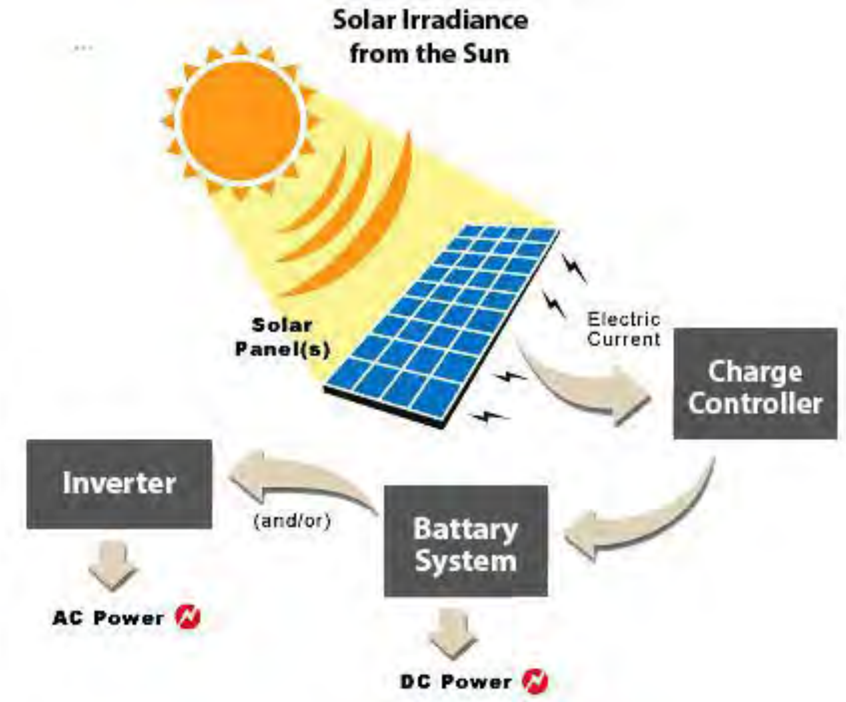
Lecture One

Introduction to renewable energy sources

Renewable energy sources derive their energy from existing flows of energy from ongoing natural processes, such as sunshine, wind, flowing water, biological processes, and geothermal heat flows. A general definition of renewable energy sources is that renewable energy is captured from an energy resource that is replaced rapidly by a natural process such as power generated from the sun or from the wind. Currently, the most promising (aka economically most feasible) alternative energy sources include wind power, solar power, and hydroelectric power. Other renewable sources include geothermal and ocean energies, as well as biomass and ethanol as renewable fuels.

Solar

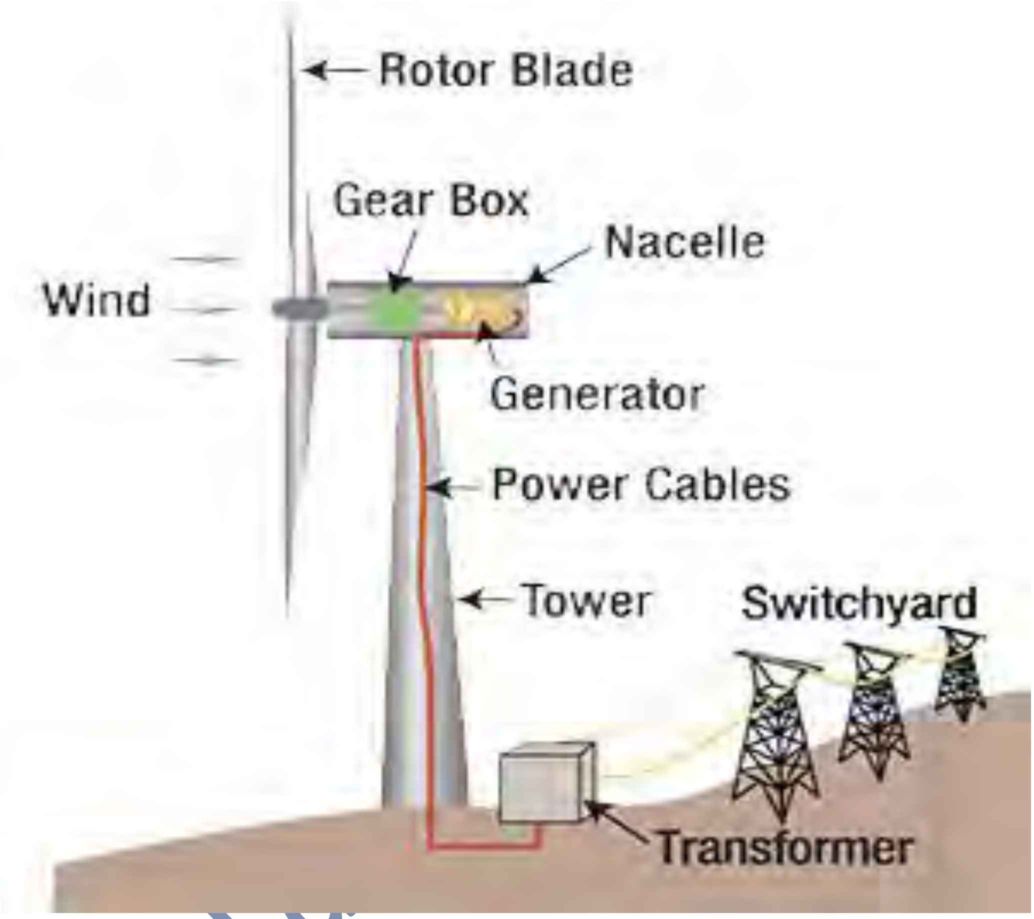
One promising technology, solar power is worth considering for it's sustainable, renewable and emissions reducing qualities. Modern residential solar power systems use photovoltaic (PV) to collect the sun's energy. Photo "means“ produced by light and voltaic ”is“ electricity produced by a chemical reaction PV cells use solar energy to generate a chemical reaction that produces electricity. Each cell contains a semiconductor; most commonly silicon in one of several forms (single-crystalline, multi-crystalline, or thin-layer), with impurities (either boron or phosphorus) diffused throughout, and is covered with a silk screen. Cells are joined together by a circuit and frame into a module. Semiconductors allow the electrons freed from impurities by the sun's rays to move rapidly and into the circuit, generating electricity. Commercial residential PV modules range in power output from 10 watts to 300 watts, in a direct current. A PV module must have an inverter to change the DC electricity into alternating current energy in order to be usable by electrical devices and compatible with the electric grid. PV modules can also be used in masse to create large-scale power plants.



Wind

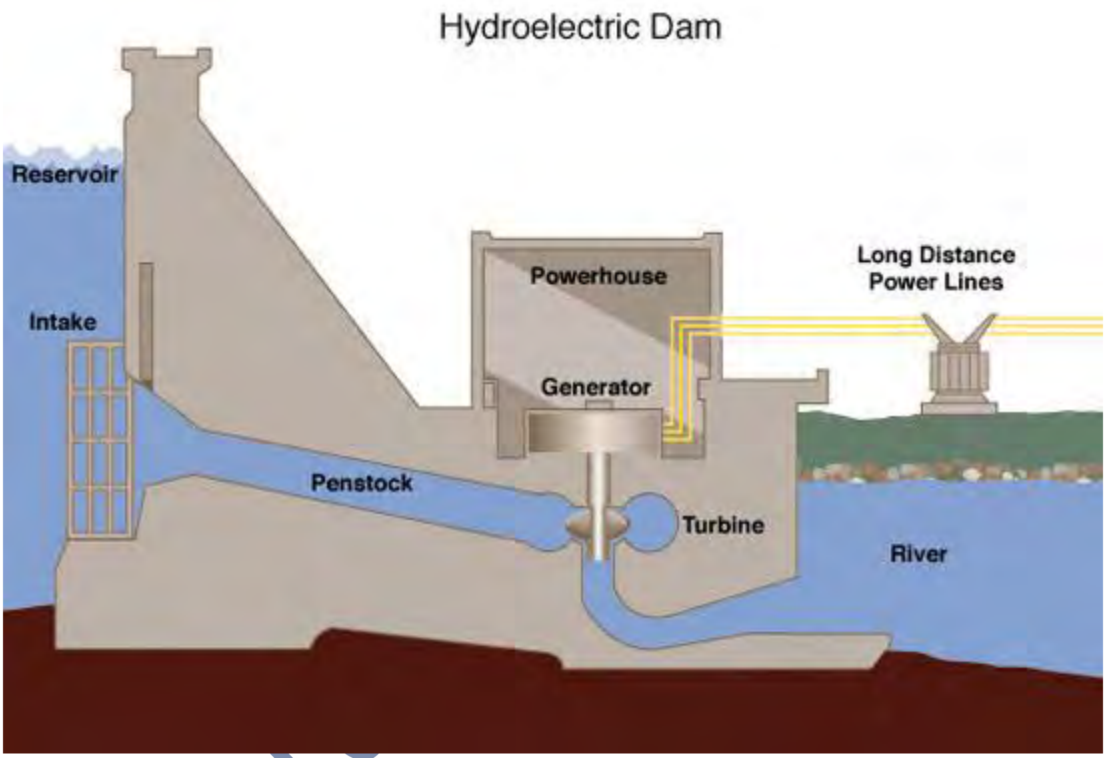
Wind energy is one of the most promising alternative energy technologies of the future. Throughout recent years, the amount of energy produced by wind-driven turbines has increased exponentially due to significant breakthroughs in turbine technologies, making wind power economically compatible with conventional sources of energy. Wind energy is a clean and renewable source of power. The use of windmills to generate energy has been utilized as early as 5000 B.C., but the development of wind energy to produce electricity was sparked by the industrialization. The new windmills, also known as wind turbines, appeared in Denmark as early as 1890.

Wind is a form of solar energy and is caused by the uneven heating of the atmosphere by the Sun, the irregularities of the Earth’s surface, and rotation of the Earth. The amount and speed of wind depends on the Earth's terrain and other factors. The wind turbines use the kinetic energy of the wind and convert that energy into mechanical energy, which in turn can be converted into electricity by means of a generator.



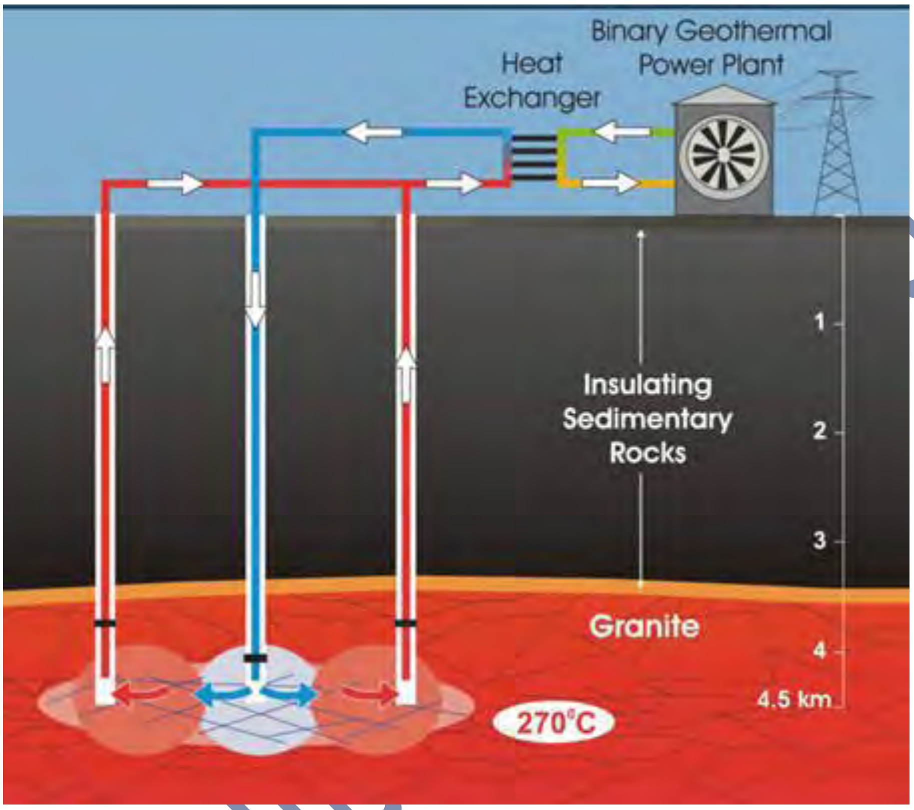
Hydroelectric Power: Harvesting energy from water is possible due to the gravitational potential energy stored in water. As water flows from a high potential energy (high ground) to lower potential energy (lower ground), the potential energy difference thereby created can be partially converted into kinetic, and in this case electric, energy through the use of a generator.

There are essentially two major designs in use that utilize water to produce electricity: the hydroelectric dam, and the pumped-storage plant. The principle is simple: the force of the water being released from the reservoir through the penstock of the dam spins the blades of a turbine. The turbine is connected to the generator that produces electricity. After passing through the turbine, the water reenters the river on the downstream side of the dam. A pumped-storage plant is very similar to the hydroelectric dam, the main difference being that the pumped-storage plant uses two reservoirs, one being considerably higher than the other.



Geothermal

Geothermal energy is one of the only renewable energy sources not dependent on the Sun. Instead, it relies on heat produced under the surface of the Earth. Geothermal energy already has several applications and could potentially provide a significant source of renewable power. There are two main applications of geothermal energy, which include producing electricity at specialized power plants, and direct-heating, which puts to direct use the temperature of water piped under the earth’s surface. Geothermal power plants take on several types of forms, depending on the type of geothermal area from which they extract energy. In any case, the plants depend on steam to power turbines and generate electricity, though the methods of producing steam vary depending on the type of geothermal reservoir.

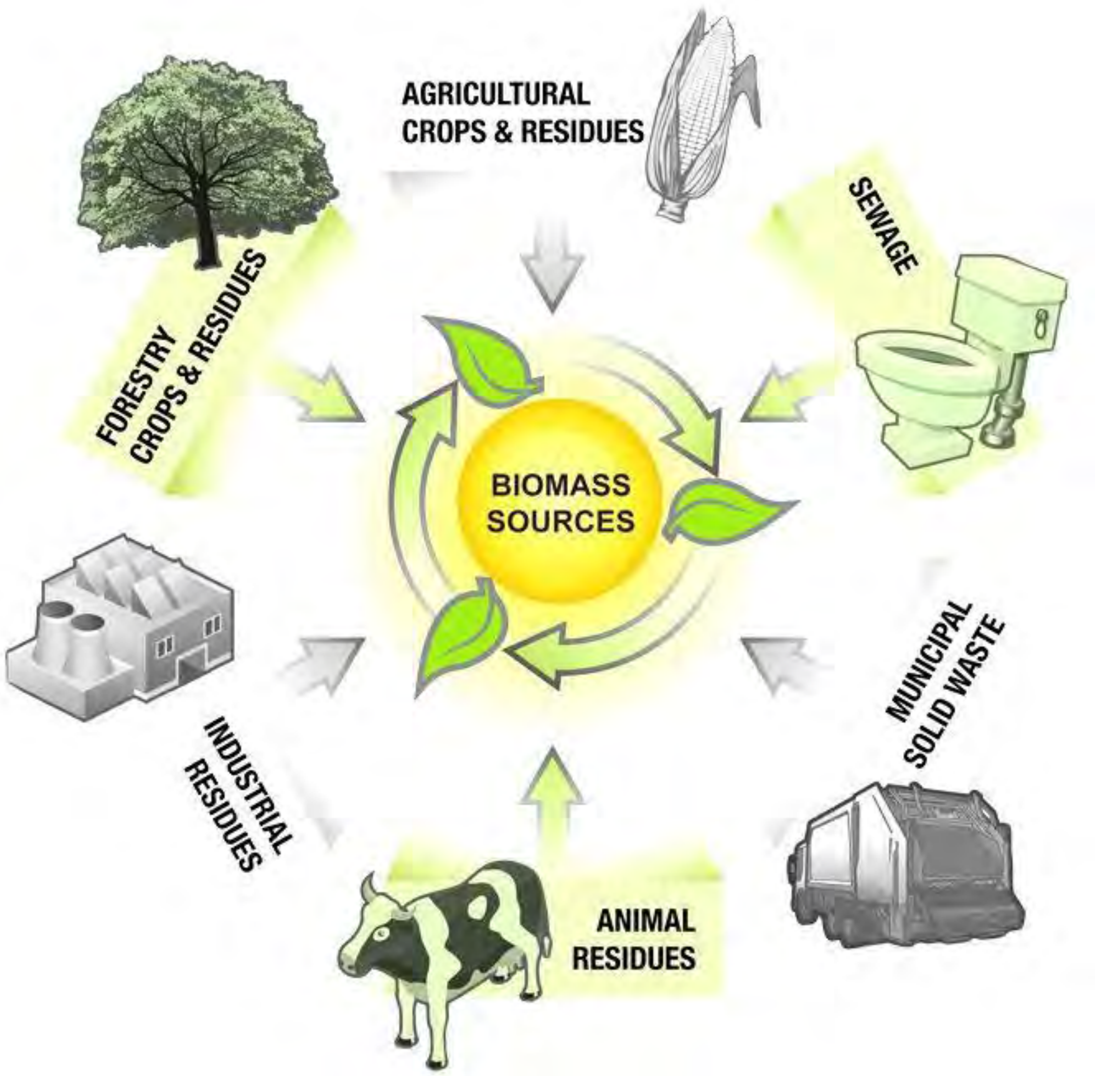


Biomass

As a pending global energy crisis appears more and more imminent, it is important to consider many different options for new energy sources. Renewable energy sources are ideal because they are more efficient, environmentally friendly and, ultimately, better for consumers.

Biomass can be converted into fuels through a number of different processes, including solid fuel combustion, digestion, pyrolysis, and fermentation and catalyzed reactions.

Electricity is generated in many places through solid fuel combustion. These products are usually wood matter, vegetation, waste from lumber yards, and the like. This process still releases a lot of carbon dioxide and other polluting gases into the environment, but helps eliminate waste efficiently.



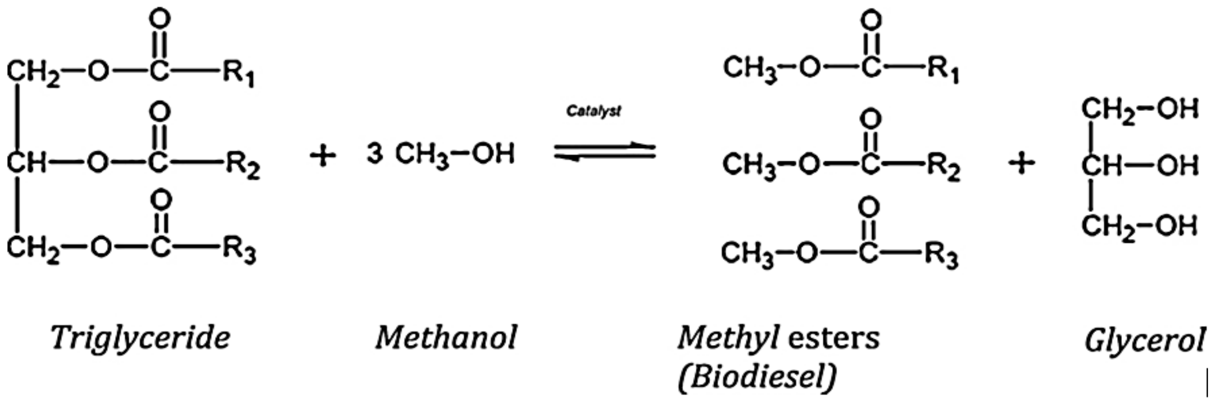
Digestion is the naturally occurring process of bacteria feeding on decaying matter and making it decompose. It is that which releases gases like methane, hydrogen, carbon monoxide, etc. In many landfills, owners are experimenting with set-ups to best collect the gases produced by such bacteria. The standard system includes pipelines running through the waste to collect the gases.

Benefits of this process include the relative lack of impurities in the gases produced and the fact that the synthesis gases (carbon monoxide and hydrogen) can be converted to any kind of hydrocarbon fuel.

A third process, pyrolysis creates a product much like charcoal, with double the energy density of the original biomass, making the fuel highly transportable and more efficient. Anhydrous pyrolysis heats the biomass at intense temperatures in the absence of oxygen or water. Most industrial processes of pyrolysis convert the biomass under pressure and at temperatures above 800° F (430°C). A liquid fuel can also be produced using this process.

The most widely used alternative fuel, ethanol, is created through fermentation of organic materials. Ethanol has a current capacity of 1.8 billion gallons per year, based on starch crops such as corn. Again, the fuel conversion process takes advantage of a natural process. Microorganism, especially bacteria and yeasts, ferment starchy, sugary biomass products (like corn), yielding products like ethanol, which can be used as fuels in a variety of applications.

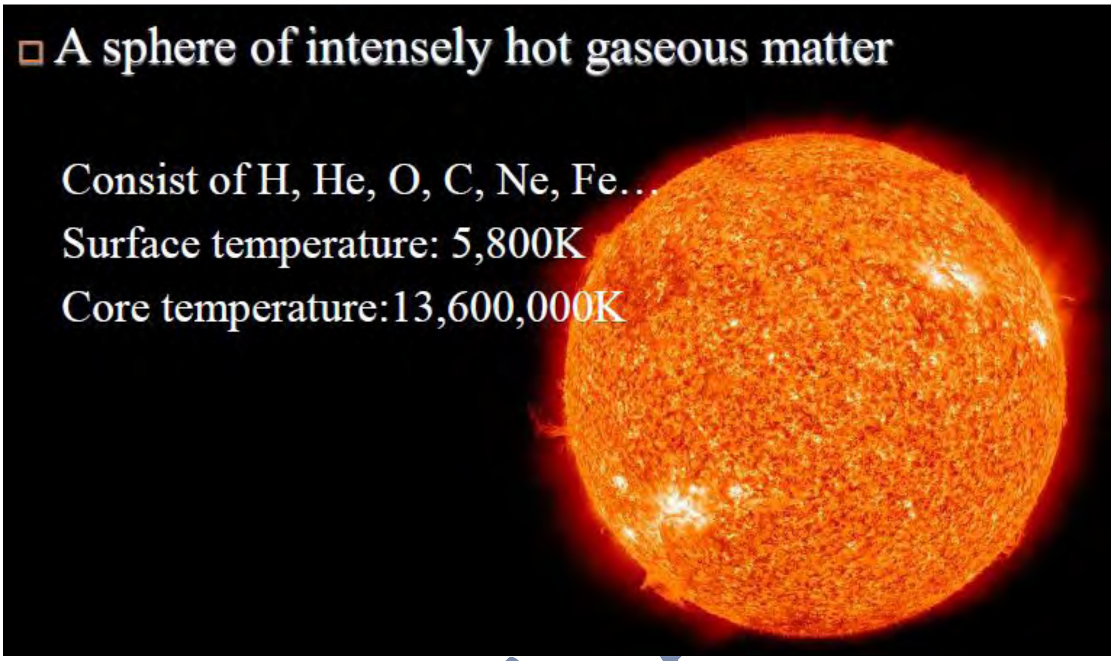
Biodiesel is an increasingly popular fuel, especially in the transportation sector. This monoalkyl ester is formed by combining fuel-grade oil, processed from sources like vegetable oil, animal fats, algae and even used cooking grease, with an alcohol (like methanol or ethanol), using a catalyst. It shows great promise as both a neat fuel (used alone) and as an additive to petroleum diesel.



Lecture Two

Solar Energy

The Sun



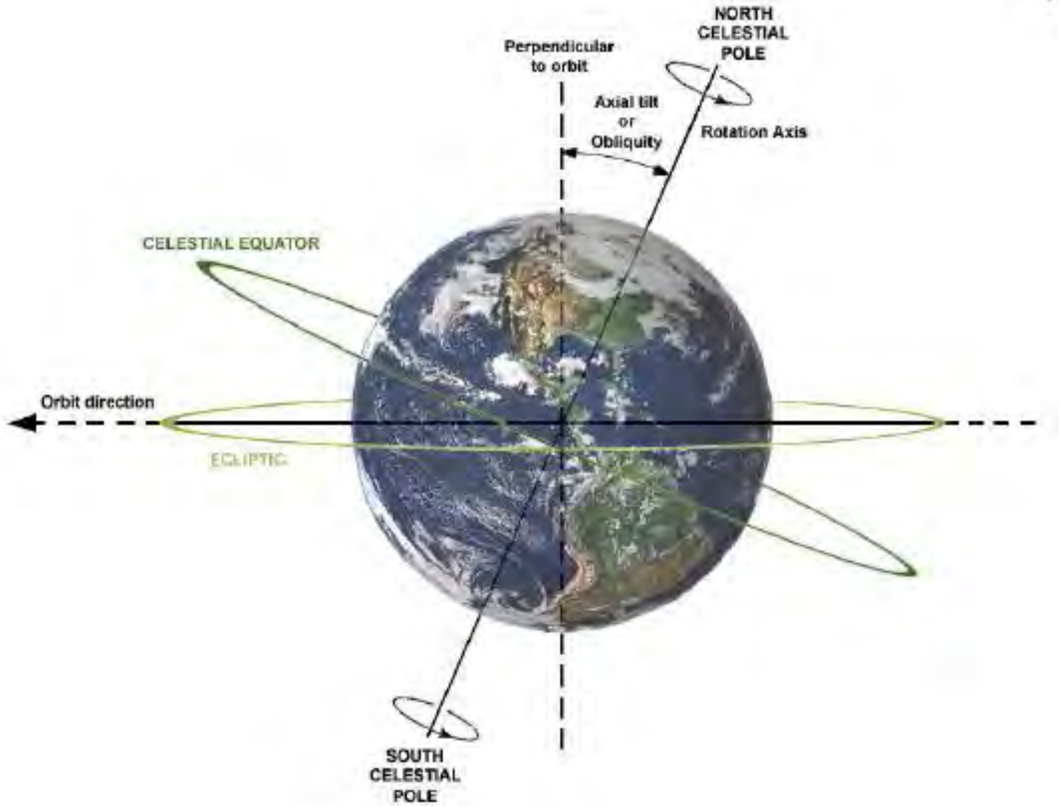
- ☐ A sphere of intensely hot gaseous matter

Consist of H, He, O, C, Ne, Fe…

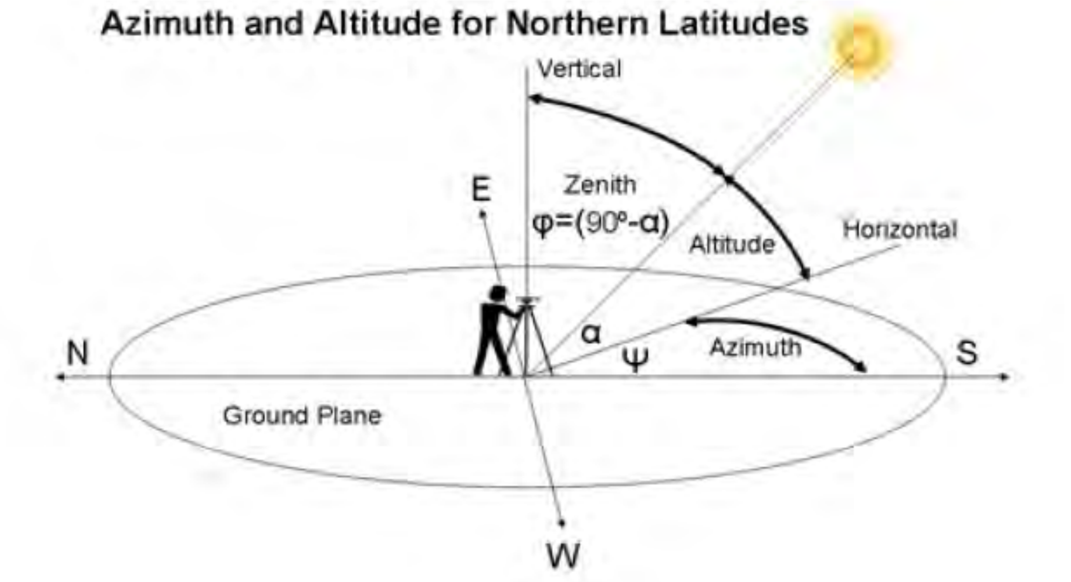
Surface temperature: 5,800K

Core temperature:13,600,000K

Between the Sun and the Earth



Position of the Sun (View from the Earth)



Azimuth angle of the sun:

Often defined as the angle from due north in a clockwise direction. (Sometimes from south)

Zenith angle of the sun: Defined as the angle measured from vertical downward.

Factors affect the Solar intensity

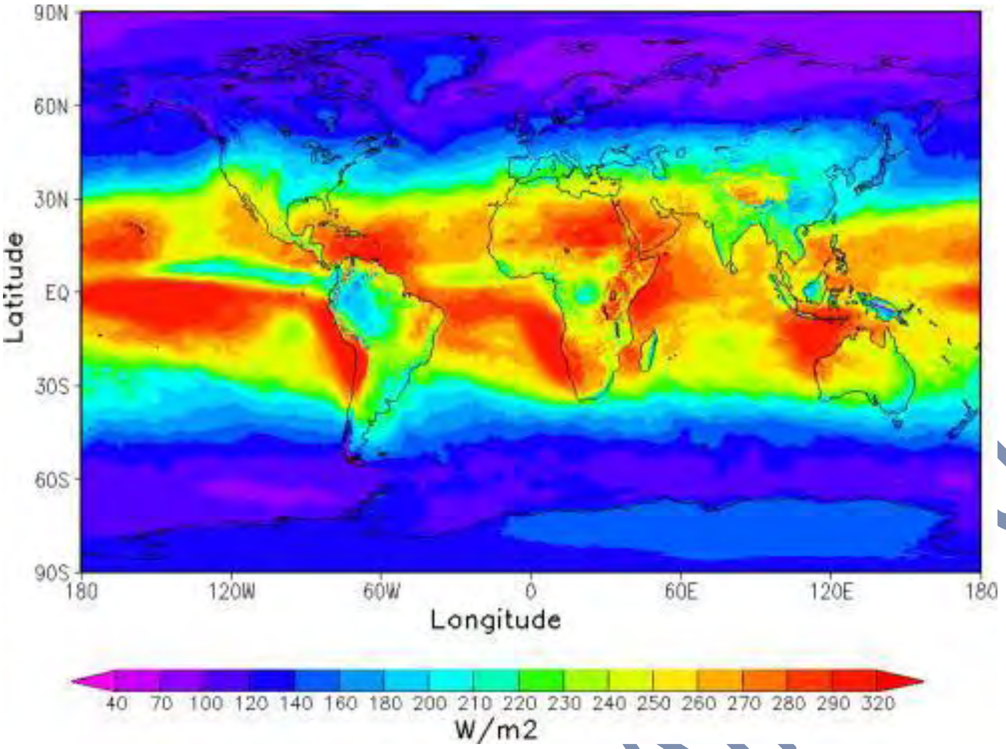
☐Latitude خط العرض

☐Altitude ارتفاع

☐Atmospheric transparency الغلاف الجوي (الشفافية الجوية)

☐Solar zenith angle زاوية القطب الشمسية

Annual global mean downward solar radiation distribution at the surface



Advantages of using Solar Energy

No pollution.

Inexhaustible.

Contribution to energy supply and CO2 reduction.

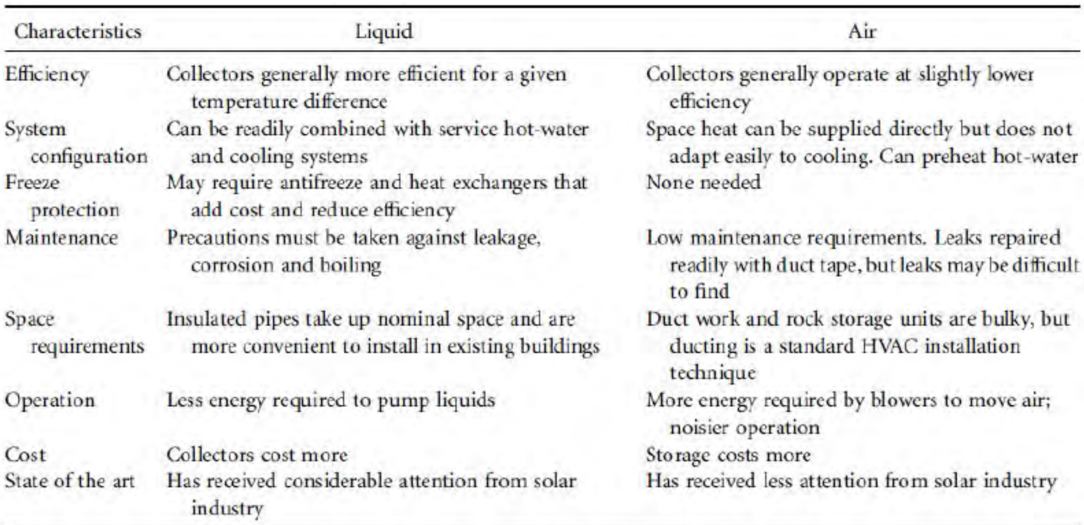
Solar Collectors

A solar thermal collector is a heat exchanger that converts radiant solar energy into heat. In essence, this consists of a receiver that absorbs the solar radiation and then transfers the thermal energy to a working fluid.

The classification of solar collectors (Table 6.1) can be made according to the type of working fluid (water, air, or oils) or the type of solar receiver used (nontracking or tracking).

Most commonly used working fluids are water (glycol being added for freeze protection) and air. Table 6.1 identifies the relative advantages and potential disadvantages of air and liquid collectors and associated systems. Because of the poorer heat transfer characteristics of air with the solar absorber, the air collector may operate at a higher temperature than a liquid filled collector, resulting in greater thermal losses and, consequently, a lower efficiency.

Table 6.1 Advantages and disadvantages of liquid and air systems

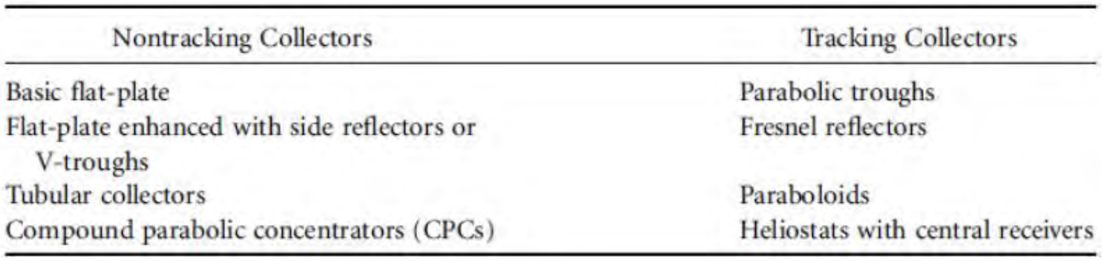


Characteristics	Liquid	Air
Efficiency	Collectors generally more efficient for a given temperature difference	Collectors generally operate at slightly lower efficiency
System configuration	Can be readily combined with service hot-water and cooling systems	Space heat can be supplied directly but does not adapt easily to cooling. Can preheat hot-water
Freeze protection	May require antifreeze and heat exchangers that add cost and reduce efficiency	None needed
Maintenance	Precautions must be taken against leakage, corrosion and boiling	Low maintenance requirements. Leaks repaired readily with duct tape, but leaks may be difficult to find
Space requirements	Insulated pipes take up nominal space and are more convenient to install in existing buildings	Duct work and rock storage units are bulky, but ducting is a standard HVAC installation technique
Operation	Less energy required to pump liquids	More energy required by blowers to move air; noisier operation
Cost	Collectors cost more	Storage costs more
State of the art	Has received considerable attention from solar industry	Has received less attention from solar industry

The choice of the working fluid is usually dictated by the application. For example, air collectors are suitable for space heating and convective drying applications, while liquid collectors are the obvious choice for domestic and industrial hot-water applications. In certain high-temperature applications, special types of oils are used that provide better heat transfer characteristics.

The second criterion of collector classification is according to the presence of a mechanism to track the sun throughout the day and year in either a continuous or discreet fashion (Table 6.2).

Table 6.2 Types of solar thermal collectors



Nontracking Collectors	Tracking Collectors
Basic flat-plate	Parabolic troughs
Flat-plate enhanced with side reflectors or V-troughs	Fresnel reflectors
Tubular collectors	Paraboloids
Compound parabolic concentrators (CPCs)	Heliostats with central receivers

The stationary flat-plate collectors are rigidly mounted, facing toward the equator with a tilt angle from the horizontal roughly equal to the latitude of the location for optimal year-round operation. The compound parabolic concentrators (CPCs) can be designed either as completely stationary devices or as devices that need seasonal adjustments only. On the other hand, Fresnel reflectors, paraboloids, and heliostats need two-axis tracking. Parabolic troughs have one axis tracking either along the east–west direction or the north–south direction.

A third classification criterion is to distinguish between nonconcentrating and concentrating collectors. The main reason for using concentrating collectors is not that more energy can be collected but that the thermal energy is obtained at higher temperatures.
This is done by decreasing the area from which heat losses occur (called the receiver area) with respect to the aperture area (i.e., the area that intercepts the solar radiation). The ratio of the aperture to receiver area is called the **concentration ratio.**

The flat-plate collector is the most common conversion device in operation today, since it is most economical and appropriate for delivering energy at temperatures up to about 1000C. The construction of flat-plate collectors is relatively simple, and many commercial models are available.

Figure 6.1 shows the physical arrangements of the major components of a conventional flat plate collector with a liquid working fluid. The blackened absorber is heated by radiation admitted via the transparent cover. Thermal losses to the surroundings from the absorber are contained by the cover, which acts as a black body to the infrared radiation (this effect is called the greenhouse effect), and by insulation provided under the absorber plate. Passages attached to the absorber are filled with a circulating fluid, which extracts energy from the hot absorber. The simplicity of the overall device makes for long service life.

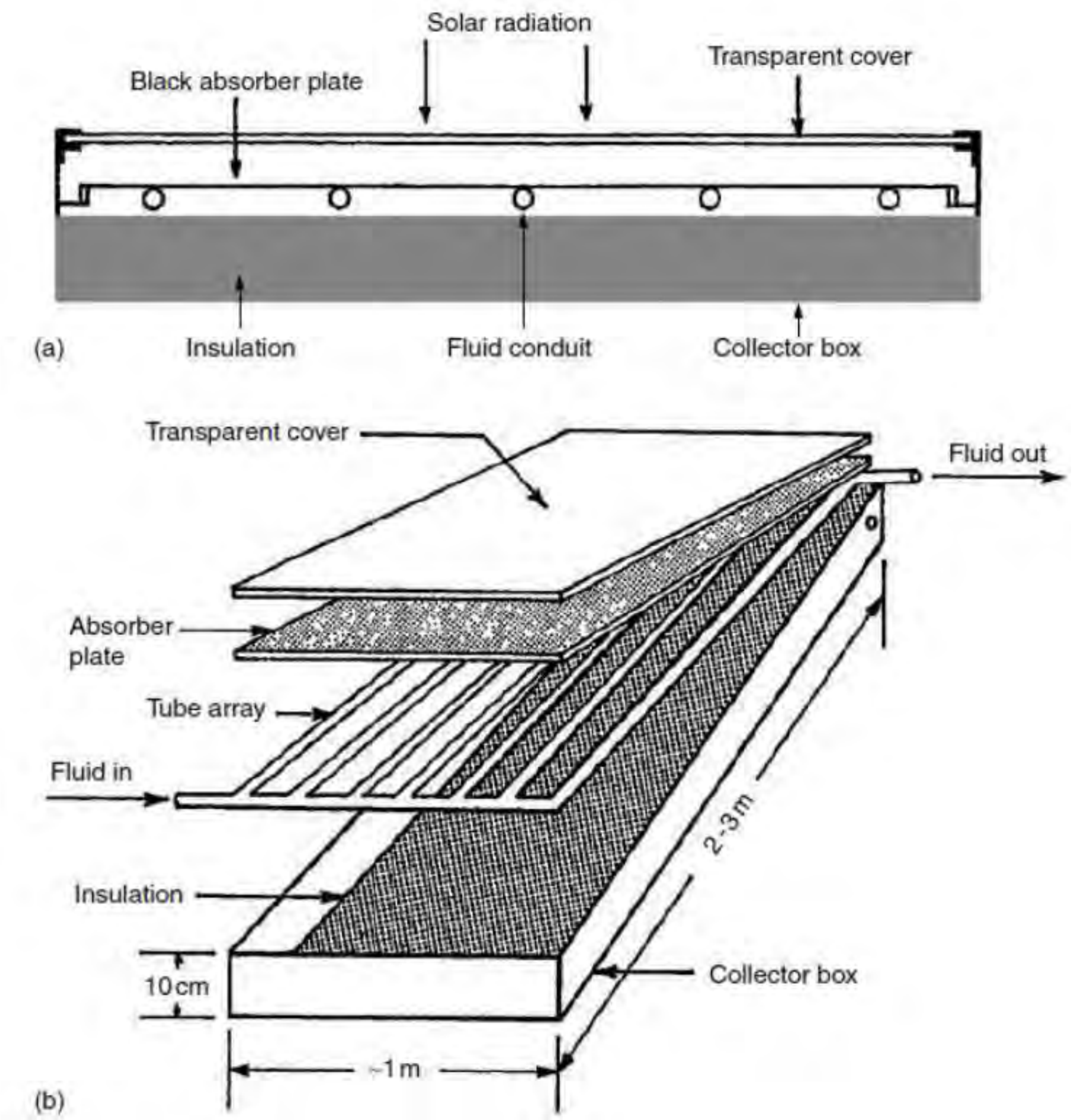


Fig. 6.1 Cross section and isometric view of a flat plate collector.

Lecture Three

Photovoltaic Systems

What is photovoltaic?

The **photovoltaic** (PV) is a method of generating electrical power by converting solar radiation into direct current electricity through some materials (such as semiconductors) that exhibit the photovoltaic effect. Photovoltaic (PV) systems generate electricity directly from solar irradiation. These systems are made-up of arrays. Arrays are composed from modules and modules are formed by cells. Basically, the principle of a cell, which is the fundamental block of a PV system, is connected to the semiconductors. The hierarchy is illustrated in Fig. 7.1.

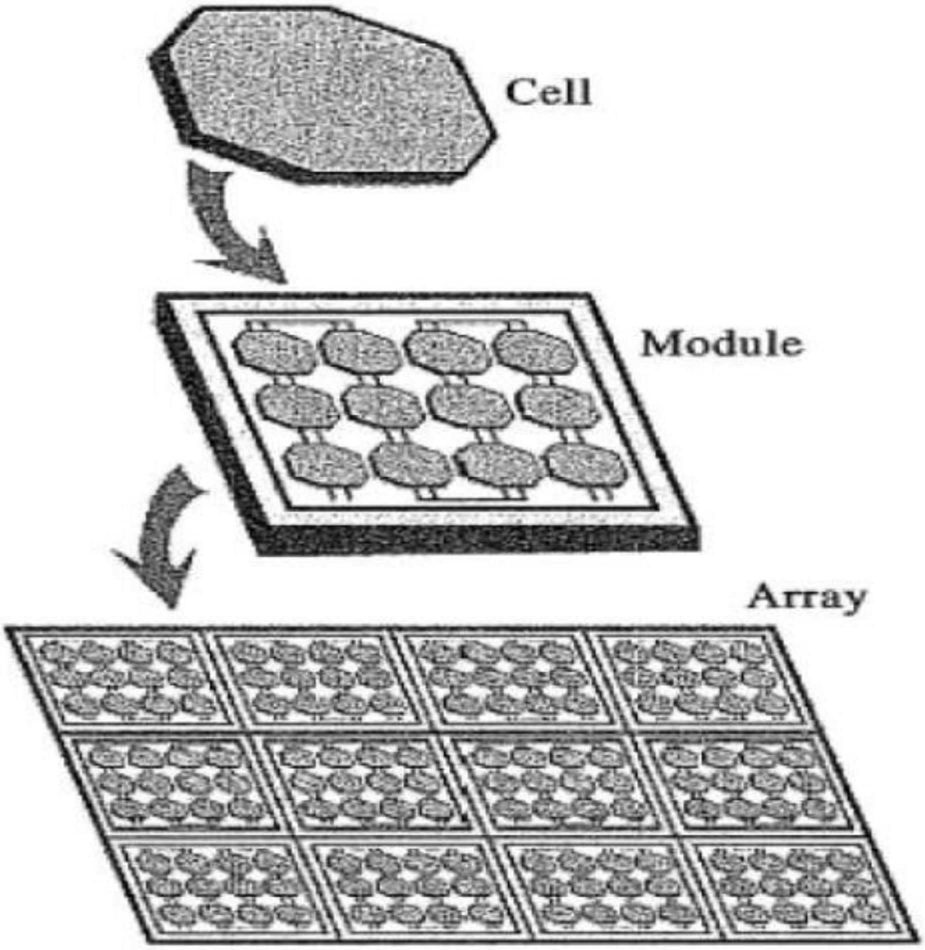


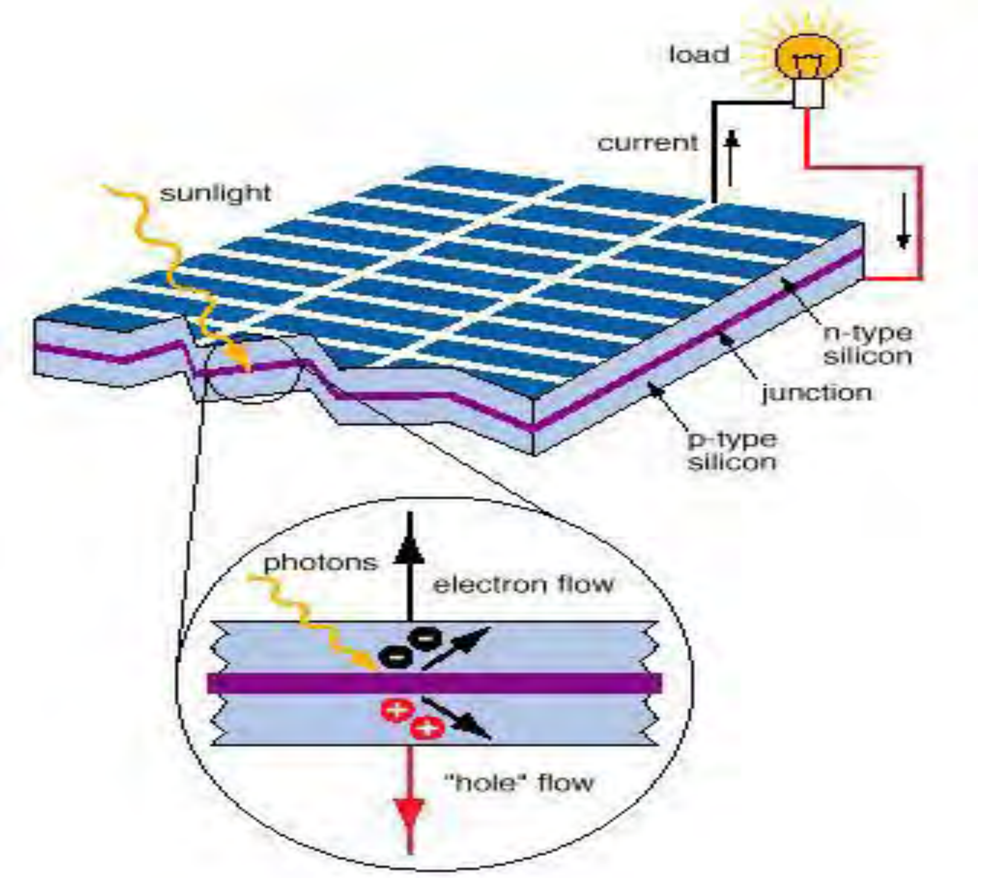
Fig. 7.1 Components of a photovoltaic system.

Solar Cell

- Sun light of certain wavelengths is able to ionize the atoms in the silicon

- The internal field produced by the junction separates some of the positive charges ("holes") from the negative charges (electrons).

- If a circuit is made; power can be produced from the cells under illumination, since the free electrons have to pass through the junction to recombine with the positive holes.



Fundamentals of PV Cells

As it is known the atoms have equal numbers of protons and electrons and this number is the atomic number appearing in the Periodic Table. Silicon for example, which is the most common material, used in electronic, micromechanical systems and PV systems has 14 electrons. The electrons are positioned in the orbits around the nucleus of the atom and the number of electrons located at the outermost orbit determines the characteristics of that material. The outermost band is called "valence band". The conductivity of a material depends on the difference in energy between an electron in the valence band and the one in the conduction band (Fig. 7.2).

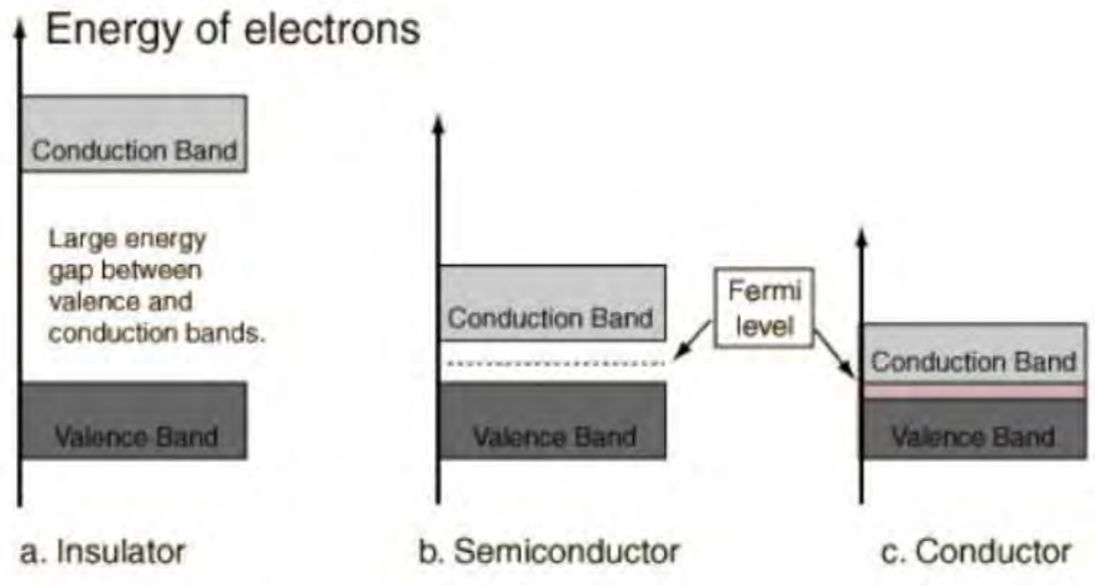
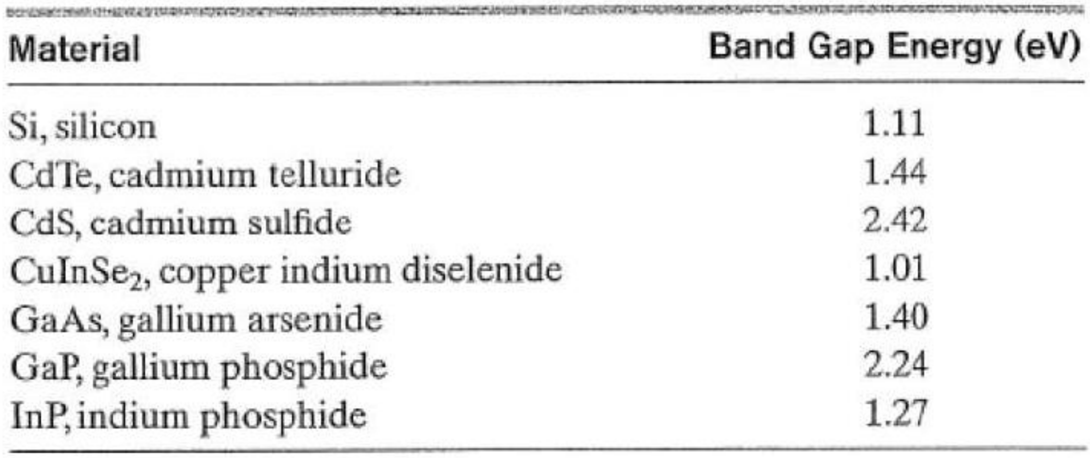


Fig. 7.2 Band energy and conductivity.

This difference is called "band energy". For the insulators this energy is greater than 3 eV. One electron volt (eV) is equal to 1.6×10^{-19} J. The conductors have relatively empty valence bands while the semiconductors have band energies less than 3 eV (Table 7.1).

Table 7.1 Band gap energies for some PV materials



Material	Band Gap Energy (eV)
Si, silicon	1.11
CdTe, cadmium telluride	1.44
CdS, cadmium sulfide	2.42
$CuInSe_2$, copper indium diselenide	1.01
GaAs, gallium arsenide	1.40
GaP, gallium phosphide	2.24
InP, indium phosphide	1.27

Silicon, Si is an intrinsically semiconductor. To accelerate the electron dislodge, this material is doped by several materials, like boron, antimony (stibium) and phosphide. Among these materials boron (B) and stibium (Sb) have 3 and 5 electrons, respectively, in their valence bands. Thus, 1 electron in doping with Sb and 1 hole in doping with boron will be generated (Fig. 7.3).

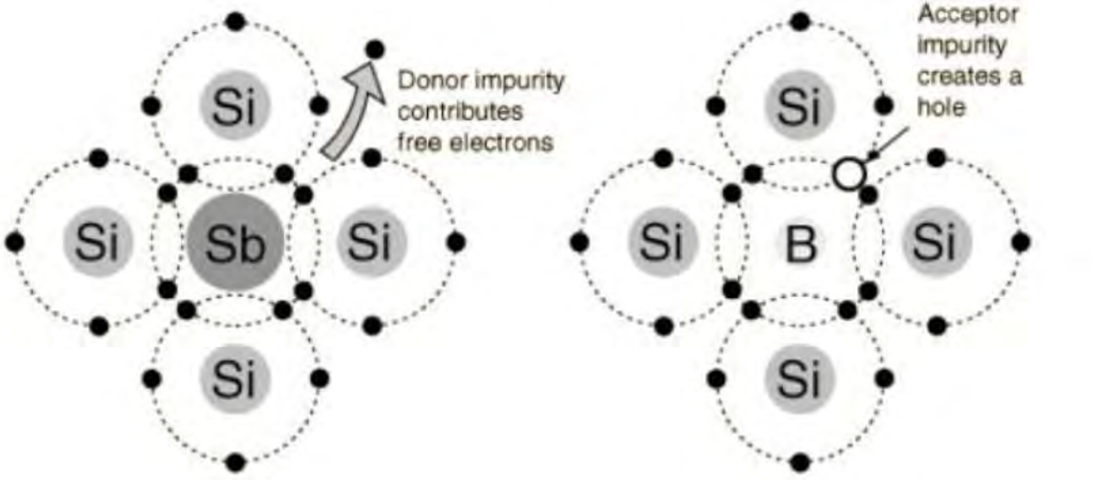


Fig. 7.3 Doping silicon for extrinsic semi conductivity.

In general, if the number of electrons in the valence band of the dopant is greater than that of the base material free electrons will be contributed. This is a n-type semi-conductor. On the other hand, if the number of electrons in the valence band of the dopant is less than that of the base material holes will be contributed which results in a p-type semi-conductor. In a junction of such p and n type semi-conductors the electron flows will be enhanced.

In Fig. 7.4, such a junction exposed to light is shown. If the photon energy is sufficient to dislodge the valence band electron, the electron will jump to the conduction band and the current flow will be initiated.

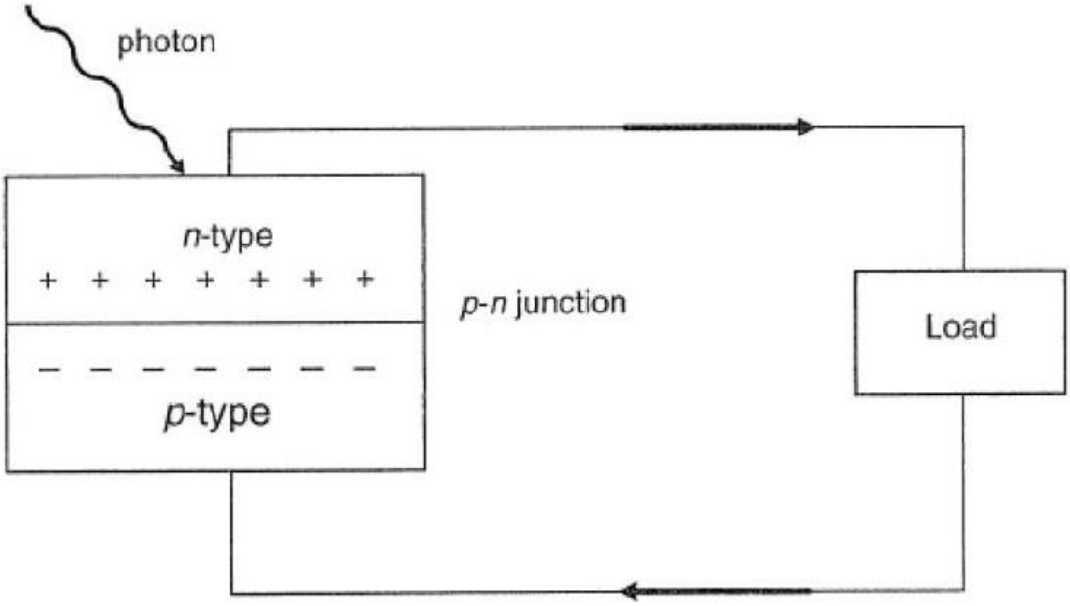


Fig. 7.4 Schematic of a PV cell.

To force the valence electron to jump the photon energy should be greater than the band energy.

The energy of the photon is: $E=h\nu$

Where h is Planck's constant, ν is the frequency, $\nu=c/\lambda$

$h= 6.625 \times 10^{-34}$ J sec.

$c=3 \times 10^{8}$ m/sec (speed of light) and λ is the wavelength of the photon. Thus the wavelength of the light to produce electricity can be determined.

Example 7.1

Determine the wavelength of light that corresponds to the band gap energy of silicon, 1.11 eV.

$$\lambda = \frac{hc}{E}$$

$$= 6.625\cdot10^{-34}\cdot\text{J sec}\ \cdot3\cdot10^{8}\cdot\frac{\text{m}}{\text{sec}}\cdot\frac{1}{1.11\ \text{eV}}\cdot\frac{\text{eV}}{1.6\cdot10^{-19}\ \text{J}}$$

$$= 1.1183\cdot10^{-6}\ \text{m} = 1.12\ \mu\text{m}$$

Hence, light with a wavelength of 1.12 μm has sufficient energy to dislodge a valence electron in silicon.

Photons with a wavelength greater than 1.12 μm contain insufficient energy to dislodge a valence electron and will induce no photovoltas effect on the silicon. If the wave length is less than 1.12 μm there is such an effect. However, a single photon can dislodge only a single electron and the difference between the band gap energy and the photon energy is absorbed as heat by the PV cell (Fig. 7.5).

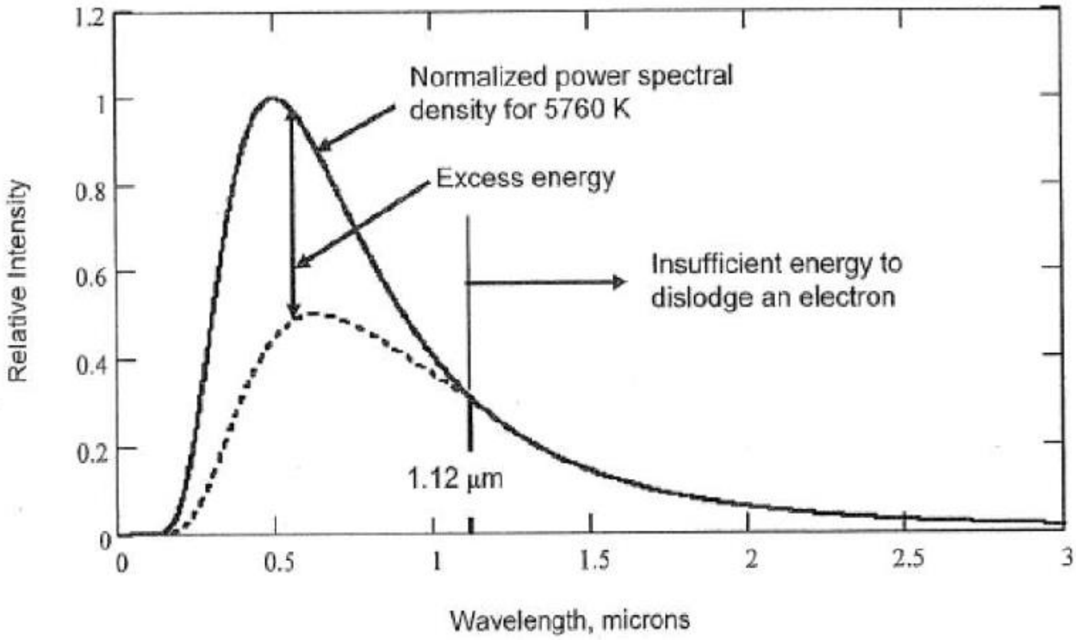


Fig. 7.5 Solar irradiation and band gap energy

If E is the photon energy and E1.12 is the energy required for the excitement of the valence electron, E/E1.12 =λ/λ1.12, excess energy is : E –E1.12=E[1-λ/λ1.12]

Excess energy, i.e. energy above the band gap equivalent, is passed on to the crystal in the form of heat. That is why the theoretical efficiency of a cell depends on the band gap (Fig. 7.6).

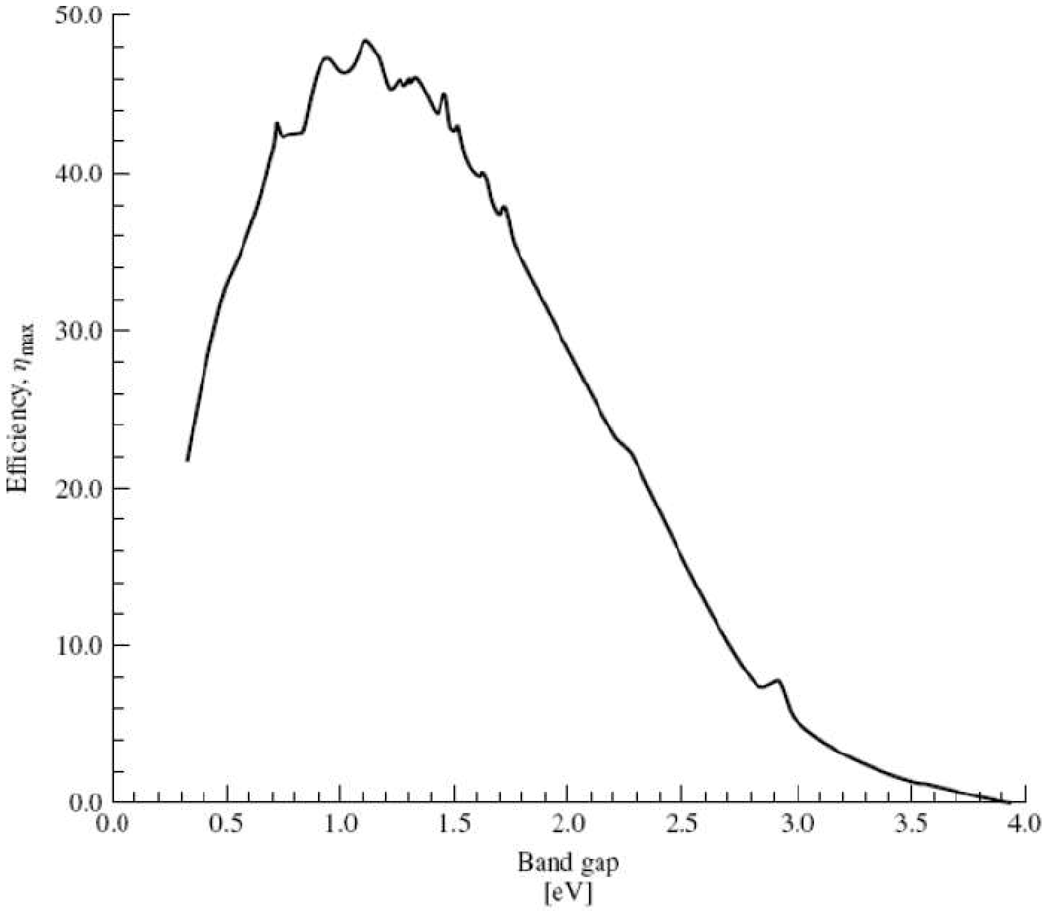


Fig. 7.6 Efficiency vs. band gap energy.

Lecture Four

Biomass Conversion Processes

Transformation of waste materials into energy can generally be accomplished through
i-) biological, ii-) thermal, and iii-) chemical processes.

5.1 Energy Recovery by Anaerobic Digestion

The anaerobic digestion process, carried out in the absence of oxygen, involves the use of microorganisms for the conversion of biodegradable biomass material into energy, in the form of methane gas and a stable humus material. Anaerobic digestion can occur under control conditions in specially designed vessels (reactors), semi-control conditions such as in a landfill, or under uncontrolled conditions as it does in the environment.

5.1.1 Organic Wastes and Biomass Used as Feedstocks in Anaerobic Digestion Process

The general scheme for a controlled anaerobic digestion process is shown in Fig. 5.1.

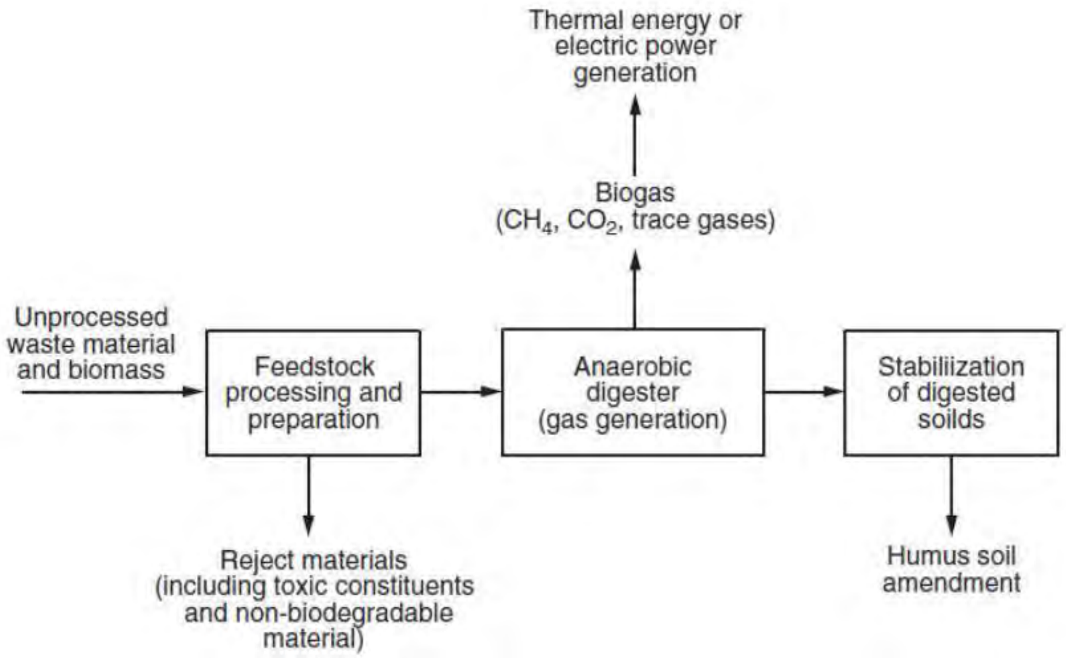


Fig. 5.1 General flow diagram of bioenergy recovery system.

The recovery of energy involves

1. Feedstock preparation,
2. Methane gas generation,
3. Stabilization of digested solids, and
4. The utilization of digester gas and humus as a source of energy and soil amendment, respectively.

Major sources of waste materials considered as a feedstock for anaerobic digestion process are (1) municipal solid waste (MSW), (2) agricultural animal waste, (3) crop residues, biomass, and energy crops, and (4) wastewater treatment plant sludge (WWTPS).

The typical composition of MSW in the U.S. is shown in Fig. 5.2. The corresponding diagram for Turkey is illustrated in Fig.5.3.

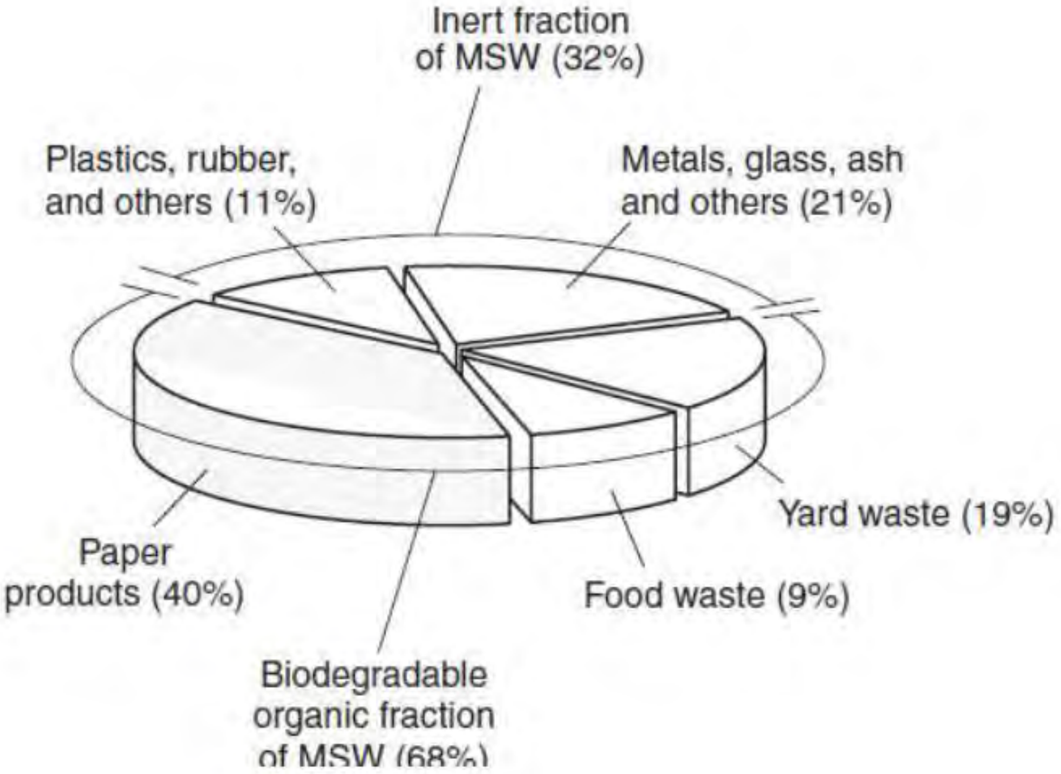


Fig. 5.2 A typical MSW composition in the U.S

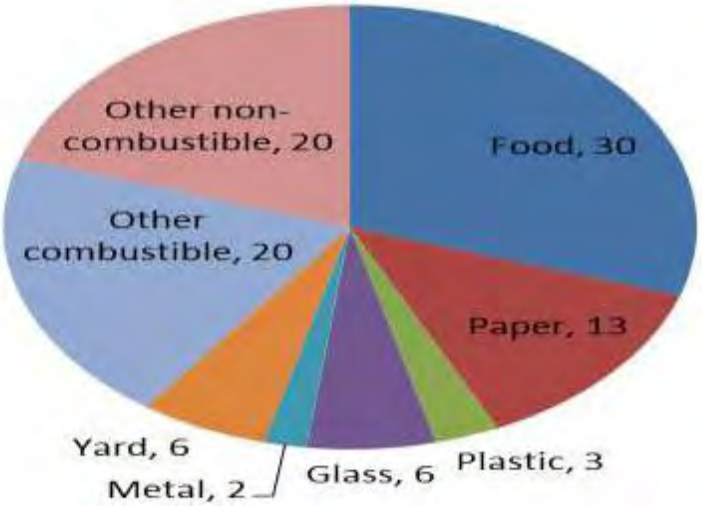
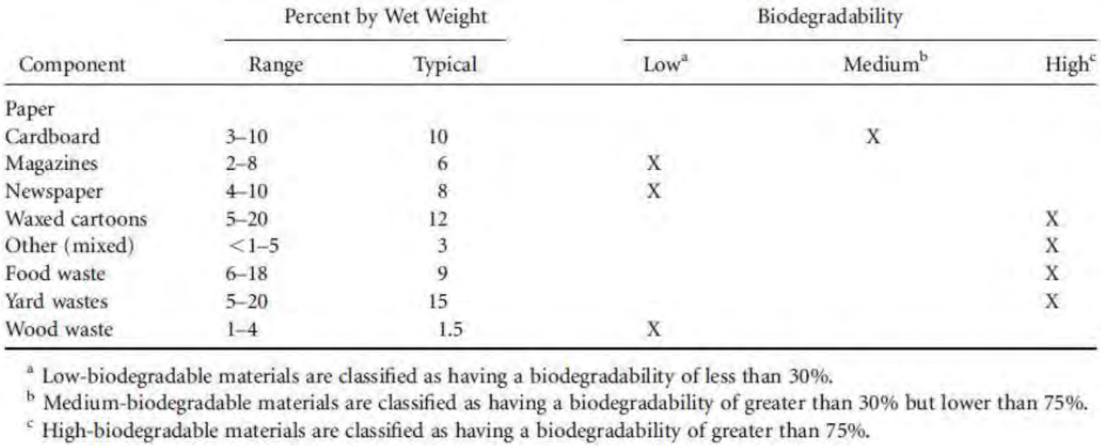


Fig. 5.3 A typical MSW composition in Turkey.

The composition of MSW may vary greatly by season, geographical area, and community socio-economic level (Fig. 5.3 is for Istanbul). The extrapolation of results from one location to another, therefore, may not be valid and should be done with caution. As shown in Fig. 5.2, paper, yard waste, and food waste are the principal biodegradable organic fractions (The corresponding value for Turkey is 49%, excluding other non-combustibles of 20%). The biodegradability of these waste materials varies substantially as reported in Table 5.1.

Table 5.1 Biodegradabality of waste compounds in US



	Percent by Wet Weight		Biodegradability		
Component	Range	Typical	Low[a]	Medium[b]	High[c]
Paper					
Cardboard	3–10	10		X	
Magazines	2–8	6	X		
Newspaper	4–10	8	X		
Waxed cartoons	5–20	12			X
Other (mixed)	<1–5	3			X
Food waste	6–18	9			X
Yard wastes	5–20	15			X
Wood waste	1–4	1.5	X		

[a] Low-biodegradable materials are classified as having a biodegradability of less than 30%.
[b] Medium-biodegradable materials are classified as having a biodegradability of greater than 30% but lower than 75%.
[c] High-biodegradable materials are classified as having a biodegradability of greater than 75%.

Factors such as particle size, time, and environmental conditions (i.e., temperature, nutrient requirements, etc.) will influence the final outcome of biodegradation. Characterization of a typical organic substrate is given in Fig. 5.4.

The fraction of ash typically depends on the nature of the organic substrate. Volatile solids (VS) is measured as loss on ignition. Only the biodegradable volatile solids (BVS) fraction of the VS has the potential for bioconversion largely, because of the presence of refractory volatile solids (RVS) which, in most digester feedstocks, is mostly lignin. Lignin is a complex organic material which is difficult for anaerobic bacteria to degrade and normally requires a long period of time for complete degradation. It is clear from Fig. 5.4 that organic substrates with high RVS and ash contents have a low biodegradability.

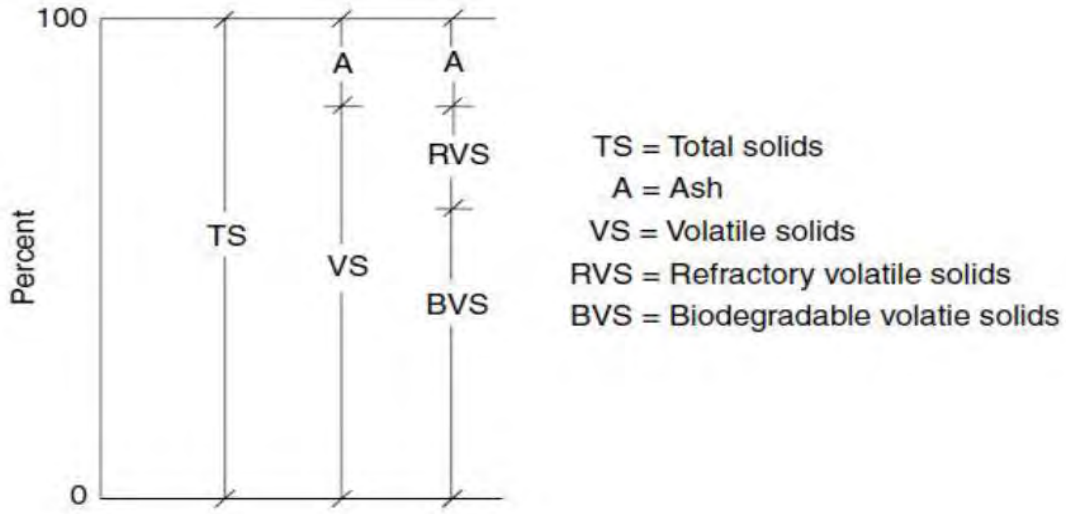


Fig. 5.4 Characterization of a typical organic substrate.

The most common method to estimate biodegradability is the measurement of lignin content. It is an analytical method commonly used for determining the BVS fraction of an organic substrate and is based on the measurement of the crude lignin content of the VS.

The following empirical relationship was developed to estimate the biodegradable fraction of an organic substrate from lignin test results:

Biodegradable fraction (BOF) = $0.83 – 0.028 \times LC$ (5.1)

Where; LC is the lignin content, as a percentage of the VS.

Example 5.1 Estimate the total BVS weight (mass) of a 100 tn./d MSW material recovery facility.

Use the following information:

1. Assume that the composition of a typical MSW waste stream given in Fig. 5.2 is valid:
2. Typical characteristics of MSW sub-fractions:

Waste Material	Total Solids, %	Volatile Solids, %TS	Lignin Content
Yard Waste	40	88	6.43
Food Waste	30	90	0.36
Paper	94	98	9.29

Solution:

According to Fig. 5.2

	Weight, lb/d	
Waste Material	Wet Weight	Dry Weight
Yard waste	38,000	15,200
Food waste	18,000	5400
Paper	80,000	75,200
Metal	42,000	42,000
Plastic	22,000	22,000

Dry weight has been calculated from TS percentage.

Again from Fig. 5.2:

$$\text{BOF/MSW per day} = (0.68)(100 \text{ tn. MSW/d}) = 68 \text{ tn.}$$

$$\text{VS weight} = \text{dry weight} \times \text{VS\%}$$

$$\text{BVS weight} = \text{VS weight} \times \text{BF}$$

Where; BF has been calculated from Eq. (5.1).

Biodegradable Waste	Dry wt, lb/d	VS, % TS	VS wt, lb/d	BF, % VS	BVS wt, lb/d
Yard Waste	15,200	88	13,376	0.65	8694
Food waste	5400	90	4860	0.82	3985
Paper (mixed)	75,200	98	73,696	0.57	42,005
Total	95,800		91,932		54,684

Lecture Five

Fundamentals of Anaerobic Digestion

The general anaerobic transformation of the biodegradable organic fraction of MSW can be described by the following equation:

$$\text{Organic matter} + H_2O + \text{nutrients} \rightarrow \text{new cells} + \text{resistant organic matter} + CO_2 + CH_4 + NH_3 + H_2S + \text{heat} \tag{5.2}$$

(For a proper bacterial metabolism, a variety of nutrients must be present in the substrate.)

For practical purposes, the overall conversion of the organic fraction of solid waste to methane, carbon dioxide, and ammonia can be represented by the following equation:

$$C_aH_bO_cN_d \rightarrow nC_wH_xO_yN_z + mCH_4 + sCO_2 + rH_2O + (d-nx)NH_3 \tag{5.3}$$

Where s=a-nw-m; r=c-ny-2s

The terms $C_aH_bO_cN_d$ and $C_wH_xO_yN_z$ are used to represent (on a molar basis) the composition of the organic material present at the start and the end of the process, respectively. If it is assumed that the organic wastes are stabilized completely, then the corresponding expression is

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3 \tag{5.4}$$

Example 5.2 Estimate the total theoretical amount of gas that could be produced from MSW under anaerobic conditions. Assume that 78% by weight of the MSW is organic material, including moisture. Further assume that the moisture content is 20%, the VS are 83.5% of the total organic solids, the BVS are 75% of the VS, and only 90% of the biodegradable VS will be converted to biogas. The overall chemical formula for the biodegradable organic material is $C_{60}H_{95}O_{38}N$.

Solution:

$$\mathrm{BVS} = 78 \times (1-0.2) \times 0.835 \times 0.75 = 39.1\ \mathrm{lb}$$

$$\mathrm{BVS_{gas}} = 39.1 \times 0.9 = 35.2$$

From Eqn.(5.4) with the given formula:

$a=60 \quad b=95 \quad c=38 \quad d=1$

$$\underset{(1437)}{C_{60}H_{94.3}O_{37.8}N} + \underset{(324)}{18.28H_2O} \rightarrow \underset{(512)}{31.96CH_4} + \underset{(1232)}{28CO_2} + \underset{(17)}{HN_3}$$

$$\text{Methane} = \frac{512}{1437}(35.2\ \mathrm{lb}) = 12.5\ \mathrm{lb}(5.7\ \mathrm{kg})$$

$$\text{Carbondioxide} = \frac{1232}{1437}(35.2\ \mathrm{lb}) = 30.2\ \mathrm{lb}(13.7\ \mathrm{kg})$$

Assuming the densities of methane and carbon dioxide, 0.0448 and 0.1235 lb/ft3 respectively;

$$\text{Methane} = \frac{12.5\ \mathrm{lb}}{0.0448\ \mathrm{lb/ft.^3}} = 279\ \mathrm{ft.^3}(7.9\ \mathrm{m^3})$$

$$\text{Carbondioxide} = \frac{30.2\ \mathrm{lb}}{0.1235\ \mathrm{lb/ft.^3}} = 244\ \mathrm{ft.^3}(6.9\ \mathrm{m^3})$$

$$\text{Methane}(\%) = [279/(279+244)] \times 100 = 53.35\%$$

$$\text{Carbondioxide}(\%) = 100 - 53.35\% = 46.65\%$$

$$((279+244)/39.1) = 13.4\ \mathrm{ft.^3/lb\ BVS}(1.48\ \mathrm{m^3/kg\ BVS})$$

$$\text{Biogas/ton of MSW} = 13.4\ \mathrm{ft.^3/lb} \times 2000 \times 0.78 \times 0.8 \times 0.835 \times 0.75 = 10.470$$

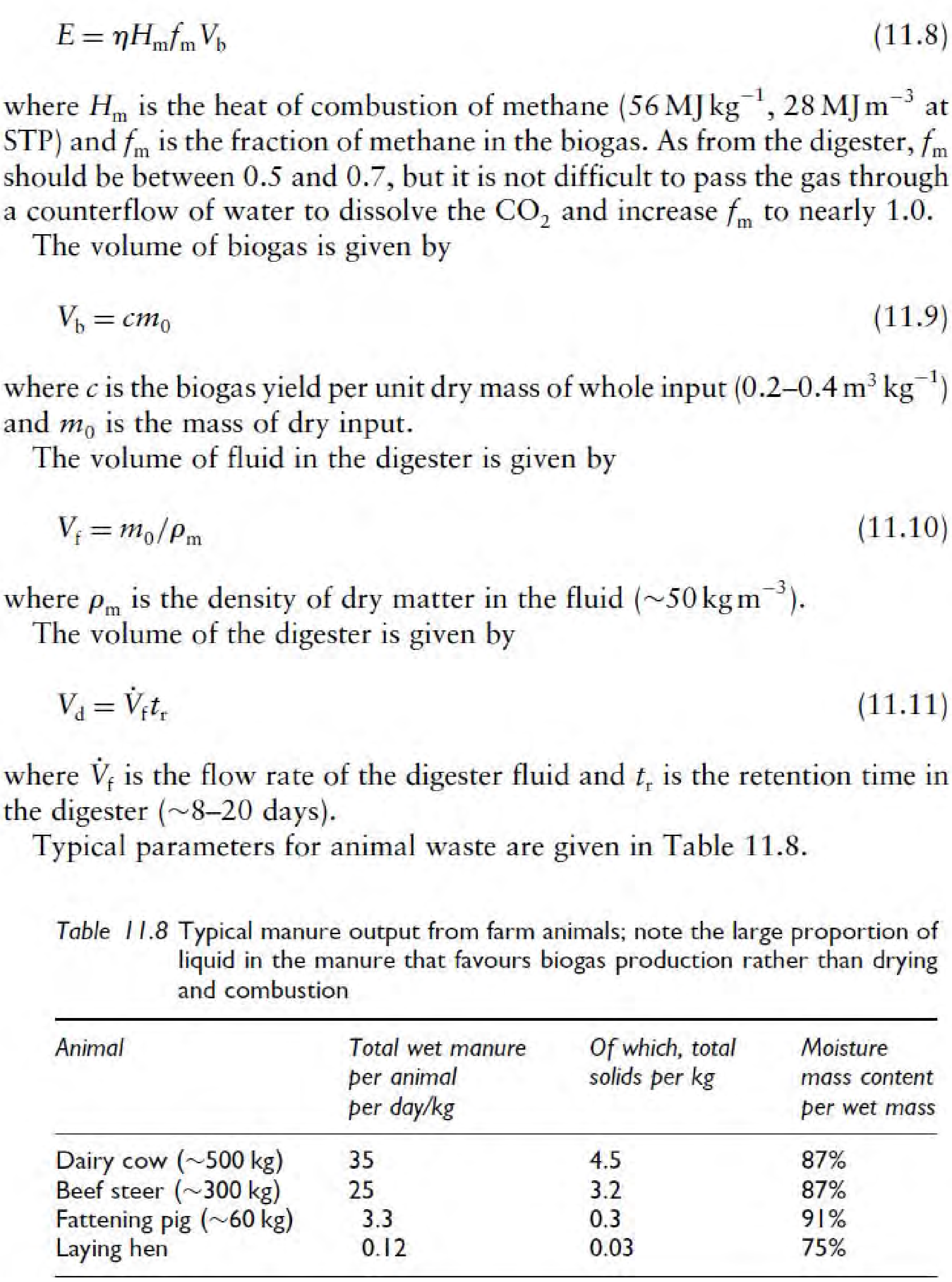
Digester sizing

The energy available from a biogas digester is given by:

$$E = \eta H_b V_b$$

Where _ is the combustion efficiency of burners, boilers, etc. (~60%). H_b is the heat of combustion per unit volume biogas (20MJm−3 at 10 cm water gauge pressure, 0.01 atmospheres) and V_b is the volume of biogas. Note that some of the heat of combustion of the methane goes to heating the CO2 present in the biogas, and is therefore unavailable for other purposes. The net effect is to decrease the efficiency.

Alternatively:



$$E = \eta H_m f_m V_b \tag{11.8}$$

where H_m is the heat of combustion of methane ($56\,\mathrm{MJ\,kg^{-1}}$, $28\,\mathrm{MJ\,m^{-3}}$ at STP) and f_m is the fraction of methane in the biogas. As from the digester, f_m should be between 0.5 and 0.7, but it is not difficult to pass the gas through a counterflow of water to dissolve the CO_2 and increase f_m to nearly 1.0.

The volume of biogas is given by

$$V_b = c m_0 \tag{11.9}$$

where c is the biogas yield per unit dry mass of whole input (0.2–$0.4\,\mathrm{m^3\,kg^{-1}}$) and m_0 is the mass of dry input.

The volume of fluid in the digester is given by

$$V_f = m_0/\rho_m \tag{11.10}$$

where ρ_m is the density of dry matter in the fluid ($\sim 50\,\mathrm{kg\,m^{-3}}$).

The volume of the digester is given by

$$V_d = \dot{V}_f t_r \tag{11.11}$$

where $\dot{V}_f$ is the flow rate of the digester fluid and t_r is the retention time in the digester (~8–20 days).

Typical parameters for animal waste are given in Table 11.8.

Table 11.8 Typical manure output from farm animals; note the large proportion of liquid in the manure that favours biogas production rather than drying and combustion

Animal	*Total wet manure per animal per day/kg*	*Of which, total solids per kg*	*Moisture mass content per wet mass*
Dairy cow (~500 kg)	35	4.5	87%
Beef steer (~300 kg)	25	3.2	87%
Fattening pig (~60 kg)	3.3	0.3	91%
Laying hen	0.12	0.03	75%

Example 11.1

Calculate (1) the volume of a biogas digester suitable for the output of 6000 pigs, (2) the power available from the digester, assuming a retention time of 20 days and a burner efficiency of 0.6.

Solution

Mass of solids in waste is approximately

$$m_0 = (0.3\,\text{kg}\,\text{d}^{-1})(6000) = 1800\,\text{kg}\,\text{d}^{-1} \tag{11.12}$$

From (11.10), fluid volume is

$$\dot{V}_f = \frac{(1800\,\text{kg}\,\text{d}^{-1})}{(50\,\text{kg}\,\text{m}^{-3})} = 36\,\text{m}^3\,\text{d}^{-1} \tag{11.13}$$

In (11.11), digester volume is

$$V_d = (36\,\text{m}^3\,\text{d}^{-1})(20\,\text{d}) = 720\,\text{m}^3 \tag{11.14}$$

From (11.9), volume of biogas is

$$V_b = (0.24\,\text{m}^3\,\text{kg}^{-1})(1800\,\text{kg}\,\text{d}^{-1}) = 430\,\text{m}^3\,\text{d}^{-1} \tag{11.15}$$

So, from (11.7), energy output is

$$\begin{aligned} E &= (0.6)(20\,\text{MJ}\,\text{m}^{-3})(430\,\text{m}^3\,\text{d}^{-1}) \\ &= 5200\,\text{MJ}\,\text{d}^{-1} = 1400\,\text{kWh}\,\text{d}^{-1} \qquad (11.16) \\ &= 60\,\text{kW}(\text{continuous, thermal}) \end{aligned}$$

If continuously converted to electricity, this would yield about 15 kW_e of electricity from a biogas-fired generator set at 25% overall efficiency.

Lecture Six

Reactor Types of Anaerobic Deregister

Batch Reactor

A batch reactor is fed once, and then the biotransformation is allowed to proceed until completion before any material is added or removed. Batch processes are necessary when the biotransformation being performed requires a long reaction time. Solids which are treated undiluted are often treated with batch reactors.

Complete-Mix Continuous Flow Reactor

A reactor to which a waste stream is fed and a treated effluent stream is withdrawn continuously is known as a continuous flow reactor. Most municipal wastewater sludge treatment processes are continuous feed processes, as municipal sludge is produced continually. The average residence time of material in a continuous feed reactor can be determined using the following equation: $t = V/Q$ (5.5)

Where; t is the residence time; V is the reactor volume and Q is the volumetric flow rate.

These reactors can also be described as well-mixed or as continuous stirred-tank reactors (CSTRs).

Anaerobic Contact Reactor

The anaerobic contact process (ACP) is used to overcome the disadvantages of the complete mix reactor without recycle. To enhance the rate of treatment, biomass is separated from the effluent and returned to the reactor. Biomass recycle can be used to reduce the reactor size and cost.

Plug-Flow Reactor

All plug-flow reactors are continuously or semi-continuously fed. In a plug-flow reactor, material passes through, ideally, without interacting with the material fed in before or after it.

The reactor can be either vertical or horizontal flow.

Anaerobic Attached Growth Reactor

Anaerobic attached growth reactors are used to prevent the depletion of the bacterial population within the reactor and, thus, improve digester efficiency.

Reactors with Recycle Flow

Often it is advantageous to recycle and mix effluent from an anaerobic reactor (digestate) with the inflowing waste stream (see Figure 5.5c, d, and e). Recycling is especially advantageous when it is necessary to inoculate the incoming waste with bacteria that have acclimated to the system. Recycling systems, however, add costs, both capital and operational, to a system.

Hence, unless it is necessary, the use of a simpler, unrecycled system is typically favored.

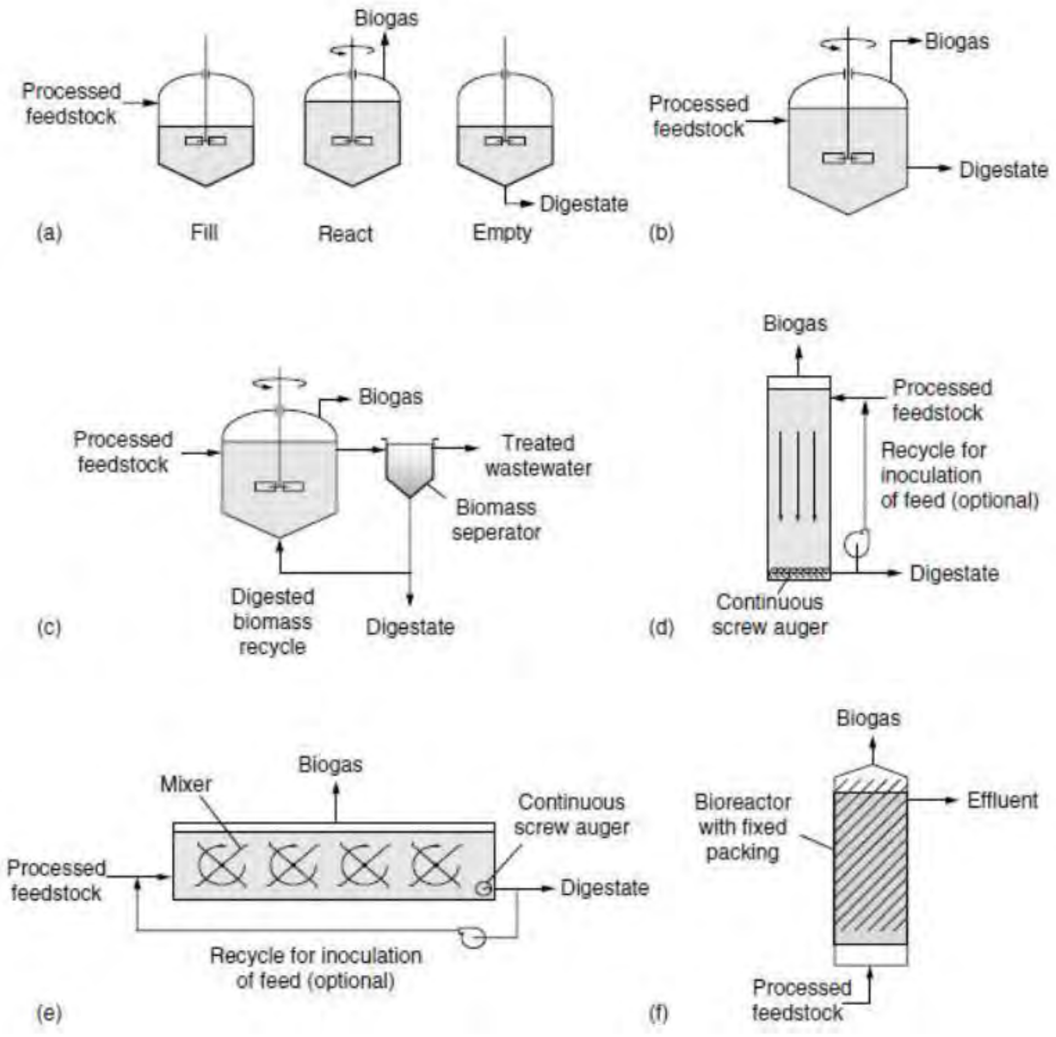


Fig. 5.5 Typical reactor types used for anaerobic digestion: (a) batch reactor, (b) complete-mix continuous flow reactor, (c) anaerobic contact reactor, (d) vertical plug-flow reactor, (e) horizontal plug-flow reactor, and (f) attached growth reactor.

Utilization of By-Products from In-Vessel Anaerobic Digestion Process

The gas produced during anaerobic digestion of biodegradable organic material in a healthy fermentation system, called **biogas**, consists mainly of a mixture of methane (CH_4) and carbon dioxide (CO_2) with small amounts of other gases, including hydrogen sulfide (H_2S), hydrogen (H_2), and nitrogen (N_2), and low molecular weight hydrocarbons.

Typically, digester gas has 50%–75% methane and 25%–50% carbon dioxide; the remaining gases are present in very small quantities. The composition of biogas, as obtained from various sources, is reported in Table 5.2.

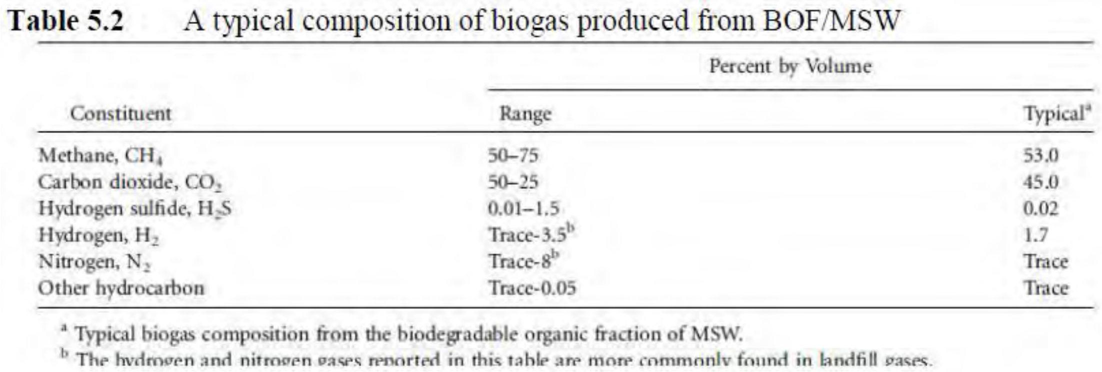


Table 5.2 A typical composition of biogas produced from BOF/MSW

Constituent	Percent by Volume Range	Typical[a]
Methane, CH_4	50–75	53.0
Carbon dioxide, CO_2	50–25	45.0
Hydrogen sulfide, H_2S	0.01–1.5	0.02
Hydrogen, H_2	Trace-3.5[b]	1.7
Nitrogen, N_2	Trace-8[b]	Trace
Other hydrocarbon	Trace-0.05	Trace

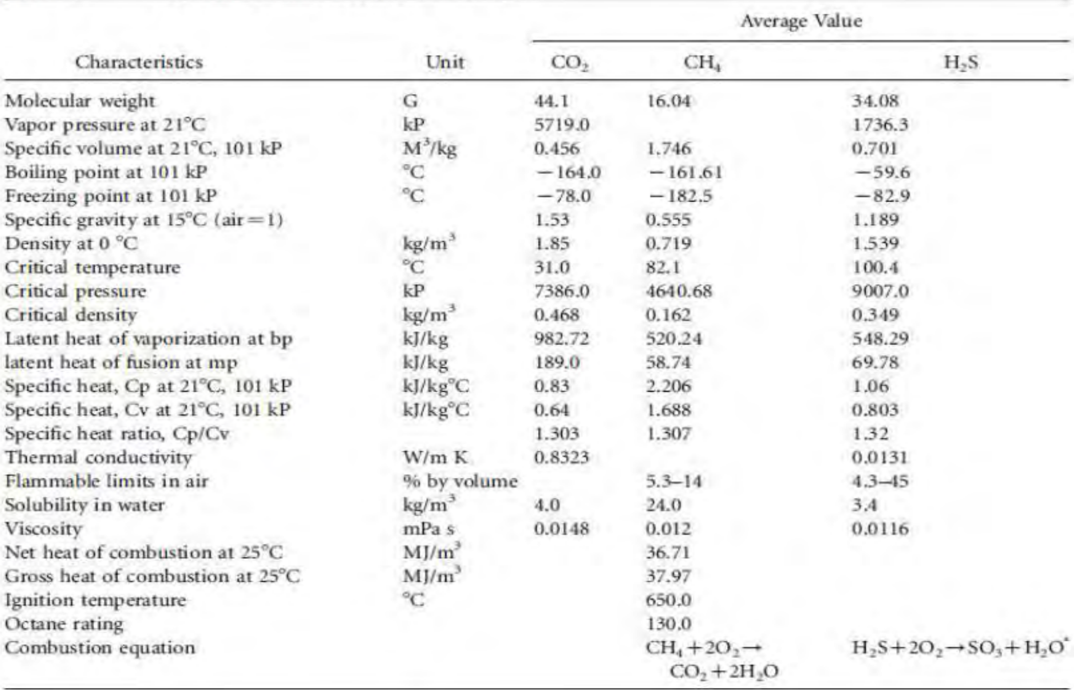
[a] Typical biogas composition from the biodegradable organic fraction of MSW.

[b] The hydrogen and nitrogen gases reported in this table are more commonly found in landfill gases.

Because biogas normally consists of a mixture of gases, biogas characteristics must be evaluated for each individual case. However, in many cases, the physical characteristics of the three main gas constituents, namely methane, carbon dioxide, and hydrogen sulfide, can be used to characterize biogas. Some physical and chemical characteristics of the principal gases found in biogas are presented in Table 5.3.

As a comparison, the weight of methane is roughly half that of air at 200C (weight ratio=1 m^3 of methane/1 m^3 of air=0.716 kg/1.293 kg=0.554). Methane gas is not very soluble in water. Only three units of methane (by volume) can be dissolved in 100 units of water at 200C and 1 atmosphere pressure. Methane is a very stable hydrocarbon compound and upon complete combustion it produces a blue flame and a large amount of heat. The complete combustion of 1 m^3 of methane can release 38 MJ or about 9500 kcal. In comparison, a complete combustion of biogas yields a caloric value of about 20–26 MJ/m3 (depending on the methane content), which represents a low fuel value compared with methane gas alone. In addition, biogas requires a pressure of about 34,450 kPa to liquefy it for storage. Therefore, biogas requires a larger storage volume for a given amount of energy than other fossil fuels.

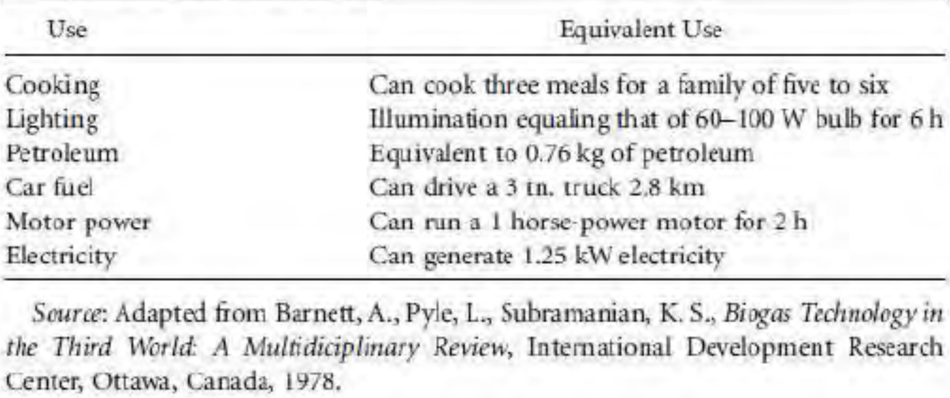
Table 5.3 Physical characteristics of biogas



Characteristics	Unit	Average Value		
		CO_2	CH_4	H_2S
Molecular weight	G	44.1	16.04	34.08
Vapor pressure at 21°C	kP	5719.0		1736.3
Specific volume at 21°C, 101 kP	M^3/kg	0.456	1.746	0.701
Boiling point at 101 kP	°C	−164.0	−161.61	−59.6
Freezing point at 101 kP	°C	−78.0	−182.5	−82.9
Specific gravity at 15°C (air=1)		1.53	0.555	1.189
Density at 0 °C	kg/m^3	1.85	0.719	1.539
Critical temperature	°C	31.0	82.1	100.4
Critical pressure	kP	7386.0	4640.68	9007.0
Critical density	kg/m^3	0.468	0.162	0.349
Latent heat of vaporization at bp	kJ/kg	982.72	520.24	548.29
latent heat of fusion at mp	kJ/kg	189.0	58.74	69.78
Specific heat, Cp at 21°C, 101 kP	kJ/kg°C	0.83	2.206	1.06
Specific heat, Cv at 21°C, 101 kP	kJ/kg°C	0.64	1.688	0.803
Specific heat ratio, Cp/Cv		1.303	1.307	1.32
Thermal conductivity	W/m K	0.8323		0.0131
Flammable limits in air	% by volume		5.3–14	4.3–45
Solubility in water	kg/m^3	4.0	24.0	3.4
Viscosity	mPa s	0.0148	0.012	0.0116
Net heat of combustion at 25°C	MJ/m^3		36.71	
Gross heat of combustion at 25°C	MJ/m^3		37.97	
Ignition temperature	°C		650.0	
Octane rating			130.0	
Combustion equation			$CH_4+2O_2 \rightarrow CO_2+2H_2O$	$H_2S+2O_2 \rightarrow SO_3+H_2O^*$

Table 5.4 lists some examples of the use of 1 m3 of biogas, at 60%–70% methane content, for common energy-consuming purposes.

Table 5.4 Equivalent uses of biogas [21]

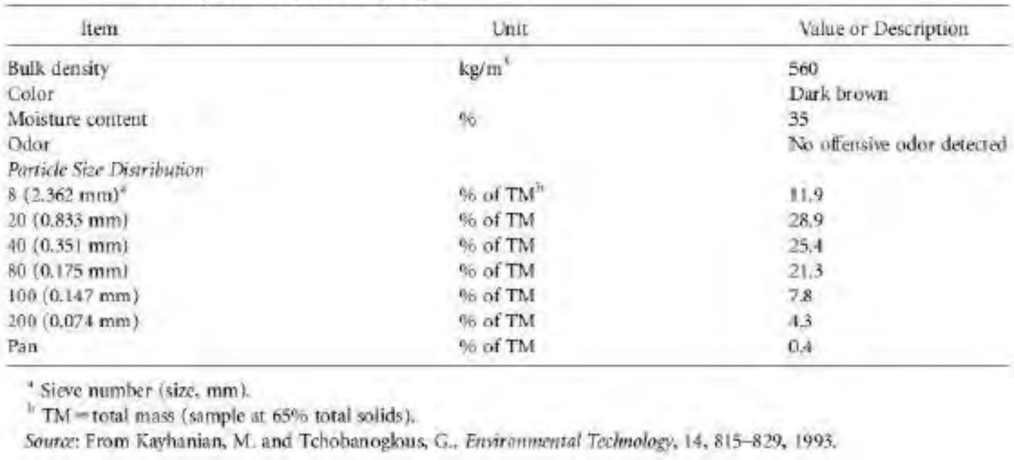


Use	Equivalent Use
Cooking	Can cook three meals for a family of five to six
Lighting	Illumination equaling that of 60–100 W bulb for 6 h
Petroleum	Equivalent to 0.76 kg of petroleum
Car fuel	Can drive a 3 tn. truck 2.8 km
Motor power	Can run a 1 horse-power motor for 2 h
Electricity	Can generate 1.25 kW electricity

Source: Adapted from Barnett, A., Pyle, L., Subramanian, K. S., *Biogas Technology in the Third World: A Multidiciplinary Review*, International Development Research Center, Ottawa, Canada, 1978.

The physical characteristics of the humus produced from an anaerobic composting using the sorted biodegradable organic fraction of MSW are presented in Table 5.5. The most effective use of the humus material is as a soil amendment. Alternatively, because the humus is combustible, it appears that it can be fired directly in a boiler, when mixed with other fuels, or palletized for use as a fuel source.

Table 5.5 Physical characteristics of humus produced from BOF/MSW by the anaerobic composting process [21]



Item	Unit	Value or Description
Bulk density	kg/m^3	560
Color		Dark brown
Moisture content	%	35
Odor		No offensive odor detected
Particle Size Distribution		
8 (2.362 mm)[a]	% of TM[b]	11.9
20 (0.833 mm)	% of TM	28.9
40 (0.351 mm)	% of TM	25.4
80 (0.175 mm)	% of TM	21.3
100 (0.147 mm)	% of TM	7.8
200 (0.074 mm)	% of TM	4.3
Pan	% of TM	0.4

[a] Sieve number (size, mm).

[b] TM = total mass (sample at 65% total solids).

Source: From Kayhanian, M. and Tchobanoglous, G., *Environmental Technology*, 14, 815–829, 1993.

Lecture Seven

Power Generation from Biomass

Although biomass encompasses many kinds of organic matter, fibrous plant material can be characterized as solid, carbonaceous fuel of high volatile content and heating value of about 18 MJ/kg. Either direct combustion or thermal gasification can be used to transform this chemical energy into electric power. Direct combustion releases heat that can be used in Sterling engines or Rankine steam power cycles. Thermal gasification yields flammable gases suitable for firing in internal combustion engines, gas turbines, or fuel cells.

Direct Combustion

Combustion is the rapid oxidation of fuel to obtain energy in the form of heat. Since biomass fuels are primarily composed of carbon, hydrogen, and oxygen, the main oxidation products are carbon dioxide and water although fuel-bound nitrogen can be a source of significant nitrogen oxide emissions. Depending on the heating value and moisture content of the fuel, the amount of air used to burn the fuel, and the construction of the furnace, flame temperatures can exceed 1650 ^{0}C.

Solid fuel combustion consists of four steps, which are illustrated in Fig. 5.9: heating and drying, pyrolysis, flaming combustion, and char combustion. Heating and drying of the fuel particle is normally not accompanied by chemical reaction. Water is driven from the fuel particle as the thermal front advances into the interior of the particle. As long as water remains, the temperature of the particle does not raise high enough to initiate pyrolysis, which is the second step in solid fuel combustion. Pyrolysis is a complicated series of thermally driven chemical reactions that decompose organic compounds in the fuel. Oxidation of the volatile gases above the solid fuel results in flaming combustion. The ultimate products of volatile combustion are CO2 and H2O although a variety of intermediate chemical compounds can exist in the flame, including CO, condensable organic compounds, and long chains of carbon known as soot. Combustion intermediates will be consumed in the flame if sufficient temperature, turbulence, and time are allowed. High combustion temperature assures that chemical reactions will proceed at high rates. The next step in combustion of solid fuels is solid–gas reactions of char, also known as glowing combustion, familiar as red-hot embers in a fire.

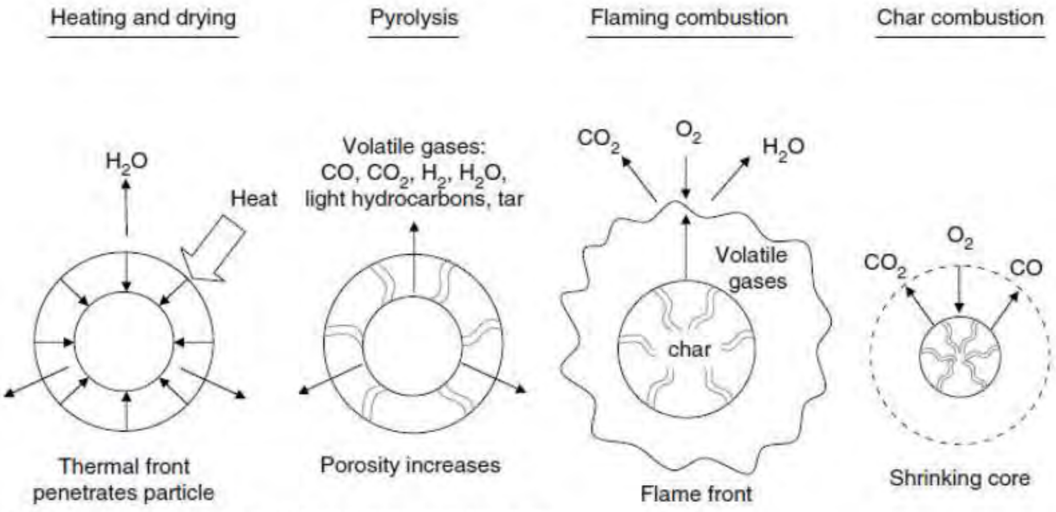


Fig. 5.9 Processes of solid fuel combustion.

Thermal Gasification

Gasification is the high temperature (750 ^{0}C–850^{0}C) conversion of solid, carbonaceous fuels into flammable gas mixtures, sometimes known as producer gas, consisting of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), nitrogen (N_2), carbon dioxide (CO_2), and smaller quantities of higher hydrocarbons. The overall process is endothermic and requires either the simultaneous burning of part of the fuel or the delivery of an external source of heat to drive the process.

The high volatile content of biomass (70–90 wt. %) compared with coal (typically 30–40 wt. %) and the high reactivity of its char make biomass an ideal gasification fuel.

Not only can producer gas be used for generation of heat and power, it can serve as feedstock for production of liquid fuels and chemicals. Because of this flexibility of application, gasification has been proposed as the basis for “energy refineries” that would provide a variety of energy and chemical products, including electricity and transportation fuels.

Solid–gas reactions in gasification convert solid carbon into gaseous CO, H_2, and CH_4:

$$\text{Carbon–oxygen reaction}: \quad C + \frac{1}{2}O_2 \leftrightarrow CO \quad \Delta H_R = -110.5 \text{ MJ/kmol}$$

$$\text{Boudouard reaction}: \quad C + CO_2 \leftrightarrow 2CO \quad \Delta H_R = 172.4 \text{ MJ/kmol}$$

$$\text{Carbon–water reaction}: \quad C + H_2O \leftrightarrow H_2 + CO \quad \Delta H_R = 131.3 \text{ MJ/kmol}$$

$$\text{Hydrogenation reaction}: \quad C + 2H_2 \leftrightarrow CH_4 \quad \Delta H_R = -74.8 \text{ MJ/kmol}$$

The first of these reactions, known as the carbon–oxygen reaction, is strongly exothermic and is important in supplying the energy requirements for drying, pyrolysis, and endothermic solid–gas reactions. The hydrogenation reaction also contributes to the energy requirements of the gasifier, although significantly more char reacts with oxygen than hydrogen in the typical air blown gasifier. The fourth step of gasification is gas-phase reactions, which determine the final mix of gaseous products:

$$\text{Water–gas shift reaction:} \quad CO + H_2O \leftrightarrow H_2 + CO_2 \quad \Delta H_R = -41.1 \text{ MJ/kmol}$$

$$\text{Methanation:} \quad CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H_R = -206.1 \text{ MJ/kmol}$$

Gasifiers are generally classified according to the method of contacting fuel and gas. The four classes of gasifiers are updraft (countercurrent), downdraft (concurrent), fluidized bed, and entrained flow. These are illustrated in Fig. 5.9.

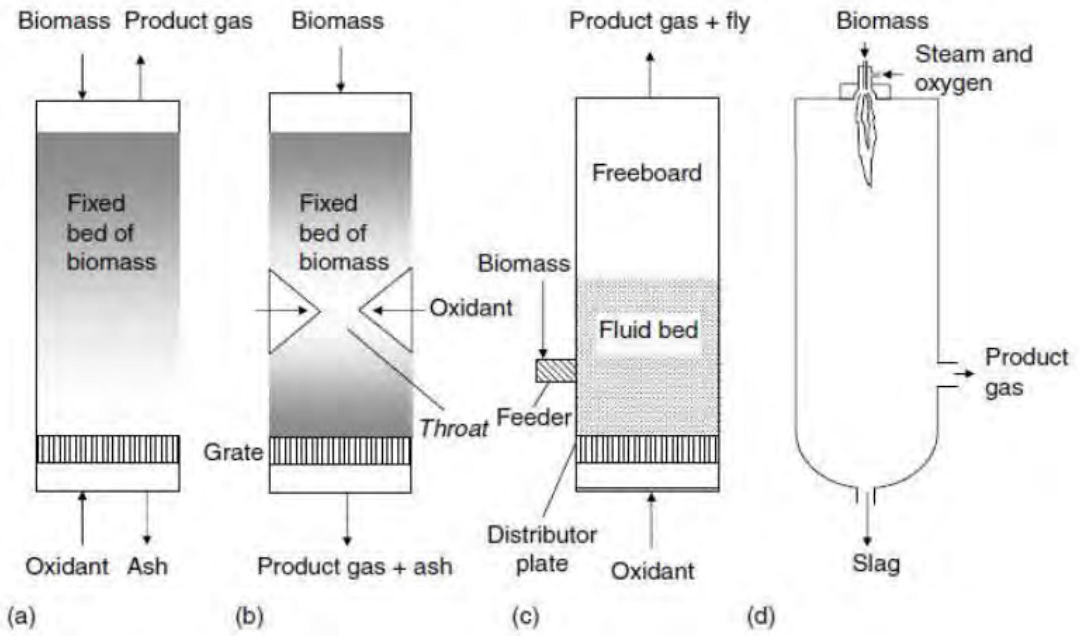


Fig. 5.9 Types of biomass gasifiers: (a) updraft, (b) downdraft, (c) fluidized bed, (d) entrained flow.

Lecture Eight

Hydrogen Production

Generalities

It is important to start out with the clear understanding that, although extremely abundant, hydrogen, unlike fossil fuels, is not a source of energy. Much of the existing hydrogen is in the form of water- hydrogen ash -and considerable energy is required to extract the desired element. Hydrogen is, at best, an excellent vector of energy. It holds great promise as:

1. Fuel for land and sea vehicles especially when used in high efficiency fuel cells.
2. Fuel for large air- and spacecraft owing to its high energy-to-weight ratio when in cryogenic form.
3. Industrial and domestic fuel for generation of heat and electricity.
4. A means for transporting large quantities of energy over long distances.

The advantages of hydrogen include:

1. Low pollution.

Hydrogen burns cleanly producing only water. It is true that, depending on the flame temperature when burned in air, small amounts of nitrogen oxides may also be generated. However, pollution may be associated with some hydrogen production processes.

2. Controllability

At ambient temperatures, hydrogen reacts extremely slowly with oxygen. Catalysts permit adjusting the reaction speed over a large range from very low temperature flames to intense ones.

3. Safety.

The numerous processes for the production of hydrogen include:

1. Chemical.
2. Electrolytic.
3. thermolytic.
4. Photolytic, and
5. Biological.

10.2 Chemical Production of Hydrogen

10.2.2 Modern Production

Hydrogen production can fall into one of several categories among which on can list:

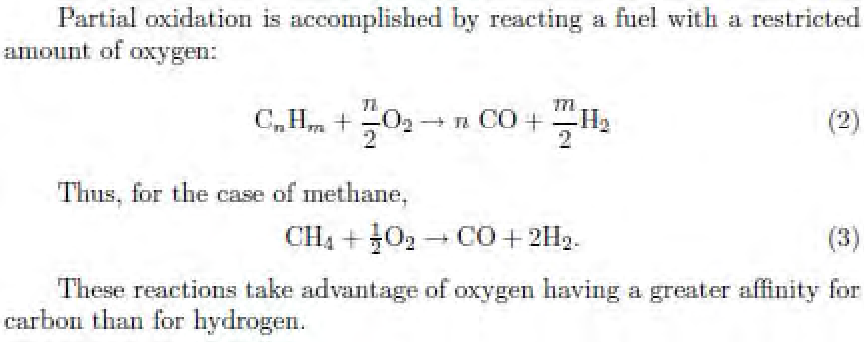
1. Production of hydrogen in modest amounts for food industry and other small consumers. Frequently, electrolytic processes discussed later on are employed because they yield purer gas.

2. Production of hydrogen in massive amounts at stationary plants as for instance in the production of ammonia.

3. Production of hydrogen in small amounts by compact on-board plants for use in fuel cell vehicles. This last application is only now being developed and promises to become of significant economic interest.

4. Production of hydrogen for use in compact residential or local electricity (and hot water) generation.

10.2.2.1 Partial Oxidation



Partial oxidation is accomplished by reacting a fuel with a restricted amount of oxygen:

$$C_nH_m + \frac{n}{2}O_2 \rightarrow n\,CO + \frac{m}{2}H_2 \tag{2}$$

Thus, for the case of methane,

$$CH_4 + \tfrac{1}{2}O_2 \rightarrow CO + 2H_2. \tag{3}$$

These reactions take advantage of oxygen having a greater affinity for carbon than for hydrogen.

10.2.2.2 Steam Reforming

In steam reforming, the fuel reacts with water that adds its hydrogen to that from the fuel and does not introduce any nitrogen into the reformate. This contrasts with the partial oxidation process. Steam reforming of a generalized hydrocarbon proceeds according to:

$$C_nH_m + n\ H_2O \rightarrow n\ CO + \left(\frac{m+2n}{2}\right) H_2 \qquad (4)$$

This reaction is also known as the **carbon-steam** reaction.

As an example consider carbon itself (let $m = 0$ to cancel out the hydrogen in the hydrocarbon). Note that in this case, all the hydrogen comes from the water, and the fuel contributes only energy.

$$C + H_2O \rightarrow CO + H_2 \qquad (5)$$

Consider also methane,

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (6)$$

10.2.2.3 Thermal Decomposition

Thermal decomposition of alcohols can be exemplified by the methanol and ethanol reactions indicated below:

$$CH_3OH \rightarrow CO + 2H_2 \qquad (7)$$

and

$$C_2H_5OH \rightarrow CO + H_2 + CH_4. \qquad (8)$$

All the hydrogen comes from the fuel used.

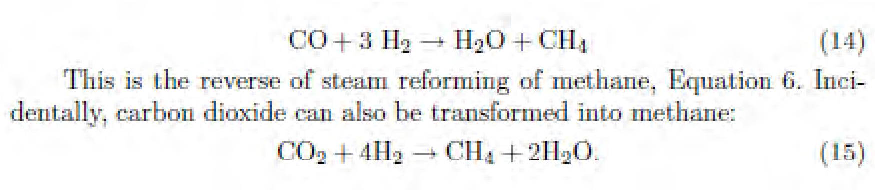
10.2.2.4 Syngas

Syngas, the mixture of CO and H2 that results from all the reactions discussed so far, can be used directly as fuel. It can even be directly used in molten carbonate and ceramic fuel cells, but, owing to the presence of the carbon monoxide, it is totally incompatible with low temperature fuel cells such as SPFCs, solid polymer fuel cells.

An important use of syngas is as a feedstock for the production of an amazing number of chemicals. Many of these have an H/C ratio substantially larger than that of syngas. For this reason, and for its used in low temperature fuel cells, a hydrogen enriching step may be needed. This is known as a shift reaction.

10.2.2.6 Methanation

The transformation of syngas into methane, part of the process of transforming any fossil fuel into the (usually) more valuable \natural gas" is called methanation. Besides being of great industrial importance, methanation is of interest to us in this text because it provides a technique for eliminating most of the CO impurity from the stream of hydrogen produced from carbon bearing fuels. The methanation reaction is



$$CO + 3\,H_2 \rightarrow H_2O + CH_4 \qquad (14)$$

This is the reverse of steam reforming of methane, Equation 6. Incidentally, carbon dioxide can also be transformed into methane:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O. \qquad (15)$$