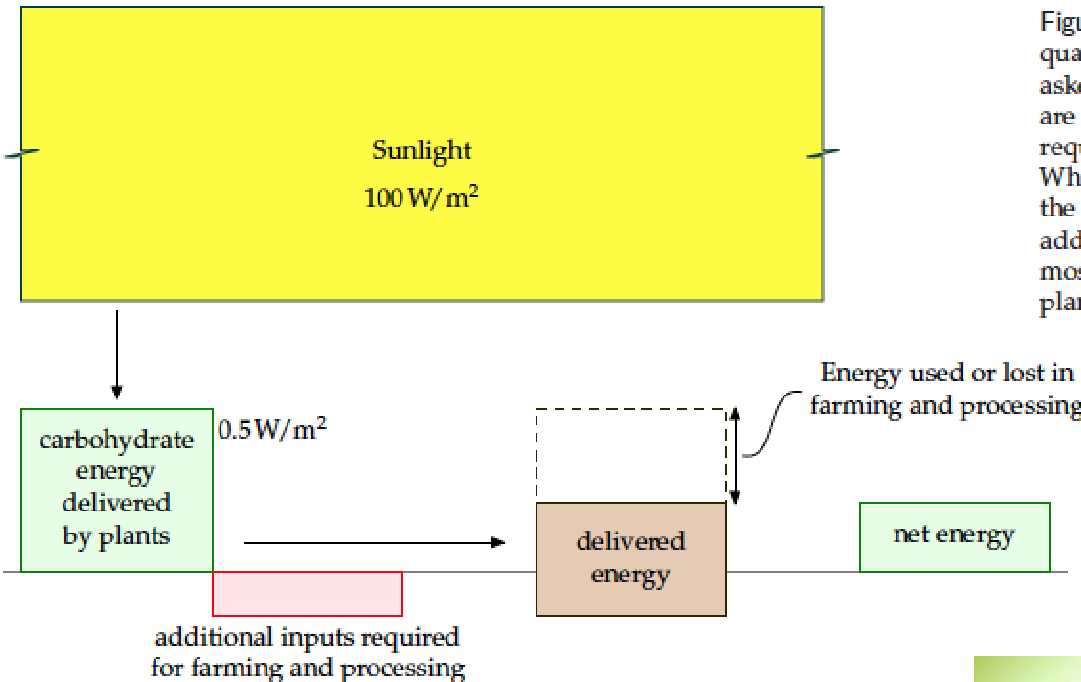
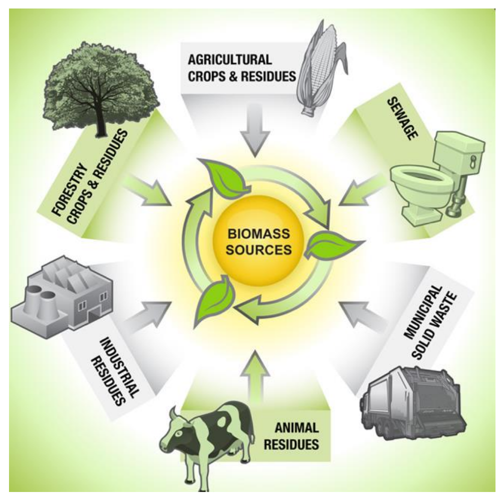


Figure 6.14. This figure illustrates the quantitative questions that must be asked of any proposed biofuel. What are the additional energy inputs required for farming and processing? What is the delivered energy? What is the *net* energy output? Often the additional inputs and losses wipe out most of the energy delivered by the plants.



Chapter 4: Bioenergy

3.1 Introduction

• **Bioenergy** is the general term for energy derived - in a great variety of ways - from **biomass**.

• All of Earth's living matter - its total mass - exists in the thin surface layer called the biosphere. Though only a tiny fraction of the total mass of Earth, it represents and *enormous* store of chemical energy.

• It is being continuously replenished by the flow of energy from the Sun, through the process of **photosynthesis**. (photo, like photon, is related to light; synthesis means putting together). In effect it takes in CO_2 from the atmosphere and water, and using light energy breaks these molecules down and reassembles them into simple sugar while releasing O_2 into the atmosphere.

• It is always good to remember that it is life that established and maintains the atmosphere of Earth as a self-regulating system, as described by James Lovelock's Gaia concept.

• If something were to sweep away all of the plant life on Earth, the resulting loss of mass would be no more than one part in a billion, **like blowing the dust off a model globe**.

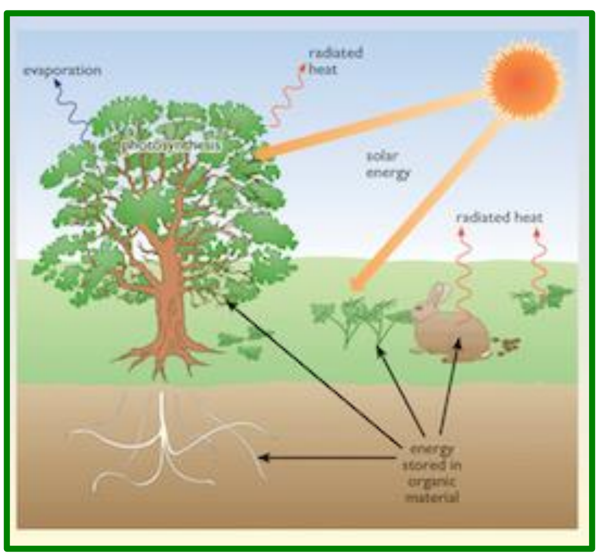
Yet the physical consequences of the infinitesimal change would be **enormous**: no more oxygen and the particular mixture of gases that makes life and Earth as we now it possible.

• The energy that has been stored in the biomass of plants is dissipated through a series of conversions. These involve **metabolic** processes such as **respiration** (essentially opposite of photosynthesis) in living matter, and physical processes such as **re-radiation** of heat energy and **evaporation** of water, These transfer the energy to the surrounding atmosphere, and eventually the energy is radiated away from Earth as low-temperature heat.

• A small fraction may accumulate over centuries as **peat**, traditionally burned for heating, and over millions of years a tiny proportion has become the **major fossil fuels: coal, oil, and gas**.

• Much of this biomass can be used as fuels by various processes. This has been used for hundreds of thousands of years by humans as **traditional biomass**. It can also be converted into **biofuels** for various purposes, and today **even 'new' or modern bioenergy**, when it is done on a grand scale.

• The bioenergy cycle on a local scale is shown below. In addition, a small fraction of the carbon from decomposing animal and plant residues (including roots) is transformed into soil organic matter, a significant carbon source.



BOX 4.1 Biomass – basic data

Note that almost all the data here is subject to considerable uncertainty.

World totals	
Total mass of living matter[1]	Approx. 1800 billion dry tonnes
Total mass in land plants[1]	1800 billion dry tonnes
Total mass in oceans[1]	4 billion dry tonnes
World population (2009)	6.8 billion
Per capita terrestrial plant biomass	270 dry tonnes
Energy stored in terrestrial biomass[2]	25 000 EJ
Net annual production of terrestrial biomass[2]	130 billion dry tonnes y^{-1}

World energy comparisons	
Rate of energy storage by land biomass[2]	2400 EJ y^{-1} (76 TW)
Rate of global primary energy consumption (2009)[3]	502 EJ y^{-1} (15.9 TW)
Biomass energy consumption[4]	50 EJ y^{-1} (1.6 TW)
Energy consumed as food[5]	29 EJ y^{-1} (0.9 TW)

Sources: 1 Slesser and Lewis, 1979; 2 Haberl et al., 2007; 3 BP, 2010; 4 IEA Bioenergy, 2009; 5 Derived from WHO, 2003.

4.2 Bioenergy past and present

From wood to coal

• Until recent times the history of human energy use was essentially the history of bioenergy. Perhaps some coal burning as early as 3,000 years ago, a very small contribution until about 1800. Indeed, bioenergy was still dominant well into the industrial evolution, with wood for heat, whale oil or tallow candles from animal fats for light, and grass and other agriculture crops as 'fuel' for the main means of nutrition, transport and haulage, horses and oxen.

• The move from bioenergy to fossil fuel was a key feature of the industrial revolution. For many centuries, the high temperatures needed for iron smelting could be achieved only in furnaces using charcoal made from wood. The impurities and variable nature of coal made it unsuitable for smelting, and attempts to make a type of **charcoal** (heat wood in a space without oxygen) had little success.

• But in the early 1700s and effective 'coal charcoal', was produced and within a few decades, this new material, now called **coke** (heat coal in a space without oxygen), was replacing charcoal throughout the industrial sector.

• The increase demand for coal led to deeper mines, and the need to pump flood water from great depths led to the first 'effective' steam engines – powered by coal. By the end of the 19th century coal was dominant in industrialized countries. The 20th century saw the rise of oil and natural gas, but it is worth noting that coal consumption also increased 7-fold between 1900 and 2008.

• It is very difficult to estimate numbers regarding the use of bioenergy, since this takes place at the local level, and few records were kept compared to the use of fossil fuels by industry, as a business.

• Biomass is the fourth largest source of energy over much of the world, accounting for at least 10% of total human energy use. It accounts for 1/3 of total primary energy consumption in developing countries (90% in some of the poorest countries) and this total contribution continues to rise. It accounts for 10% of primary energy in China and 35% in India.

• Also significant in industrialized countries with large forestry industries, or well-developed technologies for processing residues and wastes. In Sweden and Finland, where biomass contributes at least 20% of primary energy, the use of residues in the pulp and paper industries is important. Advanced systems for domestic heating, district heating and CHP (combined heat and power) have helped Sweden towards a 5-fold increase in the use of bioenergy since the 1980s.

4.3 Bioenergy as a solar energy source

• The key mechanism of bioenergy is photosynthesis:

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

Here, $C_6H_{12}O_6$ is a carbohydrate:

$C_x(H_2O)_y$

(X and y can be any integer)

The glucose molecule contains more chemical energy than the sum total in the molecules of carbon dioxide and water from which it was formed. Within the plant, glucose can be converted into more complex carbohydrates including: ➔

starches and cellulose, or it can be combined with nitrogen and other elements to form proteins and other components.

BOX 4.2 Carbon-containing compounds in biomass

Carbon is a key element in the biosphere and is found combined with a range of other elements to form a vast array of simple and complex molecules that make up the bulk of all living tissues.

The term **carbohydrate** refers to a compound consisting only of carbon, hydrogen and oxygen having a general form $C_x(H_2O)_y$ (x and y can be different but crucially there is a hydrogen : oxygen ratio of 2:1). Of importance to the discussions in this chapter are carbohydrates such as the following.

Glucose – a simple sugar, which has the chemical formula $C_6H_{12}O_6$; these small carbohydrate molecules can be linked together into polymeric chains.

Starch – a polymer consisting of many glucose units, it can be represented by the formula $(C_6H_{10}O_5)_n$, where the subscript n indicates that there are many identical $C_6H_{10}O_5$ units joined together.

Cellulose – another polymer with the formula $(C_6H_{10}O_5)_n$ but having a different overall structure that allows the formation of fibrous structures and is thus an important component in plant cell walls.

Hemicellulose – a complex polymer containing a variety of different sugar units (i.e. a polymer consisting of more than just glucose base units), found with cellulose in plant cell walls.

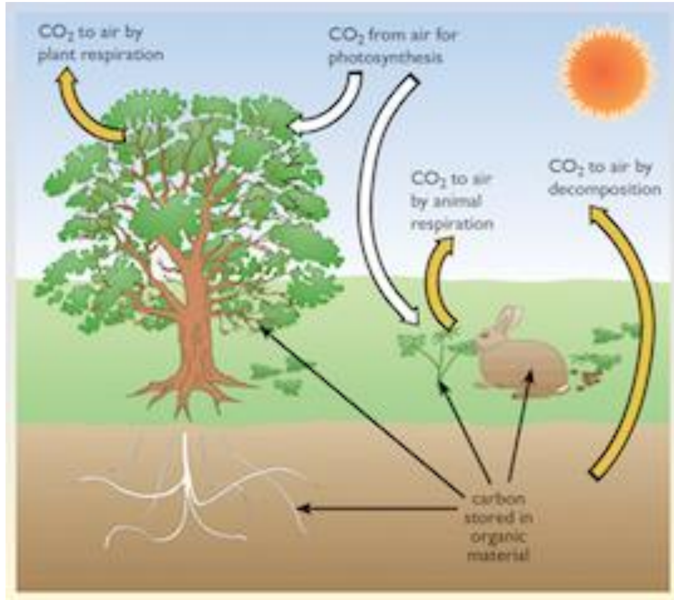
Other organic (carbon containing) compounds discussed include the following.

Lignin – a polymeric organic compound containing carbon, oxygen and hydrogen having a complex structure and found in wood.

Lipids – a class of carbon, hydrogen and oxygen containing compound: the generic term for the oils and fats contained in living tissues.

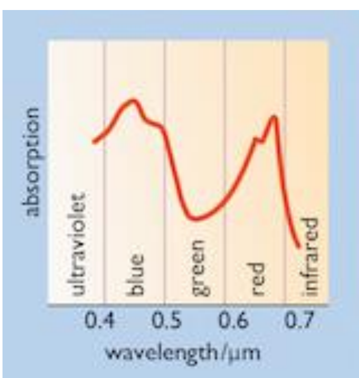
Proteins – large, highly complex organic molecules which also contain nitrogen and may consist of a number of polymeric chains. Proteins have complex folded structures.

In living organisms, these different types of compound are synthesized and broken down by the operation of specific **enzymes** (specialist proteins that act as catalysts) that enable the reactions to occur at ambient temperatures and pressures.



Conversion efficiencies

• Crop yields actually represent an extremely small conversion efficiency from solar energy to energy in biomass. In northern Europe this would be about **two thirds of one percent**. The following chart gives specifics:



BOX 4.3 Conversion of solar energy

Consider one hectare (ha) of land, in an area such as southern England where the annual energy delivered by solar radiation is 1000 kWh m^{-2} y^{-1}.

1000 kWh is 3.6 GJ and 1 ha is 10 000 m^2, so the total annual energy is	36 000 GJ
After losses about an eighth of this reaches the crop at the right time. Say	
12% of the annual energy reaches growing leaves	4320 GJ
50% of this is photosynthetically active radiation	2160 GJ
85% of which is captured by the growing leaves	1836 GJ
21% of which is converted into stored chemical energy	386 GJ
40% of which is consumed in respiration to sustain the plant or lost in photorespiration leaving	231 GJ

This is about 5.3% of the solar radiation reaching the growing plant, and only 0.64% of the original total annual energy.

• It is rather interesting - ironical - that plants are green because the do not use green wavelengths in their chemical activities, and therefore reject green from sunlight, and therefore we see it.

4.4 Biomass as a fuel

What are fuels? • Fuels are those materials from which useful energy can be extracted.

Consider: (wood, paper, coal, oil or methane, CH_4) + $2O_2$ ➔ CO_2 + $2H_2O$ + **energy**

Body fat burning: $C_{55}H_{104}O_6$ + $78O_2$ ➔ $55CO_2$ + $52H_2O$ + energy

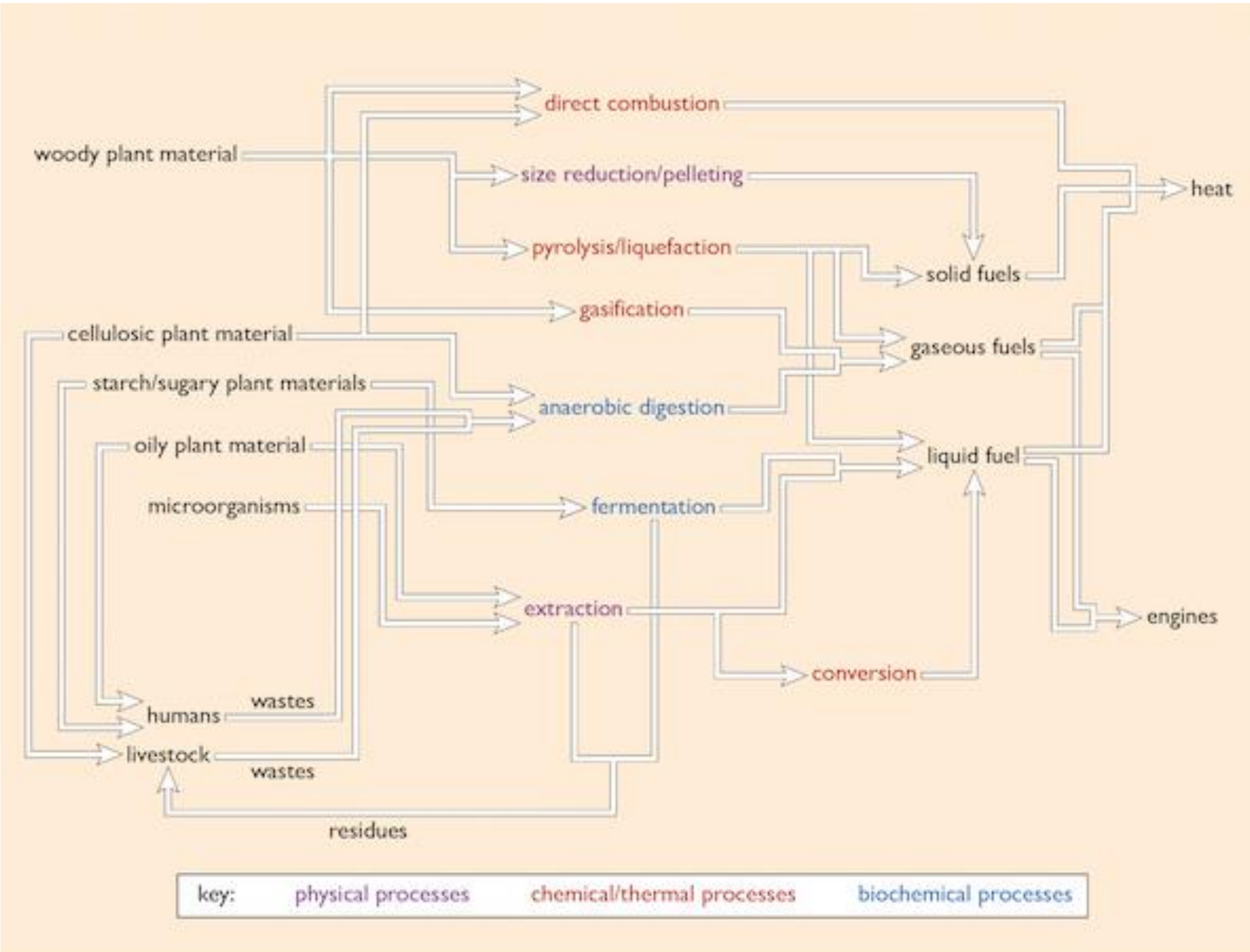
Table 4.1 Heat content (net calorific value, see Box 4.5) and CO_2 emissions

Fuel	Heat content/GJ t^{-1}	CO_2 released/kg GJ^{-1}
Coal	24	94
Fuel oil	41	79
Natural gas	48	57
Air-dry wood	~15	~80*

Fuel	Energy content GJ t^{-1}
Wood (green, 60% moisture)	6
Wood (air-dried, 20% moisture)	15
Wood (oven-dried, 0% moisture)	18
Charcoal	30
Paper (stacked newspapers)	17
Dung (dried)	16
Grass (fresh-cut)	4
Maize grain (air-dried)	19
Straw (as harvested, baled)	15
Sugar cane residues (bagasse)	17
Domestic refuse (as collected)	9
Commercial wastes (UK average)	16
Domestic heating oil	43
Coal (domestic heating, average)	28
Natural gas (at supply pressure)	48

Making use of biomass

• An important issue in the use of biomass as an energy source is the need to process it into a suitable form. The input to these processes may be purpose-grown plants in the form of energy crops, but can also be organic wastes. Residues or byproducts/crop products. Including straw, animal manures and human sewage. The output ay be useful heat, or one of a range of solid, liquid, or gaseous biofuels. The following figure shows very general outline of the primary sources of biomass, the conversion processes and the products involved:



4.5 Primary biomass energy sources: plant materials

• Energy crops, in the form of plants grown specifically to provide bioenergy, have attracted increasing attention in recent years. This has been mainly in response to the need for ALTERNATIVES to fossil fuels. To reduce the net CO_2 emissions, but also as an important saving device for countries without fossil fuel resources, and thus reducing their dependence on other countries.

Table 4.3 A broad generalized classification of primary bioenergy sources

Category	Major energy-rich components	Structural strength /resistance to natural decay	Examples	Typical yields of dry matter /t ha^{-1} y^{-1}
Woody biomass	Lignin/lignocellulose (complex carbohydrates)	High	Trees (deciduous or hardwoods)	10 (temperate) to 20 (tropics)
Cellulosic biomass	Cellulose/lignocellulose (complex carbohydrates)	Medium	Grasses (e.g miscanthus), water hyacinth, seaweeds	10 (temperate) to 60 (tropical aquatics)
Starch/sugar crops	Simpler carbohydrates	Low	Cereals (maize, sugar cane, wheat)	10 (temperate cereals) to 35 (sugar-cane)
Oily crops	Lipids (i.e. oils/fats)	Low	Oilseeds (rape, sunflower, oil palm, jatropha)	8 to 15
Microorganisms	Oils	Low	Microalgae	Unknown – still speculative

Woody (lignin) biomass: For many thousands of years trees have been used for energy as in heating and cooking in addition to construction, and still are in third-world regions where available. Tree plantations in Europe and especially Scandinavia are an important part of community heating and electricity production. This includes using scraps from trees cut for other purposes. It is a wide and difficult subject with various opinions, especially due to environmental implications. To get a wider view, read the book.

Cellulosic materials: The structural integrity of non-woody (lignin, hard) plants is provided mainly by cellulose, a polymer structure of sugars fibrous structures, especially important in cell walls. It is a major component of straw and other supporting material of all food crops. indigestible by humans,, though OK for cows, horses and other grazing animals. Originated in Asia and Africa. Suitable for combustion. Problematic water hyacinth and ocean kelp can also be harvested for control and energy. See book.

Starchy/sugar crops: The major biomass energy component of these is their sugar or starch, which can be fermented to produce ethanol as a liquid fuel. Most important of these are sugarcane (12 to 16% sugar content, stored in stems) and corn.

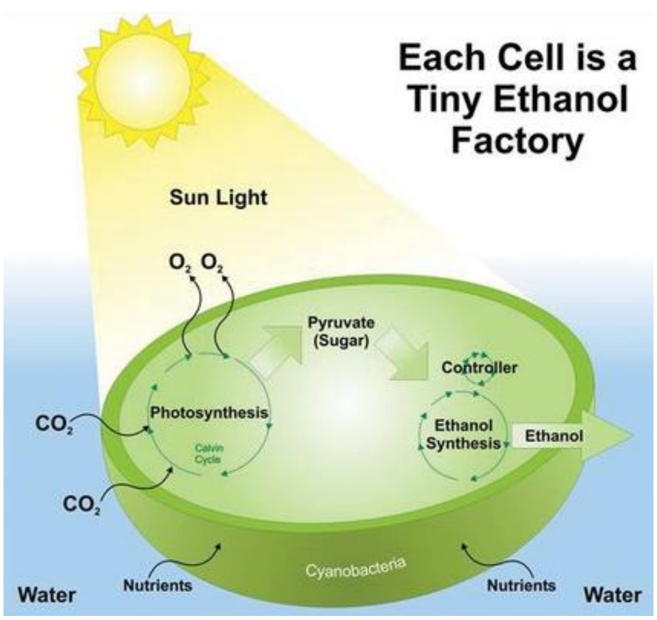
See book.

Oilseed crops: Sunflowers, oilseed rape and soya beans are grown widely for their oil in their seeds, while in tropical areas, palm is a major crop. The oils from the crops can be extracted by pressing and converted into a diesel substitute known as biodiesel. Some residues of this process as animal feed. The oil has a vast number of uses in foods, cosmetics, etc. There are already widespread misgivings about the conversion of mature forests to palm oil plantations in Indonesia and Philippines and the use of palm oil for bioenergy could lead to increases in such problems. Also, sunflower an canola (from Canada). Soya has MANY uses, as well as a wide use of protein for humans. See book!!

Microalgae and other microorganisms: Seaweeds are one form of algae, but there are also single-celled aquatic microalgae and cyanobacteria that photosynthesize. They are especially interesting because:

- grow in water and tolerant of wide range of salinity and temperature
- do not occupy land, which is useful for other things
- cells can contain a high percentage of oils
- can possibly be used to clean up
- possibly usable to capture carbon dioxide emitted from power plants

See book!!



4.6 Secondary biomass sources: wastes, residues and co-products

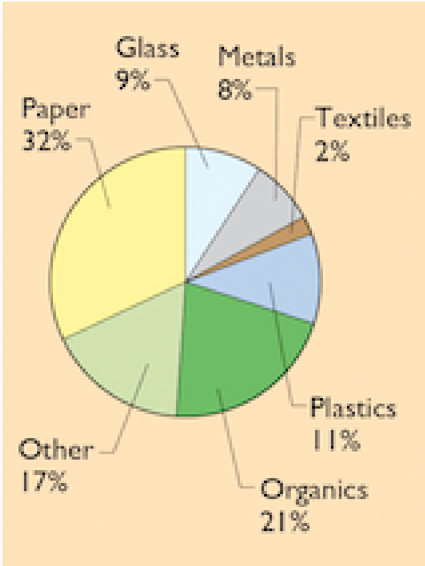
• Materials such as straw or rice husks resulting from 'non-energy' uses of biomass are sometimes discarded as 'wastes', but they are also potential sources of biomass energy. Since they are co-products and often collected and transported as part of the primary product supply chain, they tend to be much cheaper than purpose-grown forest or energy crops

Wood residues: Are there advantages to use forestry residues? Sweden believes so. See book.

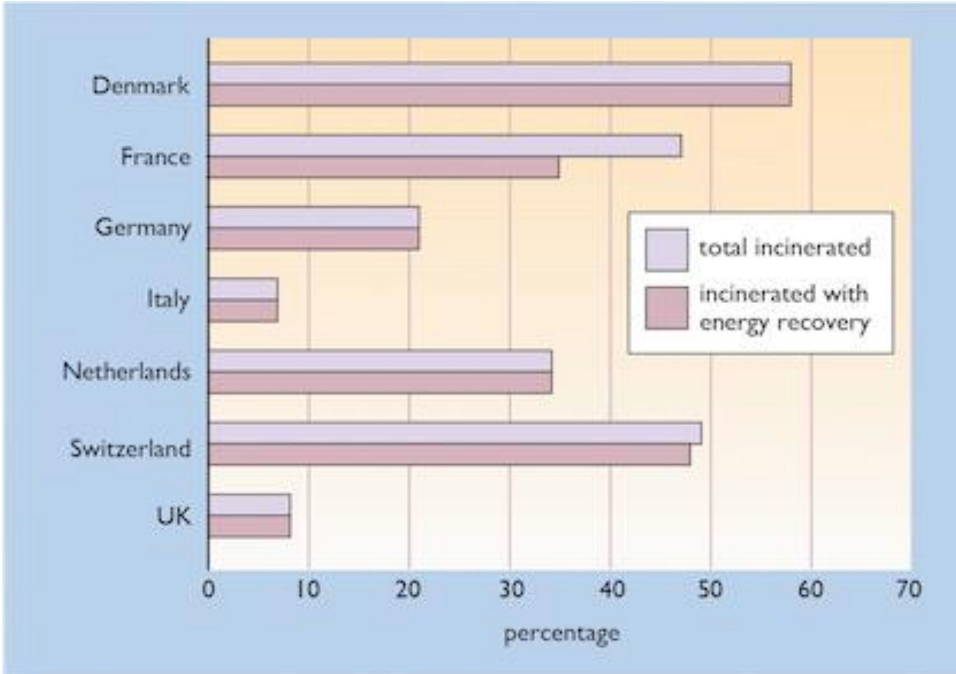
Temperate crop co-products: Worldwide, residues from wheat and maize (corn), the two main temperate cereal crops, amount to more than a billion tons per year. These residues have many uses including as bedding and feed, ad hence may be described as **co-products** rather than residues, but in major cereal-growing regions substantial quantities are plowed back into the soil.

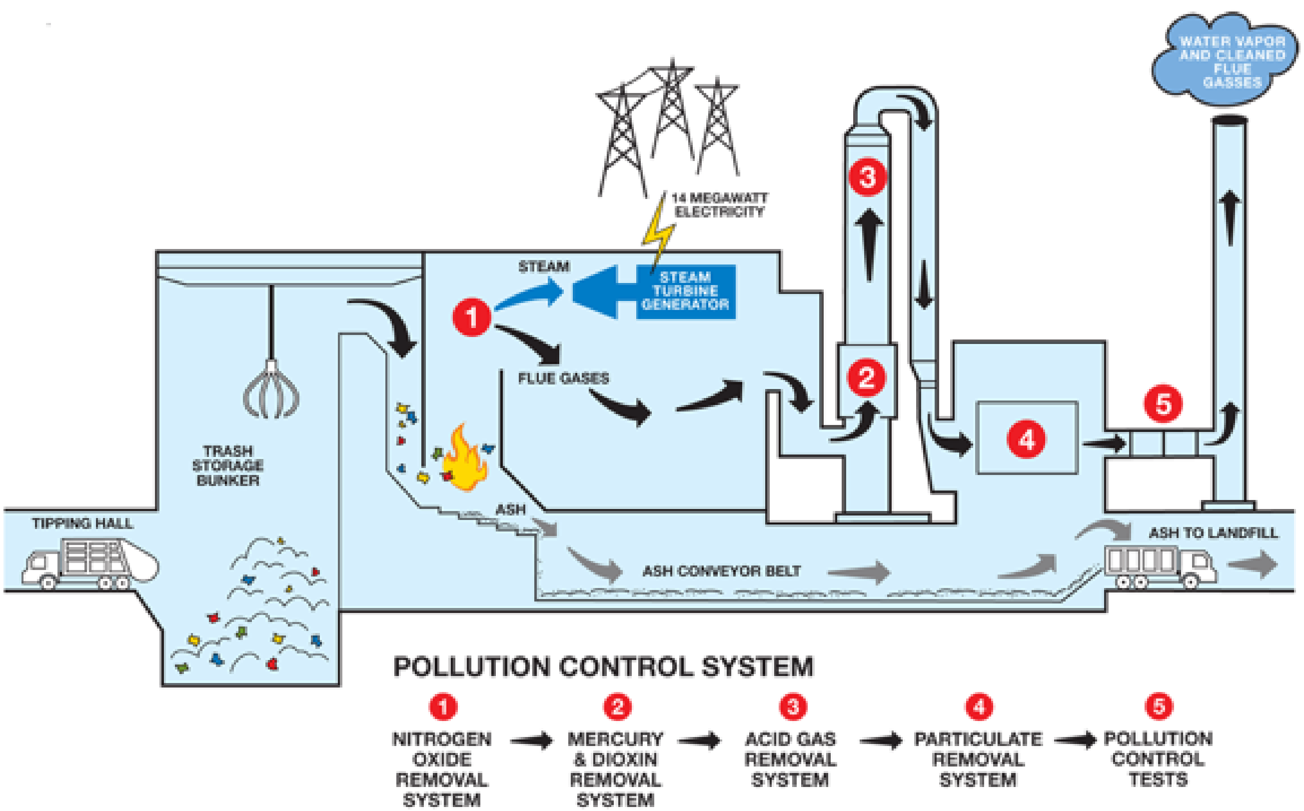
Tropical crop residues: The total energy content of the annual residues of sugar cane (bagasse) and rice (rice husks) are huge. Bagasse is used in sugar factories for raising steam and to produce electricity. The use of rice husks is more problematic. See book.

Animal wastes: Animal manure can be a major source of greenhouse gases. It also allows nutrients to be return to the soil. Complicated story. See book.



Municipal solid wastes (MSW): The average household in an industrialized country generates rather more than a ton of solid waste per year. As well as millions of tons of food waste, with households throwing away sometimes more than 25% of all food purchased. All of this is collected as Municipal Solid Waste (MEW) with a huge energy content. Both incineration with recovery, or energy-from-waste (EfW) is an important part of waste management. The heat may be used directly for district heating, or for power production, or both.





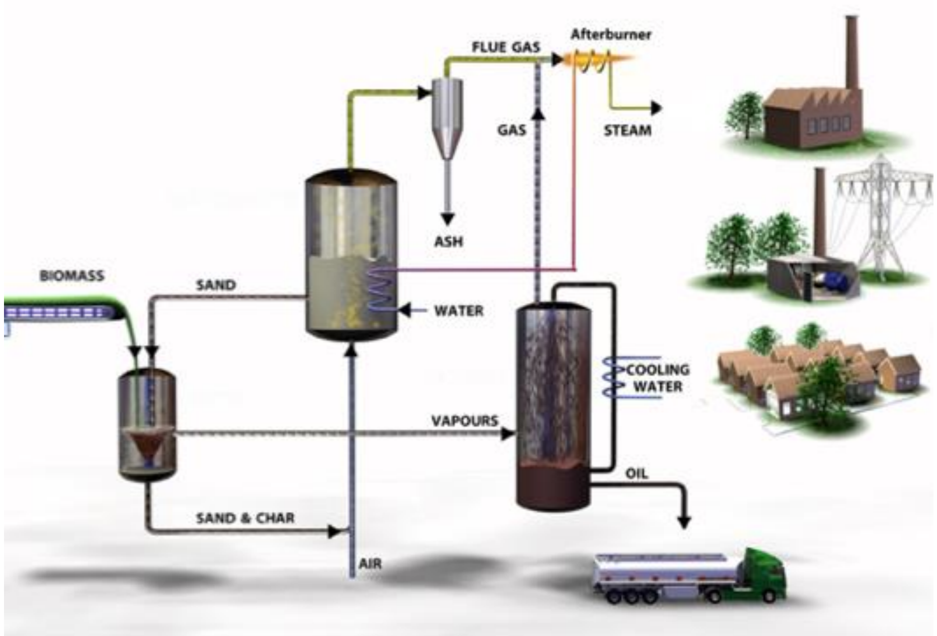
Commercial and industrial wastes: See book.

4.7 Physical processing of biomass

• The premium fuels – oil and natural gas – are valued because of their high energy density and the fact that they can be easily stored, made available where and when needed, and used in a wide range of existing appliances or machinery. Biomass resources come in a variety of physical forms, with widely varying energy content. They are likely to require processing to make them more acceptable to users or easier to transport, and then may require special equipment to release their energy in a useful form. This can involve physical, thermochemical or biochemical processes either singly or in combination.

Separation, size reduction, and pelleting: Trees and their parts can be much easier to use as an energy source by **pelleting**. Canada is a leader and Europe is increasing activity. Raw household and commercial refuse can also be pelleted.

Extraction of oils: The oil in crops such as rapeseed, soya and oil palms is contained within the seed, which also contains the plant embryo and may have a structural shell or coat for protection. The oil has to be separated from the surrounding tissues, either by pressing or by using a solvent which dissolves the oil while making it less viscous and easier to separate from the remaining material.
See book.



Transport and storage:

See book.

4.8 Thermochemical processing

• Thermochemical processing involves the use of heat and possibly the use of chemical reagents, to convert biomass into energetically more useful form. The output from such processes may be heat, or intermediate gaseous or liquid fuels.

Combustion and biomass: See book.

Pyrolysis and gasification: See book.

Hydrothermal processing: See book.

Transesterification: See book.

4 Biochemical processing

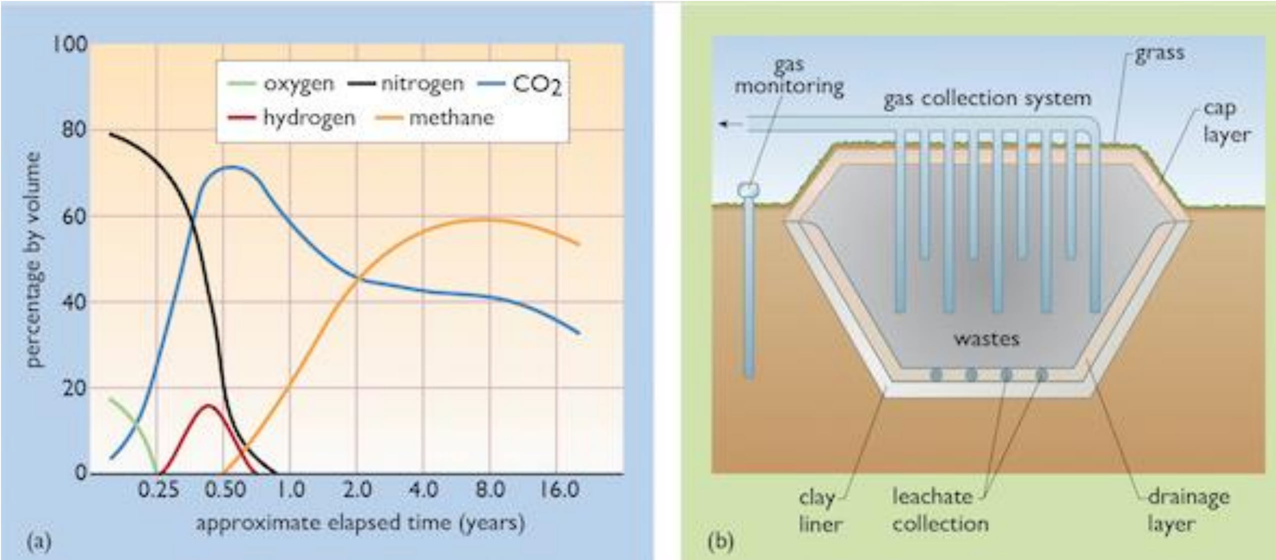
• Biochemical processes rely on the use of microorganisms to convey biomass into more useful forms for bioenergy. The processes may also involve some conventional chemical and physical stages, but the essential stage is biological.

Anaerobic digestion: The process of anaerobic digestion (AD) is complex, but in outline, bacteria break down organic material into sugars and then into various organic acids which are further decomposed to produce **biogas,** a mixture of methane, carbon dioxide and trace gases, including hydrogen sulfide. The feedstock use may include dung or sewage, food processing wastes or discarded food, agriculture residues or specially grown silage crops that are harvested green.

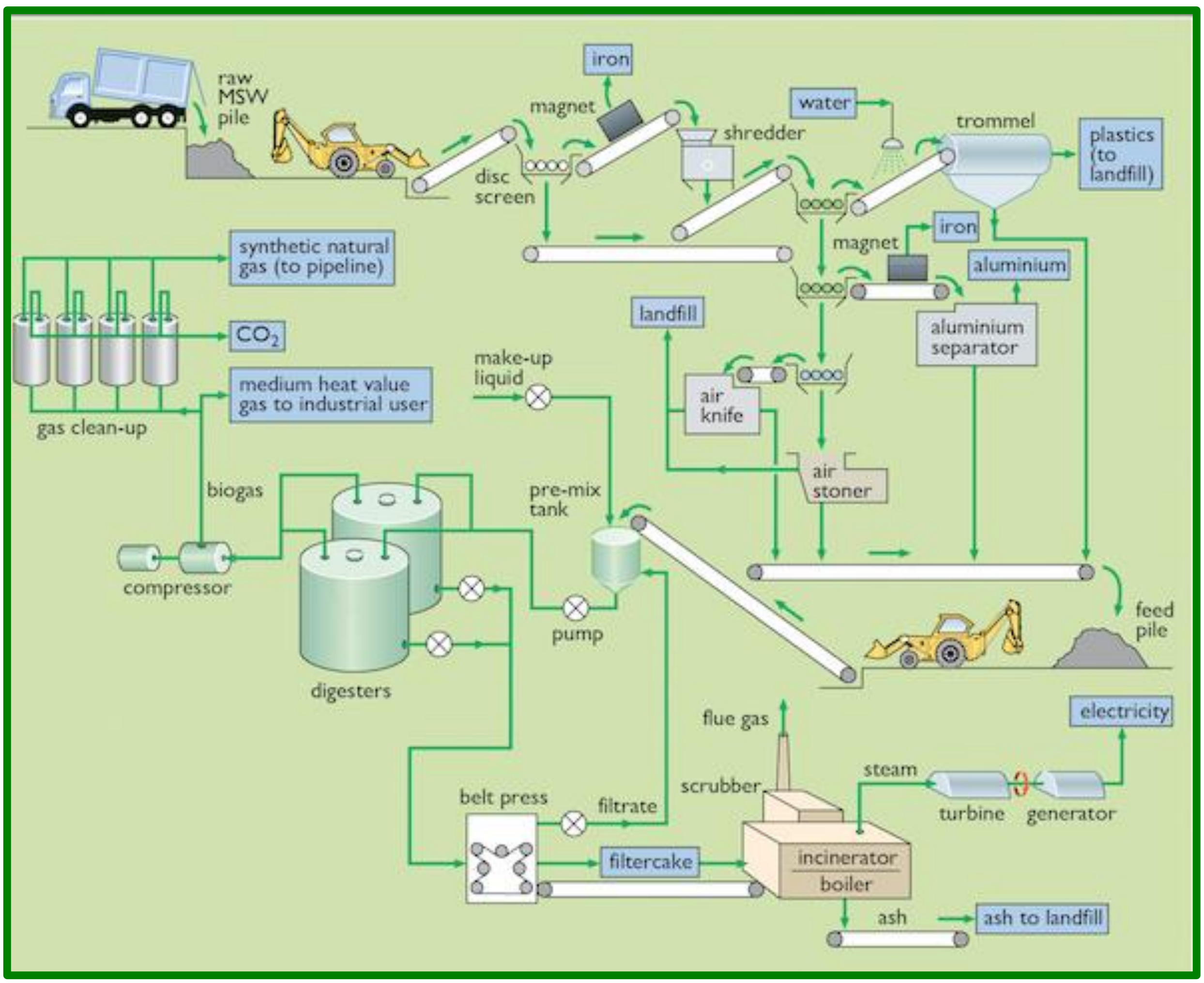
Digestion can take place in either wet or dry systems. In **wet** systems, the raw feedstock is usually converted to a slurry with up to 80-95% water, and fed into a purpose-built digester whose temperature can be controlled. The high throughput of water in wet anaerobic digestion systems may be a disadvantage, and in '**dry**' digestion systems the moisture content in the digester is much lower. This requires a higher input of energy to mix the material, but avoids the need to dispose of large volumes of water.

• On-farm digestion plant in Scotland.

• Small-scale biogas plant on India.



- a) The changing composition in a landfill site; b) Extraction of landfill gas



Fermentation to produce ethanol: Fermentation is another anaerobic biological process but here the simple sugars from the biomass feedstock are converted to alcohol and carbon dioxide by the action of a different set of microorganisms, usually **yeasts**. The required product, ethanol (C_2H_5**OH**), is then separated from other components using heat to distil the mixture, so that the ethanol boils off and can then be cooled and condensed to liquid. Bio-based ethanol (bioethanol) is most commonly used as an extender in gasohol, that is petro (gasoline) containing a percentage of ethanol. Higher blends (typically 85% ethanol, 15% gasoline – designated E85) are used in 'flexible-fuel vehicles' (FFVs) in countries such as Sweden, the USA and Brazil – in Brazil many cars run on 100% bioethanol. Rather a minor problem to modify the injector for various ratios of fuels.

• (a) Sugar cane, (b) Brazilian ethanol production plant

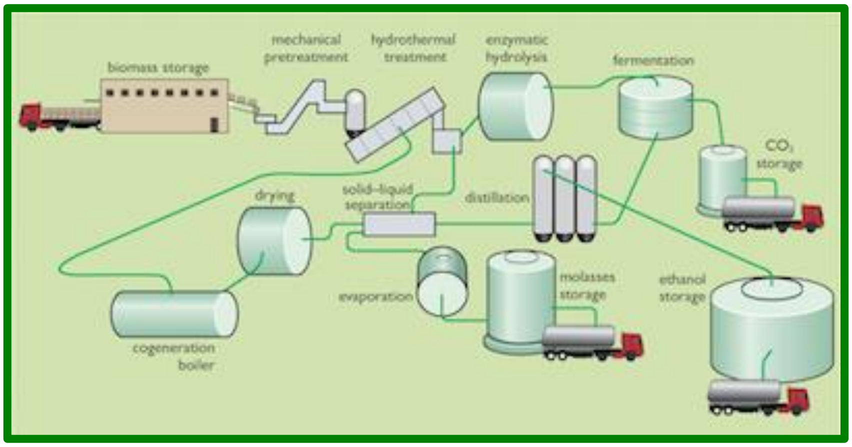
Table 4.4 Ethanol yields from a range of crops

Raw material	Litres per tonne[1]	Litres per hectare per year[2]
Sugar cane (harvested stalks)	70	400–12 000
Maize (grain)	360	250–2000
Cassava (roots)	180	500–4000
Sweet potatoes (roots)	120	1000–4500
Wood	160	160–4000[3]

• Integrated waste materials plant with 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.

(a) (b)

Enzymatic conversion: **Fermentation** to produce ethanol requires some form of soluble sugar, but as we have seen, much biomass consist mainly of **cellulose, hemicellulose, and lignin**. Following a pre-treatment of such material by, for example hydrothermal processing, the watery suspension of cellulose and hemicellulose that results can be treated with **enzymes**, which are biological catalysts. These are usually derived from microorganism such as bacteria and fungi, and are capable of breaking down the cellulose and hemicellulose to simpler carbohydrates that can be used in traditional fermenters.



4.10 Environmental benefits and impacts

• The world's biomass plays a very basic role in maintaining the environment and providing our food, animal feed, and fiber. So it is important to consider not only the **benefits** of using it for bioenergy, but also the possible **negative effects**, global and/or local, of the harnessing of these natural processes. Here are some of the more significant aspects.

Atmospheric emissions: Carbon dioxide: Even the best systems are not entirely carbon-neutral, but all the bioenergy systems, even MSW combustion, have lower CO_2 emissions than any of the fossil fuel plants.

Table 4.5 Net life cycle gaseous emissions from electricity generation systems in the UK

	Emissions[1]/t GW h^{-1}		
	CO_2	SO_2	NO_x
Combustion, steam turbine			
Poultry litter	10	2.42	3.90
Straw	13	0.88	1.55
Forestry residues	29	0.11	1.95
MSW (EfW)	364	2.54	3.30
Anaerobic digestion, gas engine			
Sewage gas	4	1.13	2.01
Animal slurry	31	1.12	2.38
Landfill gas	49	0.34	2.60
Gasification, BIGCC[2]			
Energy crops	14	0.06	0.43
Forestry residues	24	0.06	0.57
Fossil fuels			
Natural gas: CCGT[2]	446	0.0	0.5
Coal: with minimal pollution abatement	955	11.8	4.3
Coal: Flue Gas Desulfurization and low NO_x[3] burner	987	1.5	2.9

• As a greenhouse gas **methane** (CH_4) is about 25-times more powerful than CO_2. In all of the alternative energy processes that capture and burn methane while producing CO_2 actually reduce the total greenhouse gas burden. It is necessary for all process to be efficient in the capturing and burning of methane, so that it does not leak into the atmosphere.

Land use: With the explosion of interest in the US use of maize for ethanol for ethanol production in the first decade of this century, it was claimed that this diversion reduced the food supply of maize flour as a staple food in Mexico, leading to food riots. The suspicion remains that there ma be conflict between food and biofuel.

• A reduction in the biological diversity through conversion of existing vegetation to fuel crops is another concern.

• Any such loses could be amplified by the use of pesticides in bioenergy crops.

• Some bioenergy systems such as short rotation forestry can actually increase biodiversity compared to conventional agriculture.

Energy balance

Table 4.6 The range of fuel energy ratios for selected bioenergy systems reported in the literature to 2008

	Fuel energy ratio	
	Lowest	**Highest**
Lignocellulosic crops (generalized)	1.8	5.6
Switchgrass	0.44	4.43
Corn	0.69	1.95
Miscanthus (combustion)	1.16	1.16
Miscanthus (gasification)	0.99	0.99

• The fuel energy ratio – FER – is the ratio of the useful energy in the fuel to the total amount of fossil fuel used in producing the fuel including that used to construct the equipment.

4.11 Economics: See book.

4.12 Future prospects for bioenergy