos around handling feces and waste
- Managing biomass production requires specialized training
- Maintaining a consistent supply of biomass, particularly seasonal waste can be difficult

Other Considerations

- Avoid replacing food crops with energy crops (threatens food security)

Summary

- Biomass is available in many off-grid communities
- General processes for biomass conversion
    - biological digestion (biogas: carbon dioxide and methane)
    - thermal-chemical reaction (syngas: carbon monoxide and hydrogen)
    - direct combustion
- Challenges include gathering, transporting, and processing biomass