# What is Biomass?

The material of plants and animals, including their wastes and residues, is called biomass.

Through photosynthesis plants convert sunlight energy into chemical energy.

Biomass is stored sunlight energy that can be converted to:

Electricity
Fuel
Heat
Fertilizer

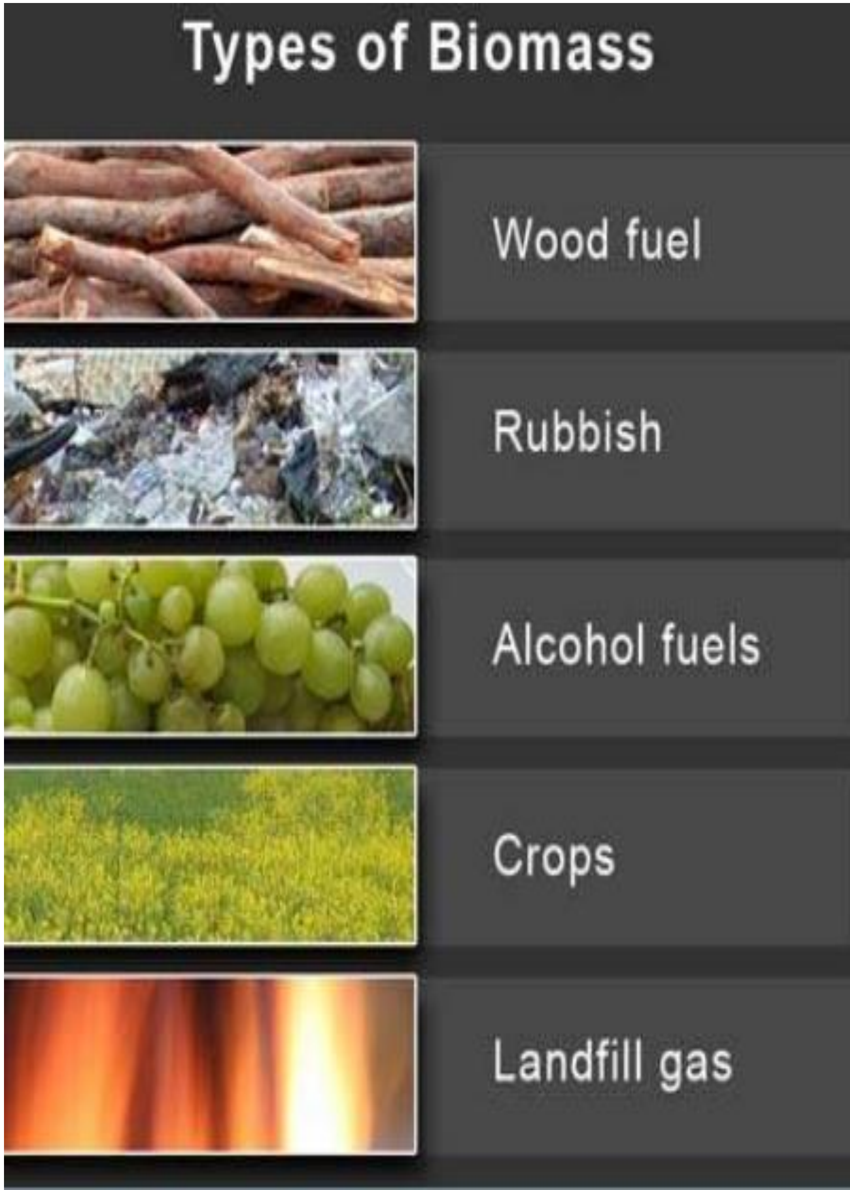
# Biomass Resources

Biomass is available almost **everywhere** in the world

Good biomass energy resources have a high yield of **dry material** and **use minimal land**

Crops should **generate more energy**
than their production consume

Biological power sources are:
Renewable
Easily stored
$CO_2$ neutral (if harvested sustainably)



# BIOMASS - SOME BASIC DATA

- Total mass of living matter (incl. moisture) - 2000 billion tonnes
- Total mass in land plants - 1800 billion tonnes
- Total mass in forests -1600 billion tonnes
- Per capita terrestrial biomass - 400 tonnes
- Energy stored in terrestrial biomass 25 000 EJ
- Net annual production of terrestrial biomass - 400 000 million tonnes
- Rate of energy storage by land biomass - 3000 EJ/y (95 TW)
- Total consumption of all forms of energy - 400 EJ/y (12 TW)
- Biomass energy consumption - 55 EJ/y ( 1. 7 TW)

# Biomass as an Energy Resource: Concept and Market

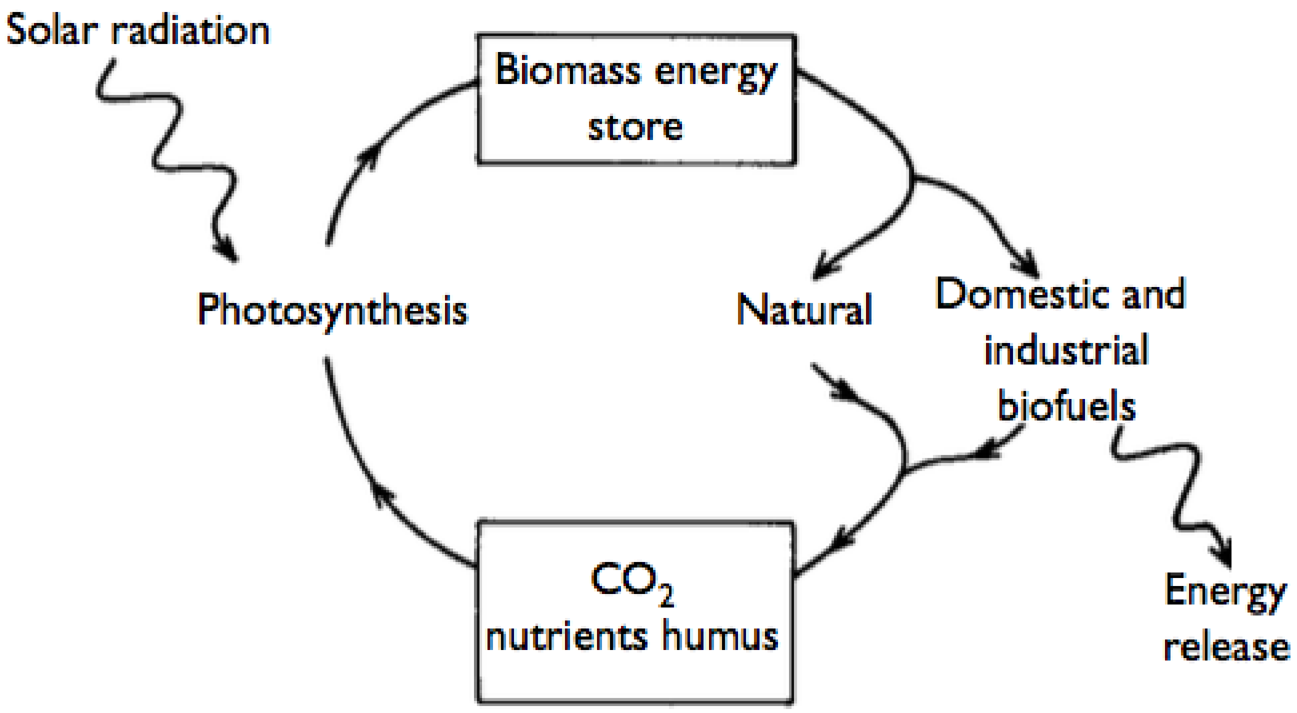
Biomass supplied most of world’s energy as late as the mid 1800s.

It delivered 1,448 Mtoe (Million ton oil equivalent) of primary energy in 2004 alone.

It accounted for 13.1% of the 11,059 Mtoe of world Total Primary Energy Supply (TPES).

Its contribution of 1,150 Mtoe represented 79%
of the total world supply of renewable energy, – followed by hydropower with a 16.8% share

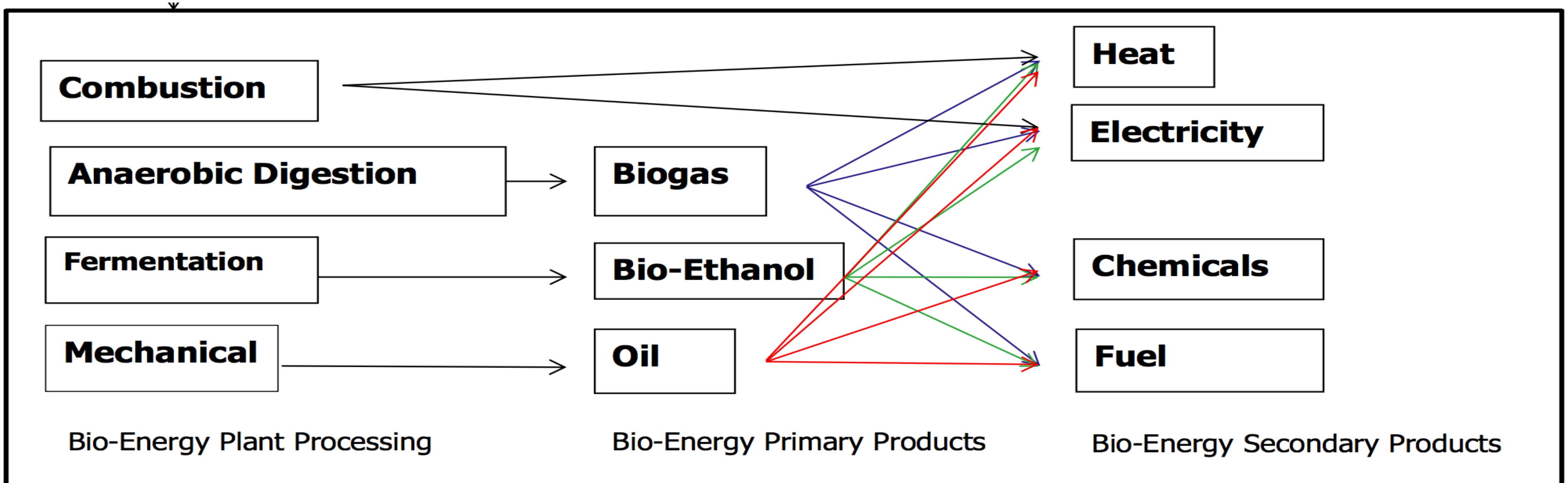
# Natural and managed biomass Systems



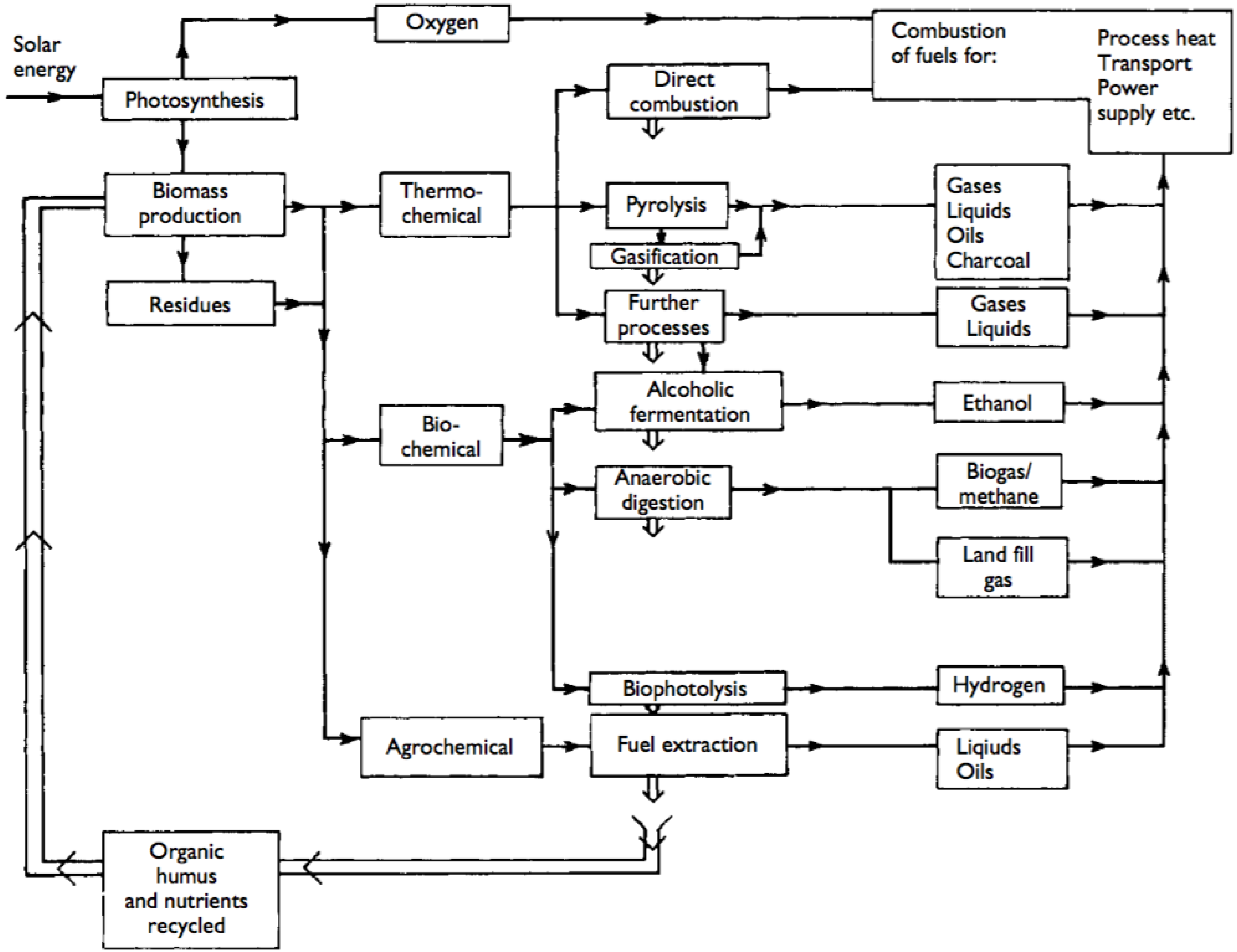
# Biomass Energy

**Biomass**

Harvesting;
Processing



# Biofuel


Solar energy
Oxygen
Photosynthesis
Combustion of fuels for:
Process heat
Transport
Power
supply etc.
Direct combustion
Biomass production
Thermo-chemical
Pyrolysis
Gasification
Gases
Liquids
Oils
Charcoal
Residues
Further processes
Gases
Liquids
Alcoholic fermentation
Ethanol
Bio-chemical
Anaerobic digestion
Biogas/ methane
Land fill gas
Biophotolysis
Hydrogen
Agrochemical
Fuel extraction
Liqiuds
Oils
Organic humus and nutrients recycled

# Biofuel Classification

- **Thermochemical**

Combustion, Pyrolysis, Gasification

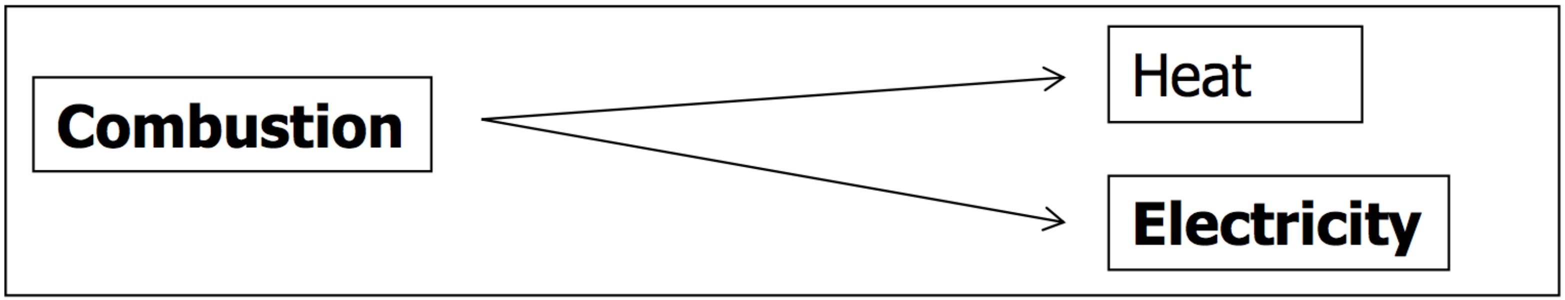
- **Biochemical**

Anaerobic digestion, Aerobic digestion, Alcoholic Fermentation, Biophotolysis

- **Agro chemical**

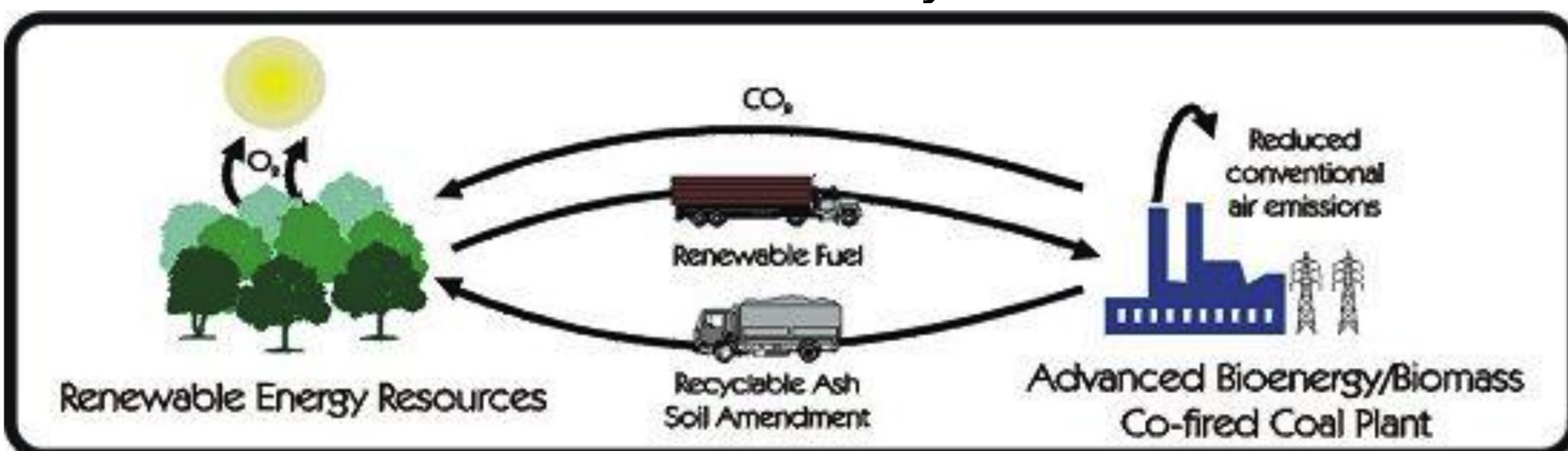
Fuel Extraction, Biodiesel and Esterification

# Thermochemical




**Biomass** can be **burned** in **power plants** to **generate electricity**

In combined Heat and Power systems, the **waste heat energy** is also used to **heat water** or nearby **homes**.



# Thermochemical

## **Combustion: Heating & Cooking**

**Combustion** → **Heat**

**Combustion** → Electricity

**Wood can be burned to –**

- **Heat** a house
- **Prepare food**

# Biochemical

**Aerobic digestion.** In the presence of air, microbial aerobic metabolism of biomass generates heat with the emission of $CO_2$, but not methane.

**Anaerobic digestion**. In the absence of free oxygen, certain micro- organisms can obtain their own energy supply by reacting with carbon compounds to produce both $CO_2$ and fully reduced carbon as $CH_4$. The process (the oldest biological ‘decay’ mechanism) may also be called ‘fermentation’, but is usually called ‘digestion’ because of the similar process that occurs in the digestive tracts of ruminant animals.

# Biochemical

**Alcoholic fermentation.** Ethanol is a volatile liquid fuel that may be used in place of refined petroleum. It is manufactured by the action of micro-organisms and is therefore a fermentation process. Conventional fermentation has sugars as feedstock.

**Biophotolysis.** Photolysis is the splitting of water into hydrogen and oxygen by the action of light. Recombination occurs when hydrogen is burnt or exploded as a fuel in air. Certain biological organisms produce, or can be made to produce, hydrogen in biophotolysis.

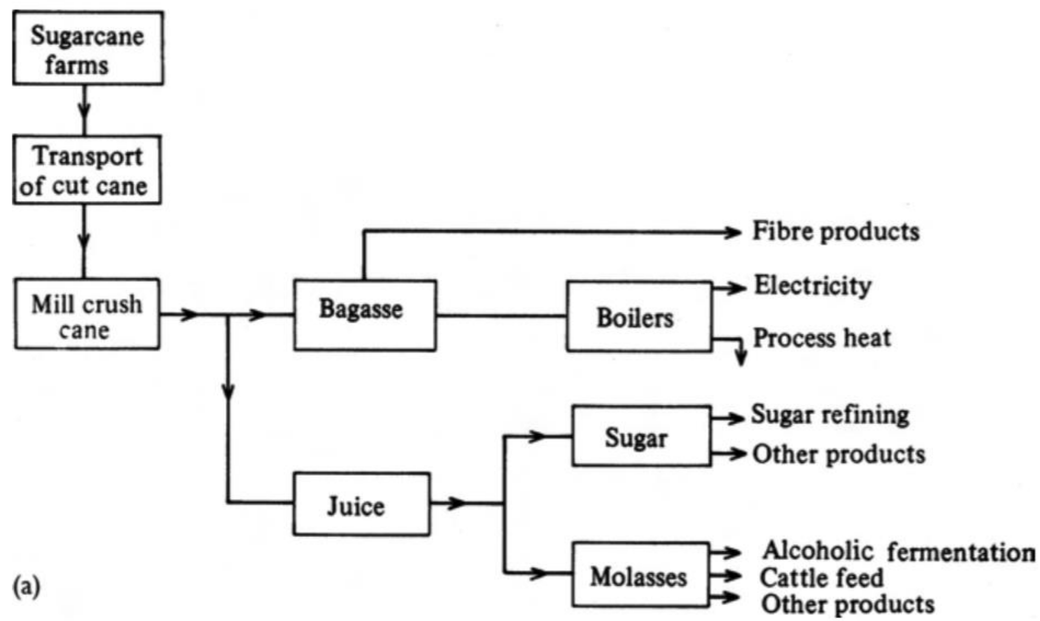
# Agrochemical

**Fuel extraction.** Occasionally, liquid or solid fuels may be obtained directly from living or freshly cut plants. The materials are called exudates and are obtained by cutting into (tapping) the stems or trunks of the living plants or by crushing freshly harvested material. A well- known similar process is the production of natural rubber latex.

**Biodiesel and esterification.** Concentrated vegetable oils from plants may be used directly as fuel in diesel engines; indeed Rudolph Diesel designed his original 1892 engine to run on a variety of fuels, including natural plant oils. However, difficulties arise with direct use of plant oil due to the high viscosity and combustion deposits as compared with standard diesel-fuel mineral oil.

# Energy Farming

Production of fuels or energy as a main or subsidiary product of agriculture (fields), silviculture (forests), aquaculture (fresh and sea water), and also of industrial or social activities that produce organic waste residues, e.g. food processing, urban refuse.



(a)

# Energy Farming

| *Advantages* | *Dangers and difficulties* |
|---|---|
| Large potential supply | May lead to soil infertility and erosion |
| Variety of crops | May compete with food production |
| Variety of uses (including transport fuel and electricity generation) | |
| Efficient use of by-products, residues, wastes | Bulky biomass material handicaps transport to the processing factory |
| Link with established agriculture and forestry | May encourage genetic engineering of uncontrollable organisms |
| Encourages integrated farming practice | |
| Establishes agro-industry that may include full range of technical processes, with the need for skilled and trained personnel | |
| Environmental improvement by utilising wastes | Pollutant emissions from poorly controlled processes |
| Fully integrated and efficient systems need have little water and air pollution (e.g. sulphur content low) | Poorly designed and incompletely integrated systems may pollute water and air |
| Encourages rural development | Large-scale agro-industry may be socially disruptive |
| Diversifies the economy with respect to product, location and employee skill | |
| Greatest potential is in tropical countries, frequently of the Third World | Foreign capital may not be in sympathy with local or national benefit |

# Geographical Distribution

*Table 11.3* Potential bioenergy by region ($EJ\,y^{-1} = 10^{18}\,J\,y^{-1} = 32\,GW$)

| *Region* | *A: Recoverable residues* | | | | *B: Potential Biomass plantations* | *(A + B)/(national energy use)* |
|---|---|---|---|---|---|---|
| | *Crops* | *Forests and woodland* | *Dung* | *Total* | | |
| see note: | [a] | [b] | [c] | | [d] | |
| *Industrialised* | | | | | | |
| US+Canada | 1.7 | 3.8 | 0.4 | 5.9 | 19 | 0.3 |
| Europe | 1.3 | 2 | 0.5 | 3.8 | 6 | 0.1 |
| Aust.+NZ | 0.3 | 0.2 | 0.2 | 0.6 | 10 | 2.8 |
| Former USSR | 0.9 | 2 | 0.4 | 3.3 | 25 | 0.5 |
| *Developing* | | | | | | |
| Latin America | 2.4 | 1.2 | 0.9 | 4.5 | 27 | 1.8 |
| Africa | 0.7 | 1.2 | 0.7 | 2.6 | 28 | 3.3 |
| China | 1.9 | 0.9 | 0.6 | 3.4 | 9 | 0.5 |
| other Asia | 3.2 | 2.2 | 1.4 | 6.8 | 18 | 0.9 |
| *world* | 12.5 | 13.6 | 5.2 | 31.2 | 142 | 0.5 |

*Source*: After Hall *et al.* (1993), based on country estimates by Biomass Uses Network.
Notes:
[a] 25% of residues from cereals, vegetables and sugar cane.
[b] 75% of mill wastes +25% of forestry residues.
[c] 12% of dung from farm animals.
[d] 8 dry tonnes per hectare per year on 10% of land now in forest or cropland or pasture.

# Crop Yield

| Crop (Assume one crop per year unless indicated otherwise) | (a) | Biomass yield ($t\,ha^{-1}\,y^{-1}$) Wet basis | Dry basis | Energy density ($MJ\,(kg\,dry)^{-1}$) | Energy from dried yield ($GJ\,ha^{-1}\,y^{-1}$) |
|---|---|---|---|---|---|
| *Natural* | | | | | |
| Grassland | | 7 | 3 | | |
| Forest, temperate | C3 | 14 | 7 | 18 | 130 |
| Forest, tropical | C3 | 22 | 11 | 18 | 200 |
| *Forage* | | | | | |
| Sorghum (3crops) | R, $C_4$ | 200 | 50 | 17 | 850 |
| Sudangrass (6 crops) | R, $C_4$ | 160 | 40 | 15 | 600 |
| Alfalfa | $C_3$ | 40 | 25 | | |
| Rye grass, temperate | $C_3$ | 30 | 20 | | |
| Napier grass | $C_4$ | 120 | 80 | | |
| *Food* | | | | | |
| Cassava (60% tubers) | | 50 | 25 | | |
| Maize (corn) (35% grain) | $C_4$ | 30 | 25 | 18 | 77[b] |
| Wheat (35% grain) | $C_3$ | 30 | 22 | | |
| Rice (60% grain) | $C_3$ | 20 | | | |
| Sugarbeet | $C_3$ | 45 | | | |
| Sugarcane | R, $C_4$ | 100 | 30 | 18 | 150[b] |
| Soya beans | $C_3$ | | | | 20[c] |
| Rapeseed | $C_3$ | | | | 30[c] |
| *Plantation* | | | | | |
| Oil palm | R, $C_3$ | 50 | 40 | | |
| *Combustion energy* | | | | | |
| Eucalyptus | R, $C_3$ | 55 | 20 | 19 | 380 |
| Sycamore | R, $C_3$ | 20 | 10 | 19 | 190 |
| Populus | R, $C_3$ | 18 | 29 | 19 | 380 |
| Willow (salix) | R, $C_3$ | 25 | 15 | 19 | 350 |
| Miscanthus | R, $C_4$ | 21 | 18 | 18 | 330 |
| Water hyacinth | $C_3$ | 300 | 36 | 19 | 680 |
| Kelp (macro-algae) | $C_3$ | 250 | 54 | 21 | 1100 |
| Algae (micro-algae) | $C_3$ | 230 | 45 | 23 | 1000 |
| *Tree exudates* | | | | | |
| Good output | | 1 | 1 | 40 | 40 |

# Energy and greenhouse gas analysis

Crops growth requires two forms of energy:

- solar irradiance and
- energy expended (labour, fuel for tractors, and manufacturing machines and fertiliser, etc.)

Gross Energy Requirement (GER) /Embedded Energy

Energy ratio (ER) is the ratio of the heat of combustion (strictly the enthalpy) of the crop to the GER.

# Energy and greenhouse gas analysis

Energy analysis is a useful tool in assessing energy-consuming and energy-producing systems, since it emphasizes the technical aspects and choices of the processes.

| | *Sugarcane* | *Cassava* | *Timber (enzyme hydrolysis)* | *Timber (acid hydrolysis)* | *Straw* |
|---|---|---|---|---|---|
| (1) Substrate | 7.3 | 19.2 | 12.7 | 20.0 | 4.4 |
| (2) Chemicals | 0.6 | 0.9 | 4.7 | 6.4 | 4.7 |
| (3) Water pumping | 0.3 | 0.4 | 0.8 | 0.3 | 0.8 |
| (4) Electricity | 7.0 | 10.5 | 176 | 7.8 | 167 |
| (5) Fuel oil | 8.0 | 29 | 42 | 62 | 42 |
| (6) Machinery and buildings | 0.5 | 1.2 | 3.3 | 0.6 | 3.3 |
| (7) Total (1)–(6) ($MJ\,kg^{-1}$) | 24 | 61 | 239 | 98 | 222 |
| (8) Net energy: [$= H_o - (7)$] | +8 | −31 | −209 | −68 | −192 |
| *If inputs (3), (4), (5) from waste:* | | | | | |
| (9) Total [(1) + (2) + (6)] | 8.4 | 21 | 21 | 27 | 12 |
| (10) Net energy [$= H_o - (9)$] | +21 | +9 | +9 | +3 | +18 |
| (11) Energy ratio[$= H_o/(9)$] | 3.6 | 1.4 | 1.4 | 1.1 | 2.5 |

# Biomass Utilization

## Direct Combustion

Biomass is burnt to provide:

- heat for cooking,
- comfort heat (space heat),
- crop drying,
- factory processes and
- raising steam for electricity production and transport.

Traditional use of biomass combustion include

- cooking with firewood, 10–20% of global energy use
- commercial and industrial use for heat and power, e.g. for sugarcane milling, tea or copra drying, oil palm processing and paper making.

# Biomass Utilization

## Domestic cooking and heating

In developing countries, especially in rural areas, 2.5 billion people rely on biomass to meet their energy needs for cooking [IEA,2006].

Household use of biomass in developing countries alone accounts for almost 7% of world primary energy demand.

# Biomass Utilization

## Domestic cooking and heating

Average daily consumption of fuel is about 0.5–1kg of dry biomass per person

Inefficient processes used for cooking such as:

Open fire – Thermal efficiency 5%

(incomplete combustion, wind and light breeze, radiation losses,evaporation)

Smoke – health hazard, sign of incomplete burning

Complete burning only emits $CO_2$ and $H_2O$ with fully combusted ash.

# Biomass Utilization

## <u>Domestic cooking and heating</u>

Cooking efficiency and facilities can be improved by

- Using dry fuel.
- Introducing alternative foods and cooking methods, e.g. steam cookers.
- Decreasing heat losses using enclosed burners or stoves, and well-fitting pots with lids.
- Facilitating the secondary combustion of unburnt flue gases.
- Introducing stove controls that are robust and easy to use.
- Explanation, training and management.

- Space heating - wasted heat from cooking

# Biomass Utilization

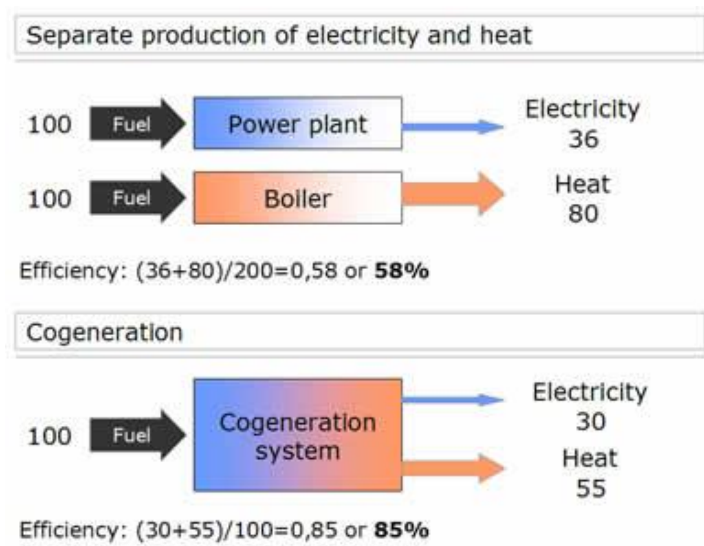
## Crop Drying

- Burning of wood and the crop residue
- Waste heat from electricity generation.
- Air is heated in a gas/air heat exchanger before passing through the crop.
- Combustion of residues for crop drying is a rational use of biofuel, since the fuel is close to where it is needed.
- Combustion in an efficient furnace yields a stream of hot clean exhaust gas☐ at about 1000 ☐C.

# Biomass Utilization

## Process heat and electricity

- Steam process heat is commonly obtained for factories by burning wood or other biomass residues in boilers.
- It is physically sensible to use the steam first to generate electricity before the heat degrades to a lower useful temperature.



# Biomass Utilization

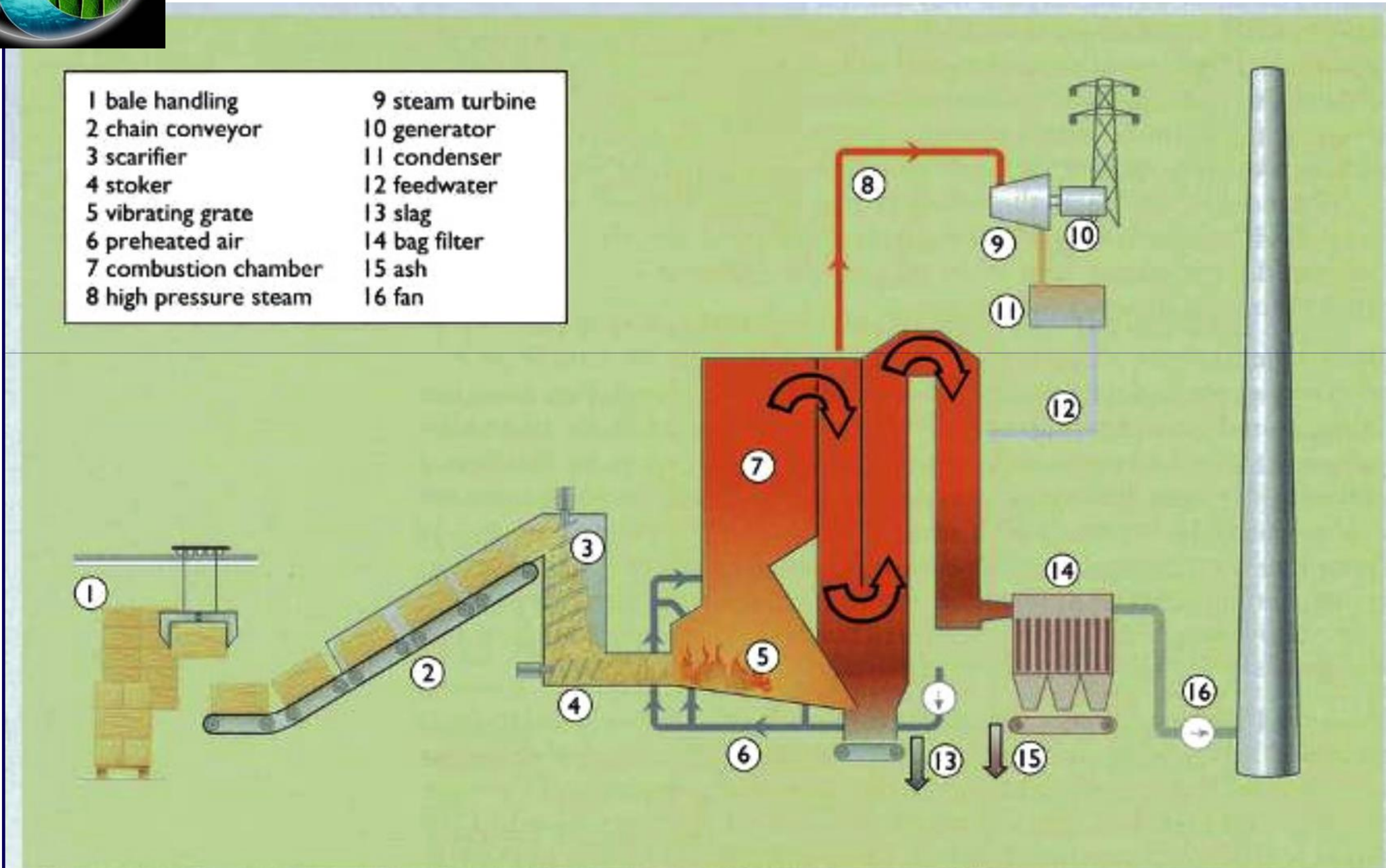



**Figure 4.6** The Elean straw-fired power station: (top) the plant; (bottom) unloading Hesston straw bales

Boyle, *Renewable Energy,* Oxford University Press (2004)

# Biomass Utilization

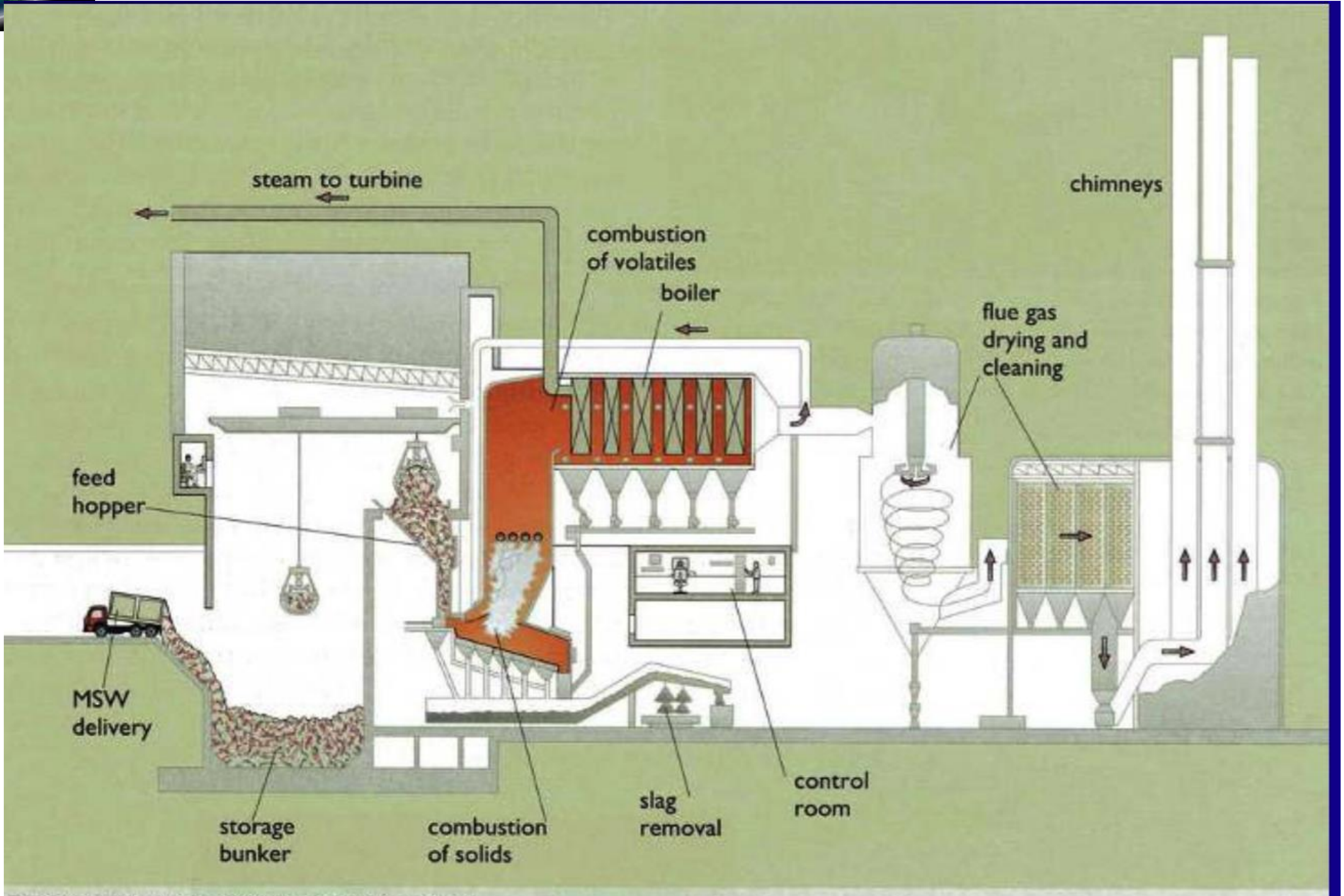



**Figure 4.10** A large MSW combustion plant

Boyle, *Renewable Energy*, Oxford University Press (2004)

# Biomass Utilization

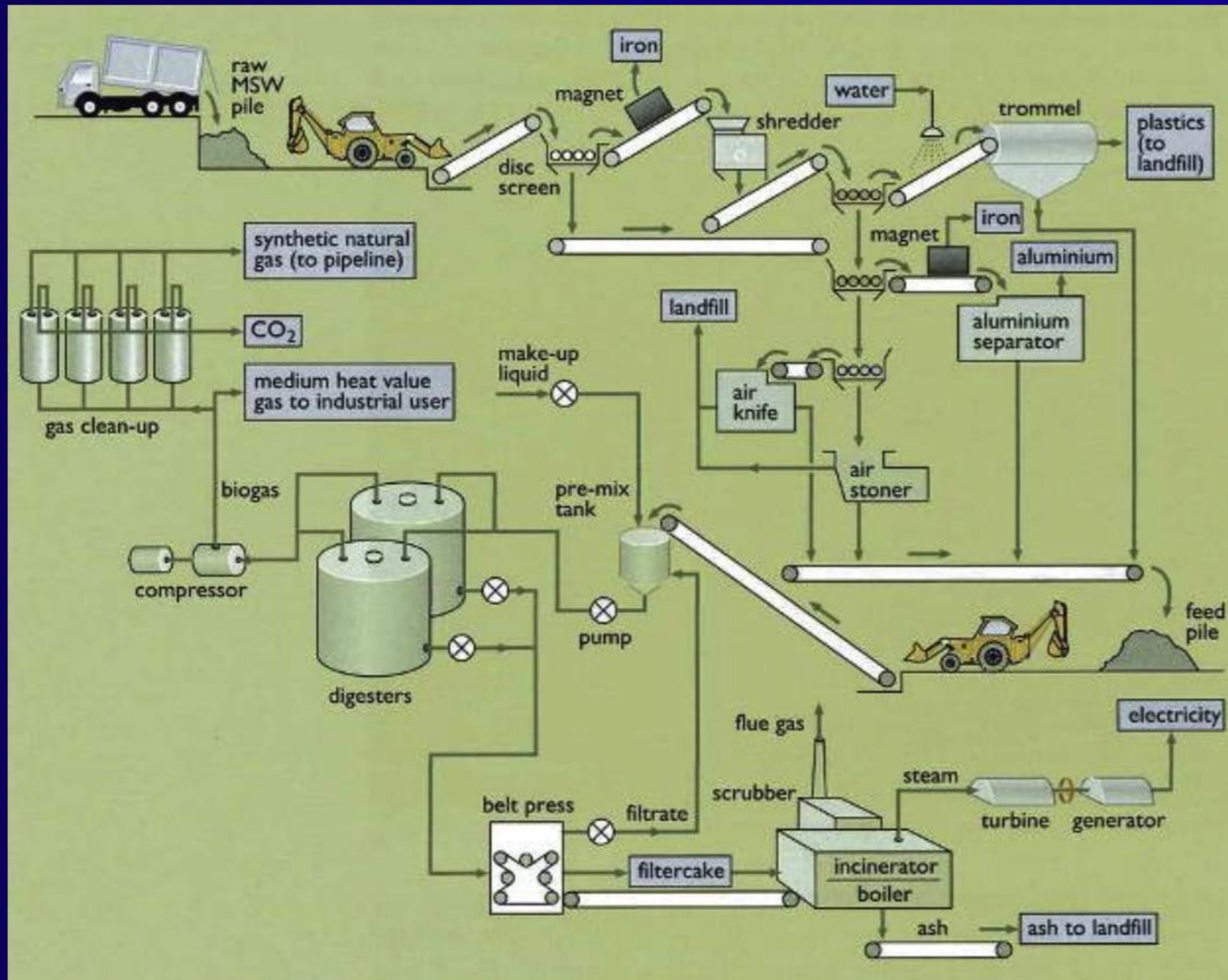



**Figure 4.16** This integrated waste materials plant has facilities for recovery of metals and removal of plastics, followed by anaerobic digestion of the remainder. The solid residue from the digester serves as fuel for power production

Boyle, *Renewable Energy*, Oxford University Press (2004)

# Biomass Utilization

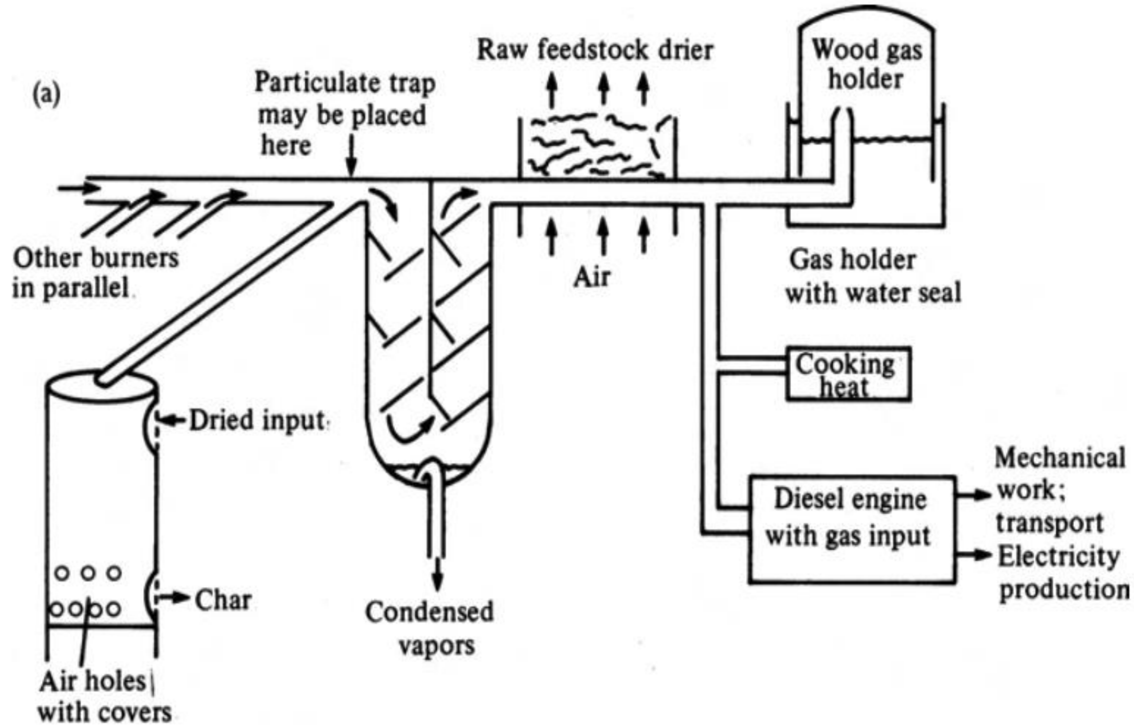
## Wood resource

- Wood is a renewable resource only if it is grown as fast as it is consumed.
- In India, present consumption of fuelwood around 200Mt$y^{-1}$, of which only about 20 Mt $y^{-1}$ constitutes sustainable availability from forests. About 100 Mt $y^{-1}$ is derived from non-forest sources. Non-sustainable extraction from forests .
- The proportion of rural women affected by fuelwood scarcity is around 60% in Africa, 80% in Asia and 40% in Latin America.
- Coppicing is successful with many tree species; it reduces (costly) labour for planting and weeding, and also reduces soil erosion.

# Biomass Utilization

## Pyrolysis

Pyrolysis is an irreversible thermochemical conversion process for biomass in the complete absence of an oxidant.




https://www.youtube.com/watch?v=IvZFfx7XhQE
http://www.cortus.se/flash/WoodRoll_process.swf

# Biomass Utilization

## Pyrolysis

Input ~ wood, biomass residues, municipal waste or indeed coal.

Products ~ gases, condensed vapours as liquids, tars and oils, and solid residue as char (charcoal) and ash.

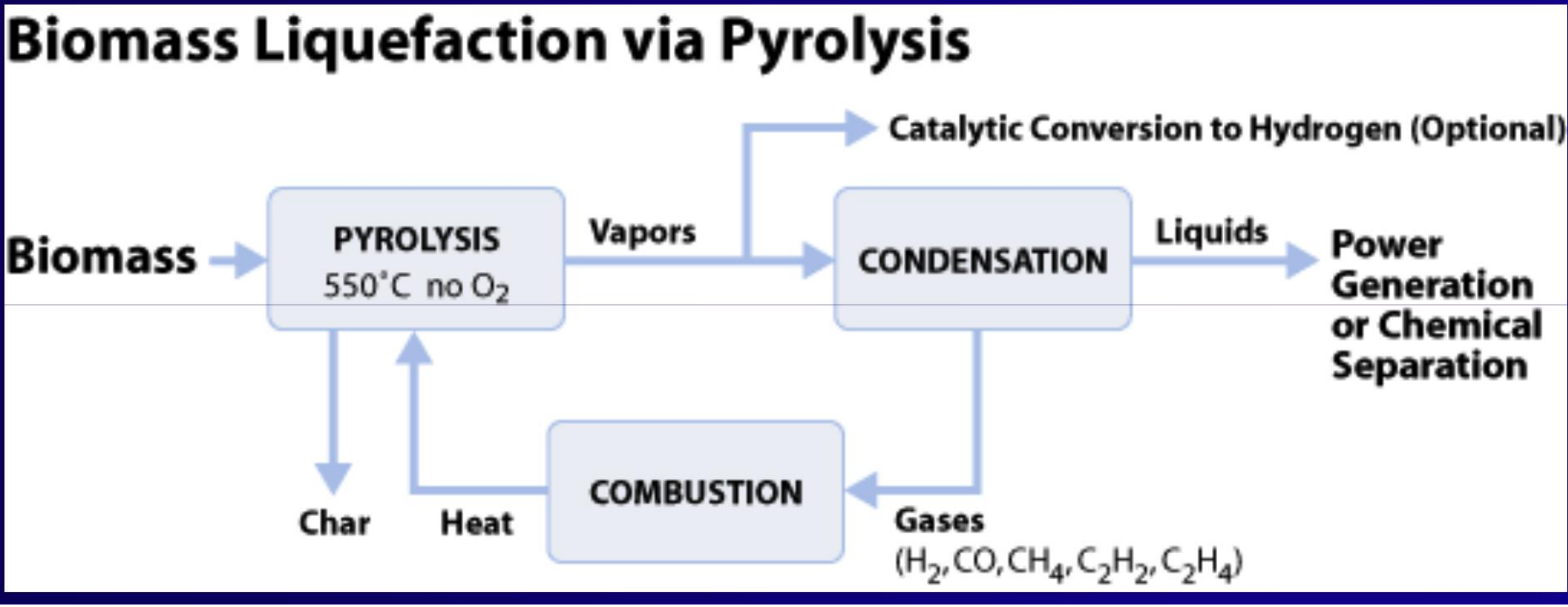
Gasification is pyrolysis adapted to produce a maximum amount of secondary fuel gases.

Efficiency is the ratio of heat of combustion of the secondary fuels produced and the heat of combustion of the input biomass as used.

80-90% efficiency can be reached

Pyrolysis transforms hazardous organic materials into gaseous components, small quantities of liquid, and a solid residue (coke) containing fixed carbon and ash.

# Biomass Utilization



# Biomass Utilization

## Pyrolysis

The air/fuel ratio during combustion is a critical parameter affecting both the temperature and the type of product.

Pyrolysis units are most easily operated at temperatures less than 600□° C.

At < 600° □C there are generally four stages in the distillation process:

1 ~100–120 ° C. Input material dries with moisture passing up through the bed.

2 ~275 □ C. The output gases are mainly $N_2$ , CO and $CO_2$ ; acetic acid and methanol distil off.

3 ~280–350° C. Exothermic reactions occur, driving off complex mixtures of chemicals (ketones, aldehydes, phenols, esters), $CO_2$, CO, $CH_4$, $C_2H_6$ and $H_2$. Certain catalysts, e.g. $ZnCl_2$, enable these reactions to occur at smaller temperature.

4 >350° □C. All volatiles are driven off, a larger proportion of $H_2$ is formed with CO, and carbon remains as charcoal with ash residues.

# Biomass Utilization

## Gasification

- Biomass heated with no oxygen
- □Gasifies to mixture of CO and H2 (called “syngas” for synthetic gas)
- □□Mixes easily with oxygen
- □Burned in turbines to generate electricity (like natural gas)
- □Can easily be converted to other fuels, chemicals, and valuable materials

# Biomass Utilization

## Other Thermochemical Processes

- Hydrogen reduction
- Hydrogenation with CO and steam

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$C_n(H_2O)_n + (n+1)H_2 \rightarrow nH_2O + H(CH_2)_nH$$

- Acid and enzyme hydrolysis
- Methanol liquid fuel (Methanol used as fuel in SI engine)

# Biomass Utilization

## Alcoholic Fermentation

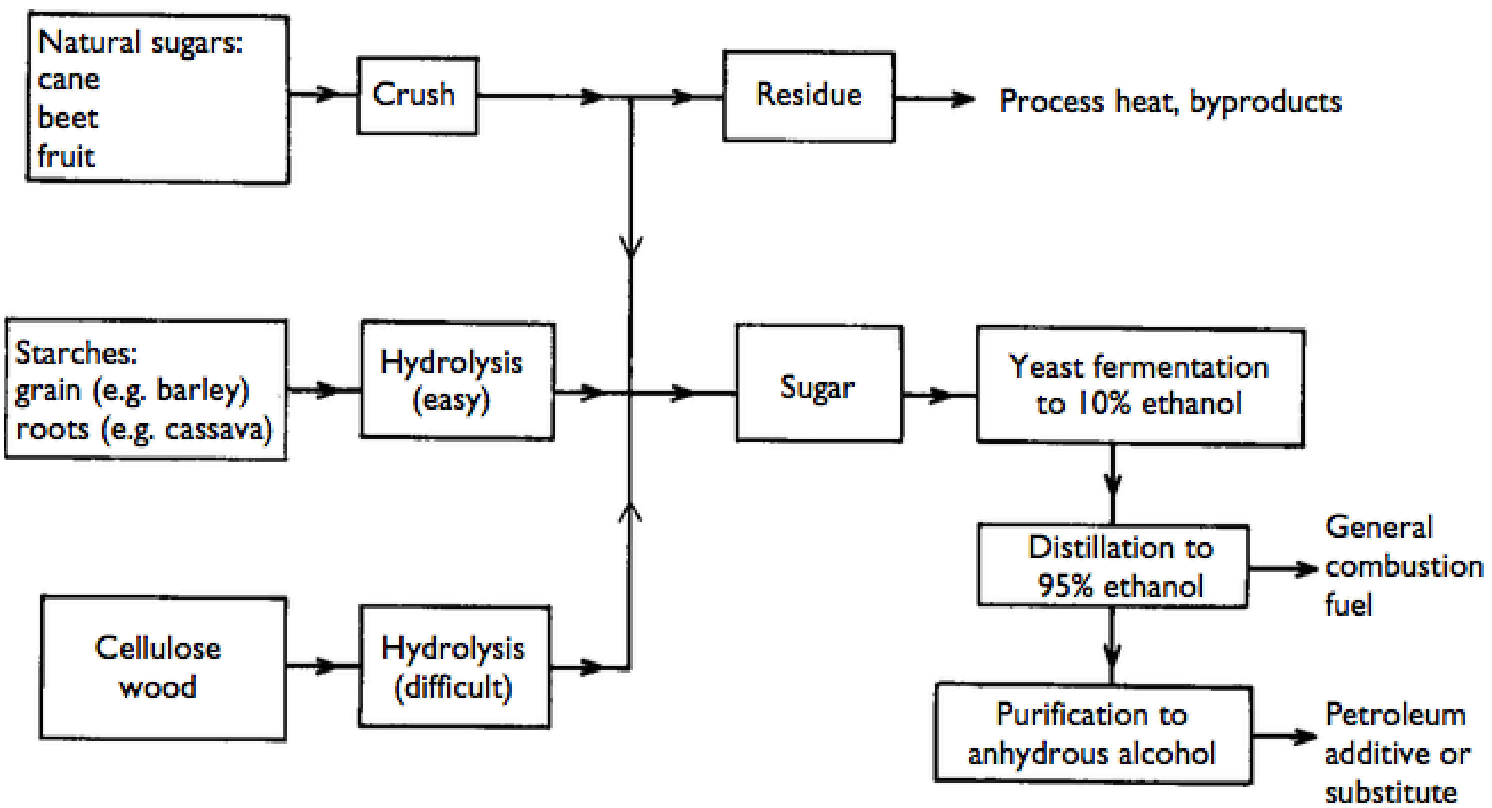
- Biomass can be converted directly into liquid fuels (biofuels) for transportation needs

☐ The two most common types of biofuels are ethanol and biodiesel

- ☐ Ethanol is an alcohol, created by fermenting biomass high in carbohydrates. It is used as a fuel additive to cut down carbon monoxide and other emissions
- ☐ Biodiesel is made by combining alcohol with vegetable oil, animal fat or other recycled cooking grease and is also an additive to reduce emissions. Pure biodiesel is a renewable alternative fuel for diesel engines.

# Biomass Utilization

## Alcoholic Fermentation



# Biomass Utilization

## Methods for obtaining sugar

- Directly from sugarcane : using sugar cane, using molasses, process heat from bagasse
- From sugar beet : sugar can be fermented but obtaining process heat is difficult. More expensive process
- From starch crops. Starch crops, e.g. grain and cassava, can be hydrolyzed to sugars. amylose and amylopectin. Enzymes used to break chains. Used in whiskey distilleries and corn syrup manufacture.
- From cellulose Cellulose comprises about 40% of all biomass dry matter. It is potentially a primary material for ethanol production on a large scale. Structure is more resistant to breakdown into sugars under hydrolysis than the equivalent links in starch. Acid hydrolysis is possible but expensive.

# Biomass Utilization

- <u>Ethanol Fuel Use</u>

Liquid fuels are of great importance because of their ease of handling and controllable combustion in engines

- As 95% (hydrous) ethanol, used directly in modified and dedicated spark-ignition engines;
- Mixed with the fossil petroleum in dry conditions to produce gasohol, as used in unmodified spark-ignition engines
- As an emulsion with diesel fuel for diesel compression engines.

The ethanol additive has antiknock properties, used in place of lead can reduce pollution.

The excellent combustion properties; 20% more power .

Fuel consumption by volume in similar cars using petrol, gasohol or pure ethanol is in the ratio 1:1:1.2, i.e. pure ethanol is only 20% inferior by this criteria.

# Biomass Utilization

## Anaerobic digestion for biogas

- Decomposition of organic matter by anaerobic bacteria in an oxygen-starved environment
- Organic waste is digested in a machine that limits access to oxygen encouraging the generation of $CH_4$ and $CO_2$ by microbes in the waste. This digester gas is then burned as fuel to make electricity
- Decaying biomass and animal wastes are broken down naturally to elementary nutrients and soil humus by decomposer organisms, fungi and bacteria.
- The processes are favoured by wet, warm and dark conditions.

# Biomass Utilization

## Anaerobic digestion for biogas

Aerobic bacteria are favoured in the presence of $O_2$ with the biomass carbon being fully oxidised to $CO_2$. This composting process releases some heat slowly and locally, but is not a useful process for energy supply. Potentially no $CH_4$, less harmful GHGs.

Anaerobic bacteria in closed conditions, with no $O_2$ available from the environment, exist by breaking down carbohydrate material. The carbon may be ultimately divided between fully oxidised $CO_2$ and fully reduced $CH_4$.

# Biomass Utilization

## Anaerobic digestion for biogas

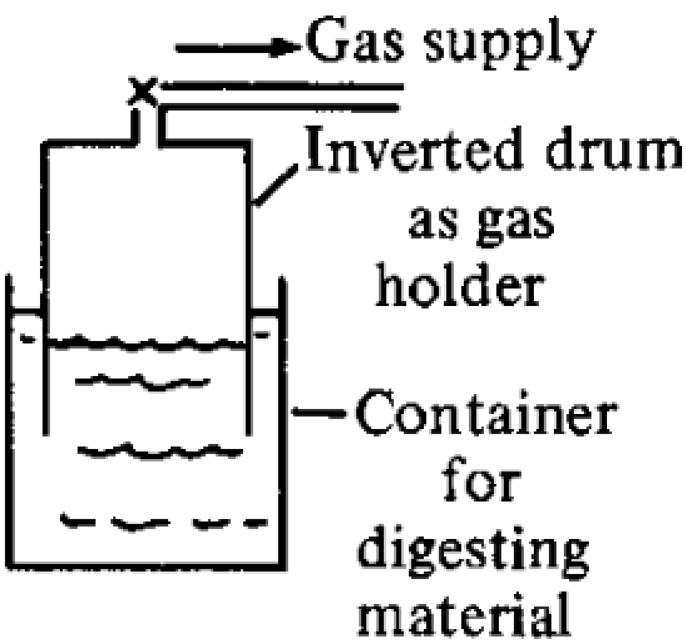
Biogas is the $CH_4/CO_2$ gaseous mix evolved from digesters, including waste and sewage pits; to utilise this gas, the digesters are constructed and controlled to favour methane production and extraction.

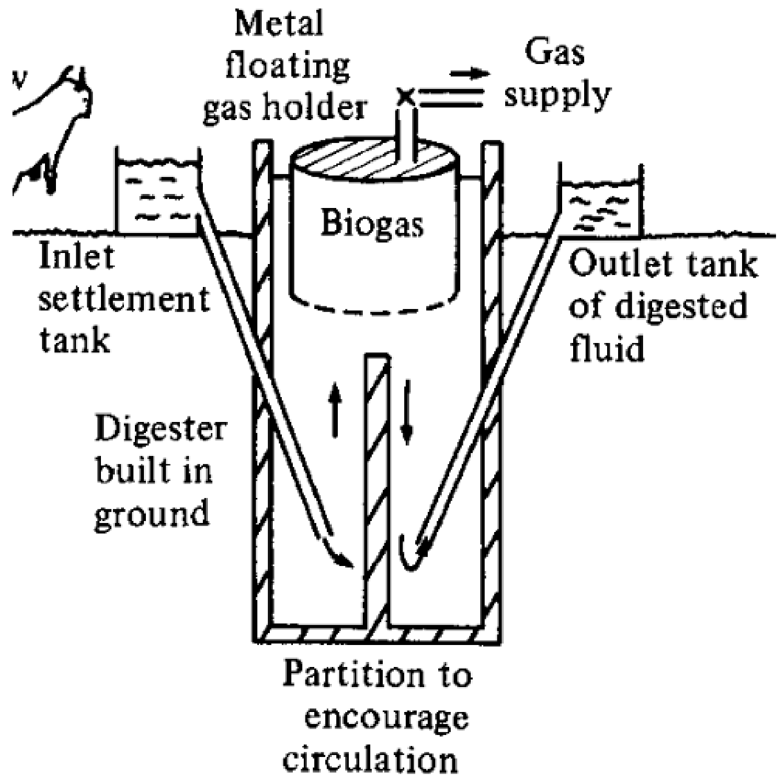
The energy available from the combustion of biogas is between 60 and 90% of the dry matter heat of combustion of the input material.

https://www.youtube.com/watch?v=24Zxr2KHW6s
https://www.youtube.com/watch?v=3UafRz3QeO8

# Biomass Utilization

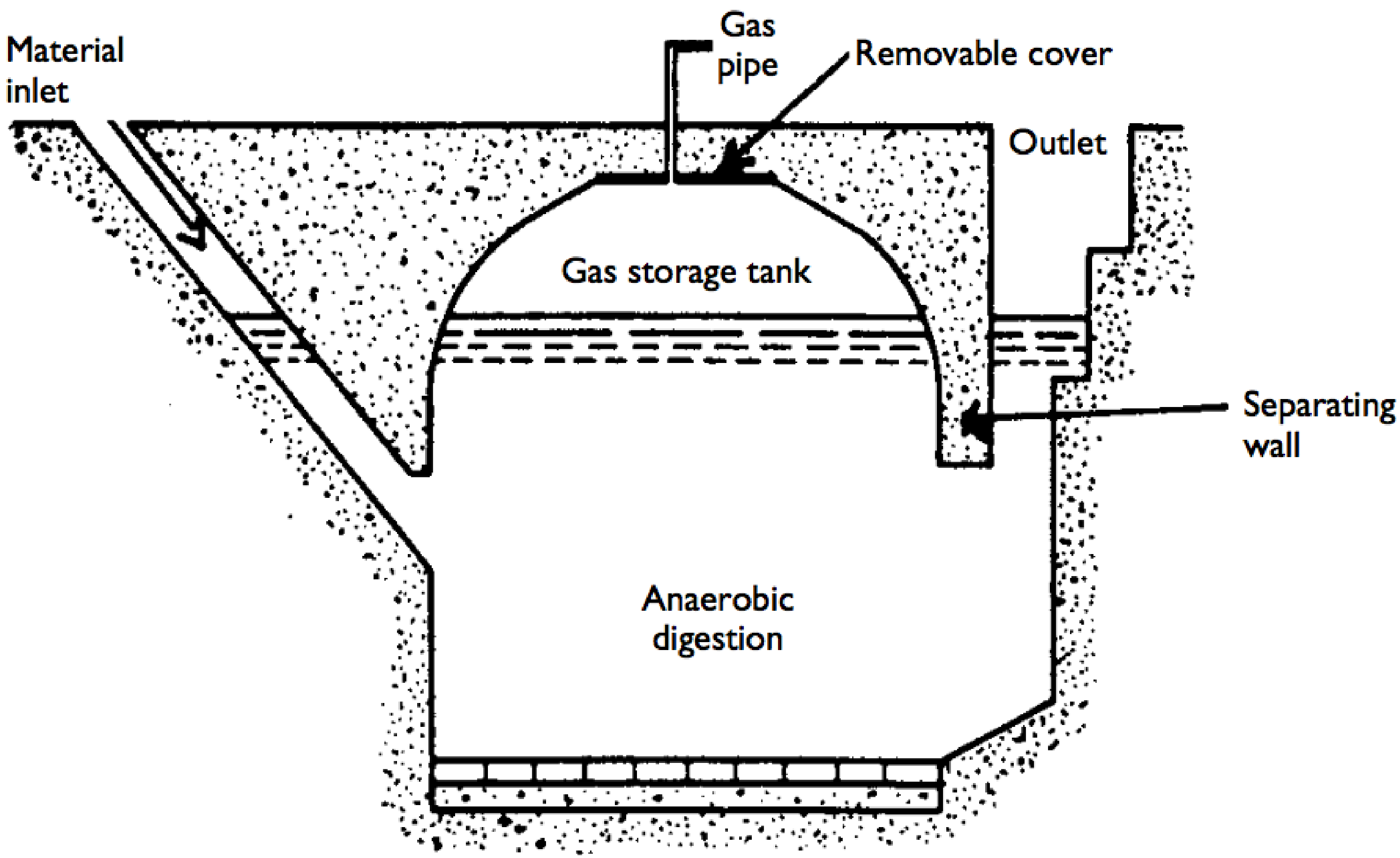
## Anaerobic digestion for biogas



# Biomass Utilization

## Anaerobic digestion for biogas



# Biomass Utilization

## Anaerobic digestion for biogas

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow 3nCO_2 + 3nCH_4$$

- 95% of the mass of the material is water.
- The reactions are slightly exothermic,
- Only about 10% of the potential heat of combustion need be lost in the digestion process - 90% conversion efficiency
- Digestion is seldom allowed to complete because of larger timescales, 60% conversion is common.
- Gas yield is about 0.2 to 0□4m$^3$ per kg of dry digestible input at STP.
- Three temperature ranges. Digestion at higher temperature proceeds more rapidly than at lower temperature, with gas yield rates doubling at about every 5□C of increase.

# Biomass Utilization

## Anaerobic digestion for biogas

- The temperature ranges are
- (1) psicrophilic, about 20□C, (2) mesophilic, about 35□C, and (3) thermophilic,about 55□ C
- Few digesters operate at 55□C unless the purpose is to digest material rather than produce excess biogas.
- In general, the greater is the temperature, the faster is the process time.

The biochemical processes occur in three stages, each facilitated by distinct sets of anaerobic bacteria.

# Biomass Utilization

## Anaerobic digestion for biogas

- Insoluble biodegradable materials, are broken down to soluble carbohydrates and fatty acids (hydrogenesis). This occurs in about a day at 25□C in an active digester.
- Acid forming bacteria produce mainly acetic and propionic acid (acidogenesis). This stage likewise takes about one day at 25□C.
- Methane forming bacteria slowly, in about 14 days at 25 □ C, complete the digestion to a maximum ~70%$CH_4$ and minimum ~30%$CO_2$ with trace amounts of $H_2$ and perhaps $H_2S$ (methanogenesis). $H_2$ may play an essential role, and indeed some bacteria, e.g. Clostridium, are distinctive in producing $H_2$ as the final product.

# Biomass Utilization

## Digester Sizing

$$E = \eta H_b V_b$$

$$E = \eta H_m f_m V_b$$

$f_m$ should be between 0.5 and 0.7

$$V_b = c m_0$$

$$V_f = m_0 / \rho_m$$

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

$t_r$ is the retention time in the digester