RENEWABLE ENERGY
BIOENERGY

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LECTURE OUTLINE

- ❑ Bioenergy past & present
- ❑ Biomass as solar energy store
- ❑ Biomass as fuel
- ❑ Biomass resources
- ❑ Bioenergy processing & conversion technologies
- ❑ Discussion: Costs, Environmental impact & future prospects

Bioenergy Past & Present

Basic Terminology

- **Bioenergy** is the general term for energy derived from organic materials such as wood, straw, oilseeds or animal wastes which are, or were recently, living matter,

referred to collectively as **biomass**.

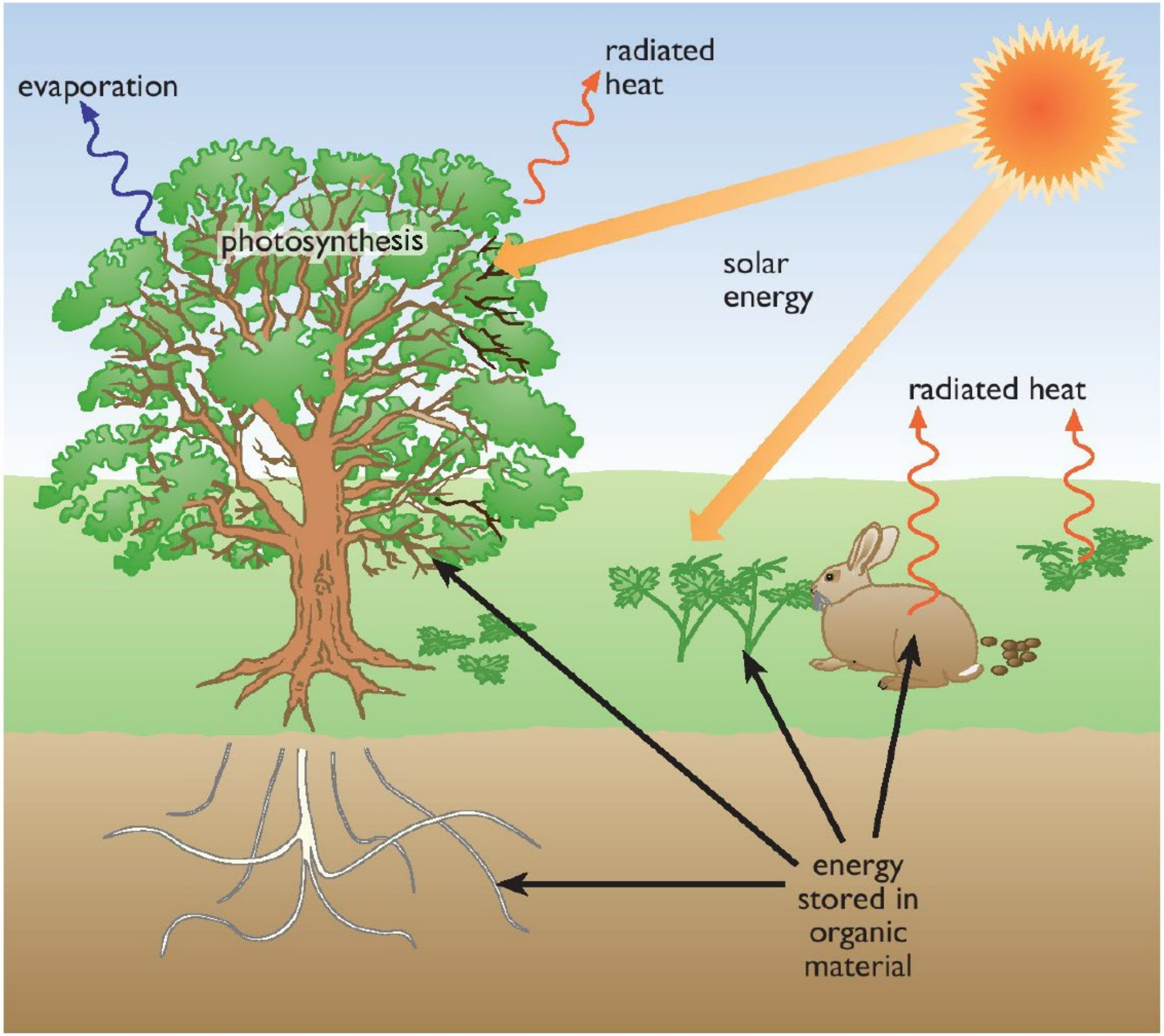
- The **biosphere**. It forms only a tiny fraction of the total mass of the Earth, but represents an enormous store of chemical energy .

- **photosynthesis** is a process that takes in carbon dioxide from the air and uses it to make living material, releasing oxygen.

- The energy stored in biomass is dissipated **metabolic** processes such as **respiration** (effectively the reverse of photosynthesis), and physical processes such as re-radiation and **evaporation.**

- Biomass will be metabolized within a year, accumulate over decades in trees and 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.

The Bioenergy Cycle



Bioenergy Past & Present

Past

- The move from bioenergy to fossil fuel was a key feature of the Industrial Revolution.
- The increased demand for coal led to deeper mines, and the need to pump flood water from great depths led to the first steam engines – powered of course by coal.
- By the end of the nineteenth century, coal was dominant in the world's **industrialized countries**.
- The twentieth century saw the rise of oil and natural gas, but it is worth noting that coal consumption also increased seven-fold between 1900 and 2008

Bioenergy Past & Present

Present

- Bioenergy accounts for at least 10% of total human energy use, and about a third of total primary energy consumption in the developing countries

- It remains important even in the more advanced of these, accounting for up to 10% of primary energy in China and 30% in India.

- In Sweden, Finland and Latvia, biomass contributes 22%, 26% and 32% of energy consumption respectively.

Biomass as a Solar Energy Store

Photosynthesis Mechanism

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

- The first product on the right of the equation is glucose ($C_6H_{12}O_6$), a **carbohydrate**
- Although glucose is not necessarily the final 'vegetable matter' it is the crucial building block in subsequent biomass producing reactions.
- Thus a plant *grows* by using solar energy to convert carbon dioxide and water into carbohydrate

Carbon-Containing Compounds in Biomass

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 (polysaccharides).

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 C6H10O5 units joined together.

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

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.

Carbon-Containing Compounds in Biomass

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.

The Carbon Cycle

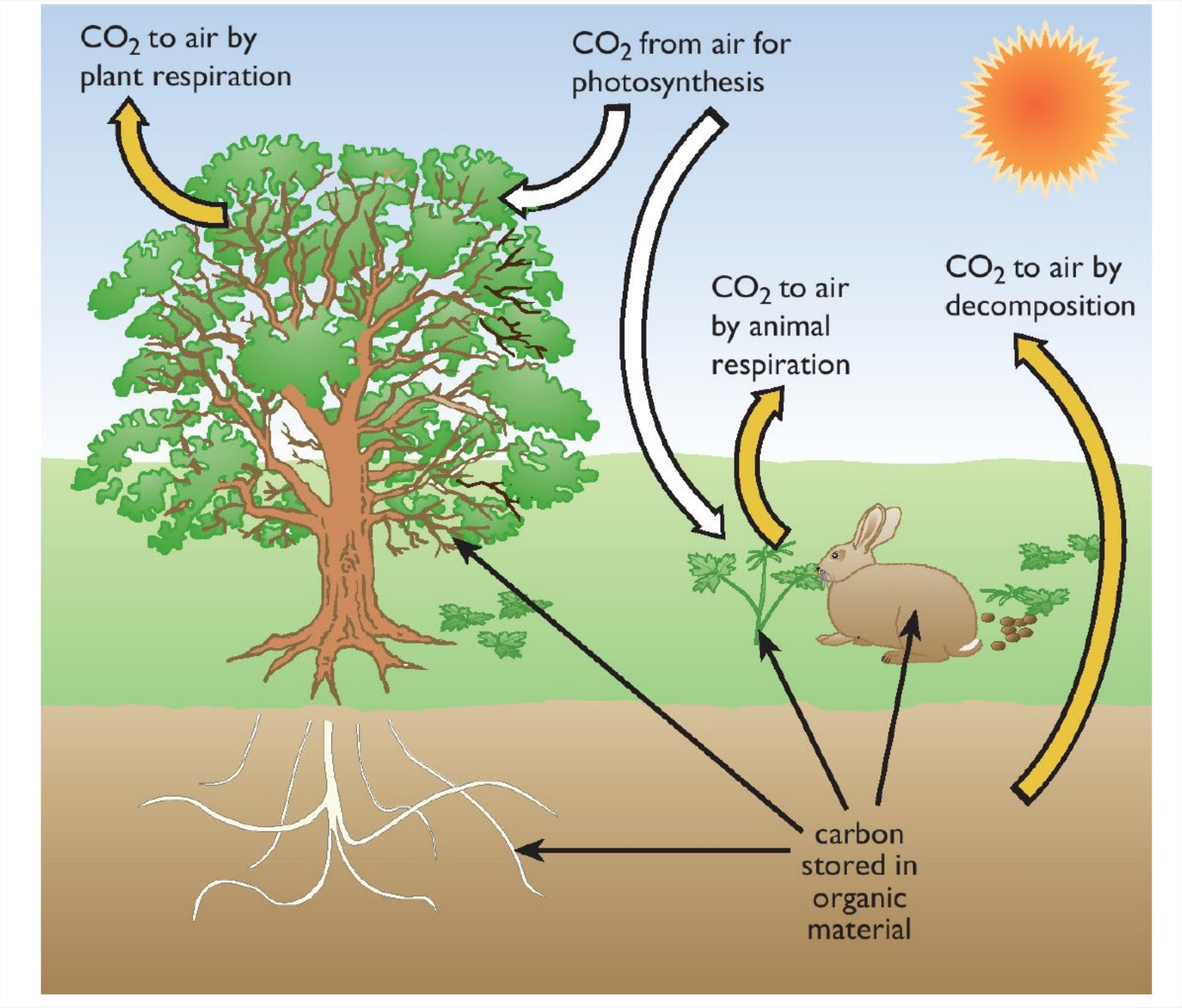
- Some of the energy-rich carbohydrate formed is broken down within the plant through the process of respiration, releasing energy to power the synthesis of proteins and other components.

- Respiration the reverse of photosynthesis, with oxygen taken in, carbon dioxide given off and energy released.

- We have a continuous process, with energy from the Sun being stored in the form of carbon-based biomass which may persist for a time, or be consumed by another organism.

- Over time, nearly all this biomass is respired, releasing energy which is ultimately reradiated back to outer space, and carbon dioxide which returns to the atmosphere

The Carbon Cycle



Conversion Efficiencies

- The **yield** of a crop is the mass of biomass produced per hectare per year.
- For an **energy crop**, that is, the air-dry mass of plant matter produced annually on an area of one hectare can be as little as one dry ton or as much as thirty dry tons.
- This represents a range from perhaps 15 GJ to 540 GJ per hectare per year.
- Conversion efficiency from solar energy is very low, around 0.64%. See example.

Example on 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.

Conversion Efficiency of C3 & C4 Plants

- In the C3 plants, too much light relative to the CO_2 available in the leaf can lead to damage caused by the main photosynthetic enzyme producing a toxic molecule called **phosphoglycolate** rather than useful three-carbon compounds.

- Photorespiration protects the plant from damage by using previously stored energy to break down the phosphoglycolate, releasing carbon dioxide but wasting 30% of the stored energy.

Conversion Efficiency of C3 & C4 Plants

- Maize, sugar cane and miscanthus concentrate CO2 in the cells where photosynthesis is carried out, so there is never a shortage and no risk of damage.

- They produce a four-carbon molecule as the first product of photosynthesis.

- For C4 plants grown in tropical regions an overall efficiency closer to 1%. Can be achieved.

- Photovoltaic (PV) cells can achieve solar to electrical energy conversions of from 10 to over 25%.

- However, plants are currently much cheaper per square meter of light intercepting surface!

Biomass as Fuel

Energy Values of Biomass Fuels

Methane Burning (Combustion)

Full combustion each methane molecule reacts with two oxygen molecules:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{energy.}$$

CH_4	+	$2O_2$	→	CO_2	+	$2H_2O$
$12 + (4 \times 1)$	+	$2 \times (2 \times 16)$	→	$12 + (2 \times 16)$	+	$2 \times (2 \times 1 + 16)$

We can see, therefore, that burning 16 tonnes of CH_4 releases 44 tonnes of CO_2.

The energy content of methane is 55 GJ t^{-1} if the water vapour produced is condensed but only 50 GJ t^{-1} if it isn't (see Box 5.5). This is the amount of heat produced by burning one tonne of methane and thus releasing 2.75 tonnes (2750 kg) of CO_2.

Heat Content 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-dried wood	~15	~80*

Heat Content (Net Caloric Value (NCV))

Fuel	Energy content	
	GJ t^{-1}	GJ m^{-3}
Solid wood (green, 60% moisture)	6	7
Solid wood (air-dried, 20% moisture)	15	9
Solid wood (oven-dried, 0% moisture)	18	9
Charcoal	30	*
Miscanthus bales (0% moisture)	18	2.4
Dung (dried)	16	4
SRC chip (30% moisture)	13	2.9
Maize grain (air-dried)	19	14
Straw (as harvested, baled)	13	1.3
Sugar cane residues (bagasse)	17	10
Domestic refuse (as collected)	7	1.5
Commercial wastes (UK average)	15	*

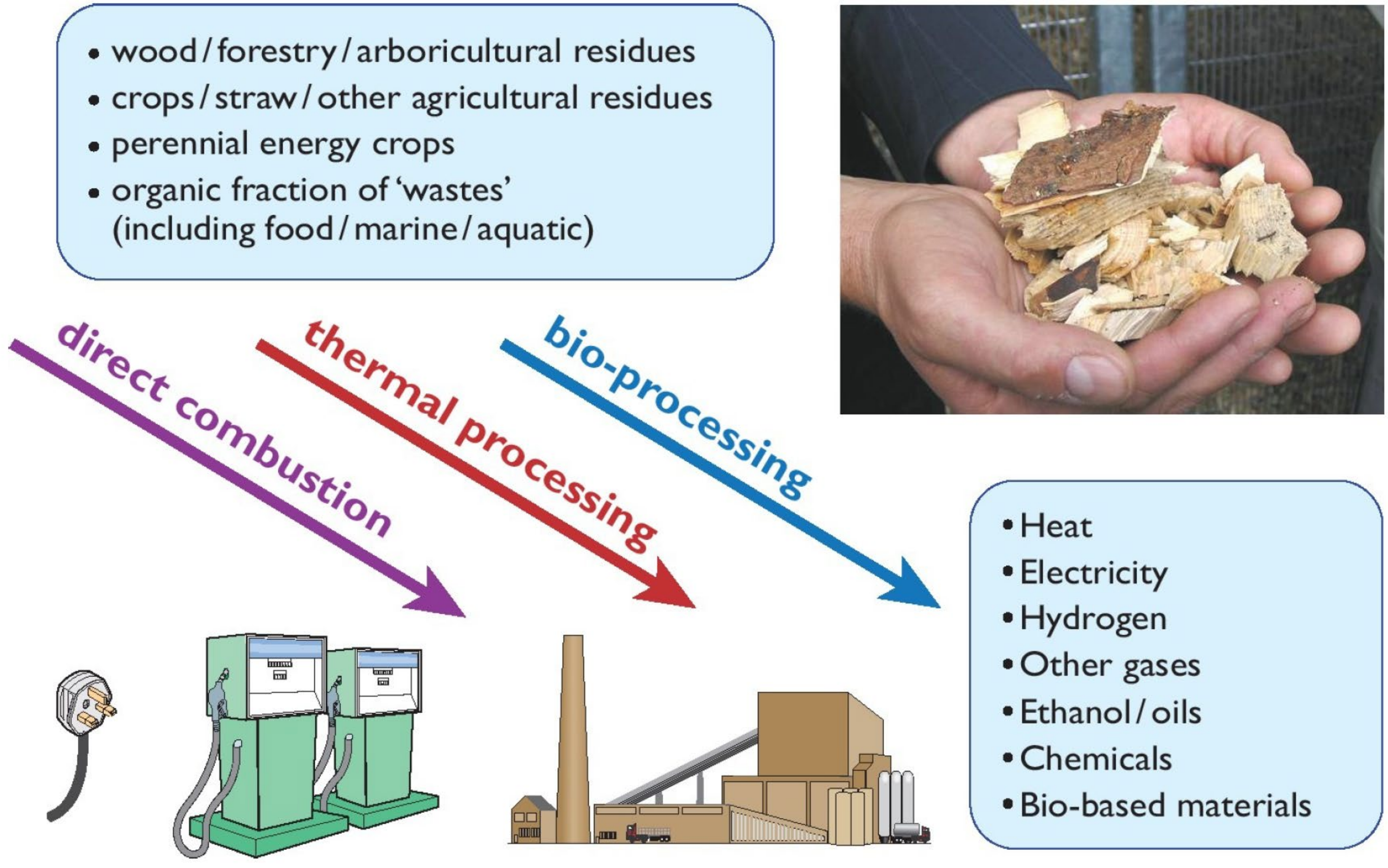
Effects of Water Moisture

- Values for biomass, industrial wastes, coal and oil are normally quoted as the lower heat value (LHV) or net calorific value (NCV) of the fuel.

- This assumes that any water vapor produced is not condensed. However, if it is condensed, then a higher heat value (HHV), also called the gross calorific value (GCV) is appropriate.

- For methane, the GCV is about 10% higher than the LCV. For hydrogen the difference is 17%.

Biomass is Versatile, both in source and application



Biomass Resources

Primary Bioenergy Sources

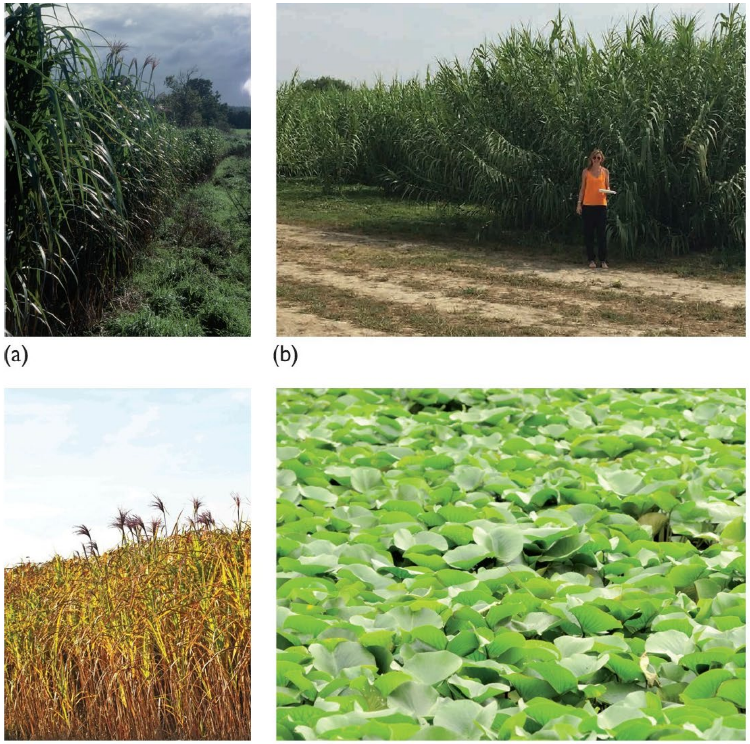
Category	Major energy-rich components	Structural strength /resistance to natural decay	Examples	Typical yields of dry matter /t ha^{-1} y^{-1}
Woody	Lignin/lignocellulose (complex carbohydrates)	High	Trees (deciduous or hardwoods)	10 (temperate) to 20 (tropics)
Cellulosic	Cellulose/lignocellulose (complex carbohydrates)	Medium	Grasses, water hyacinth, seaweeds	10 (temperate) to 60 (tropical aquatics)
Starchy/sugary	Relatively simple carbohydrates	Low	Cereals, sugar cane, tubers/roots	10 (temperate cereals) to 60 (sugar-cane)
Oily	Lipids (i.e. oils/fats)	Low	Oilseeds (rape, sunflower, oil palm, jatropha)	8 to 15
Microorganisms	Oils	Low	Microalgae	Not yet known at scale

(1) Wood

Species	Yield (dry matter) /t ha-^{1} y-^{1}	Rotation period* /years	References
Poplar	10–33.7	8–21	Manzone et al., 2009; Havlicková and Weger, 2009; Fiala and Bacenetti, 2012
Willow	4.15–12	10–22	Mola, 2011; Rosenqvist and Dawson, 2005
Eucalyptus	10–20.5	8 – 15	Iriarte et al., 2010; Jiménez et al., 2013

(2) Cellulosic Materials

Crop	Yield (dry matter) /t ha^{-1} y^{-1}	References
Miscanthus	10–40	Heaton et al., 2004
Switchgrass	10–25	Venturi and Venturi, 2003
Giant reed (A. donax)	7–61	Mantineo et al., 2009



(a) (b) (c) (d)

Figure 5.6 Cellulosic bioenergy crops which are currently being deployed or developed: (a) miscanthus, (b) giant reed, (c) switchgrass/reed canary grass and (d) water hyacinth.

(3) Starchy/ Sugar Crops

Figure 5.8 Starch/sugar crops: (a) sugar cane, (b) maize harvesting, (c) sugar beet

- Replanting sugar cane may take place every 5–10 years, so sugar cane is sometimes called a ‘semi-perennial’ crop.
- In contrast, almost all the other crops in this category are annuals that provide a single harvest from each sowing.

(4) Oilseed Crops

- Sunflowers, oilseed rape and soya beans are grown widely for the oil in their seeds, while in tropical areas, oil palm is a major crop.

- Soya oil, like palm oil, is a major source of protein for human and livestock feed.

- It has an advantage over other herbaceous crops in that it is a *leguminous crop*. It is therefore less dependent on external supplies of nitrogen fertilizer since it can fix nitrogen from the air through the agency of *Rhizobium* bacteria present in its roots.

(5) Microalgae and other micro-organisms

- Seaweeds are one form of large algae or macro-algae.
- There are also single-celled aquatic microalgae and cyanobacteria that photosynthesize.
- They grow in water, and are tolerant of wide ranges of salinity and temperature.
- They do not occupy land that could be used for other products
- The cells of the algae can contain high percentages of oils,
- They can be used simultaneously to clean up waters polluted with plant nutrients .
- Some forms are also seen as candidate material for the capture of carbon dioxide from power plants.

Figure 5.9 A possible bioreactor design for use of microalgae as an energy source

Secondary Sources

(1) Wood residues: Around 15% of the standing tree crop is left behind as **forestry residues**

(2) Temperate crop co-products: residues from wheat and maize (corn) amount to more than a billion tonnes per year, with an estimated energy content of 15–20 EJ.

(3) Tropical Crop Residue: The total energy content of the annual residues of two major tropical food crops, **sugar cane** and **rice**, is estimated to be about 18 EJ. **Bagasse**, the fibrous residue of sugar cane after juice extraction, is used in sugar factories as a fuel for raising steam and to produce electricity.

(4) Rice husks are among the most common agricultural residues in the world, making up about one-fifth of the dry weight of unmilled rice. Around 40 million tonnes of rice husks were produced in China in 1999.

Secondary Sources

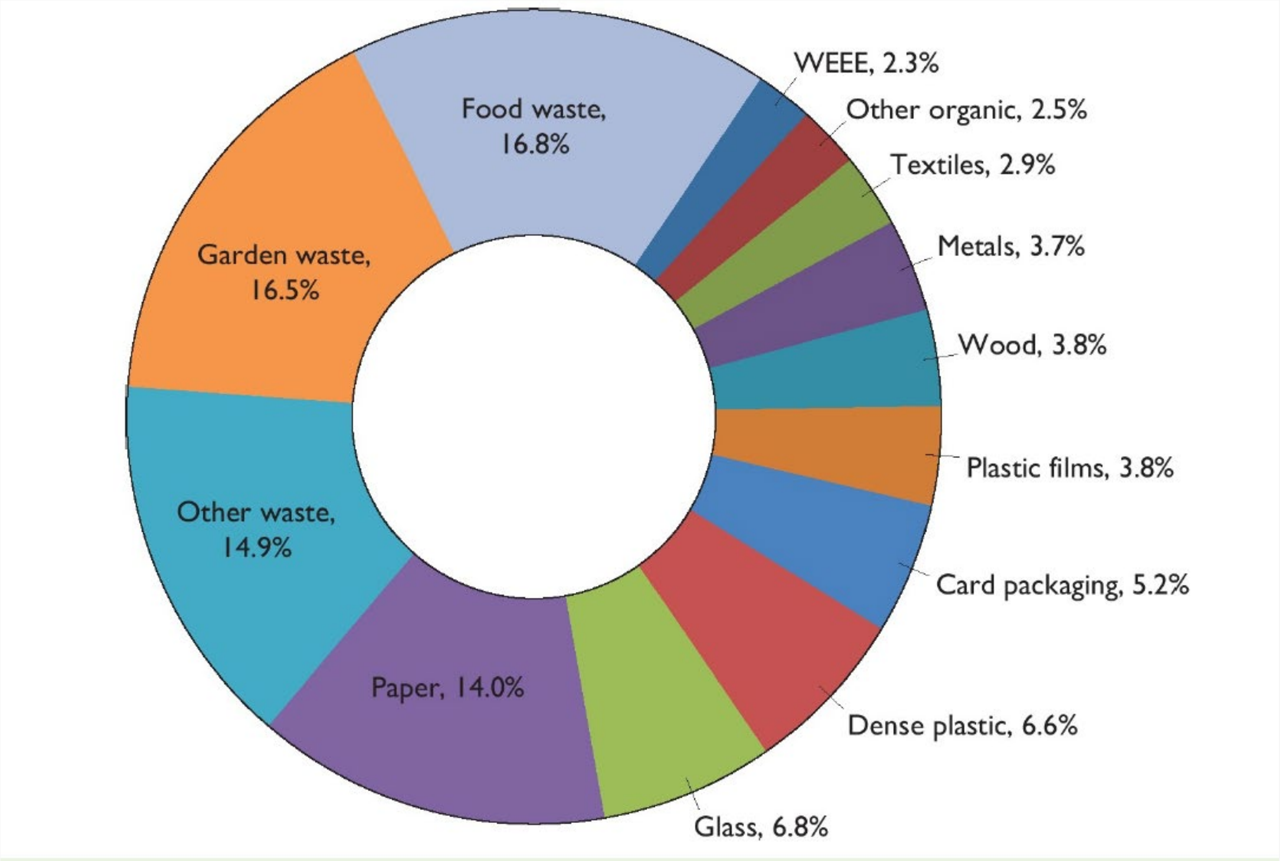
(5) Animal wastes: Manure from grazing livestock that is deposited in the field decomposes **aerobically** through respiration, releasing mainly carbon dioxide. However, manure and slurry from housed livestock that is stored in bulk decomposes **anaerobically** (in the absence of air) releasing methane rather than carbon dioxide.

(6) **Poultry litter:** a mixture of chicken droppings and material such as straw, wood shavings etc., has a relatively low moisture content compared to other manures, and an energy content in the range 9–15 GJ t−1.

Secondary Sources

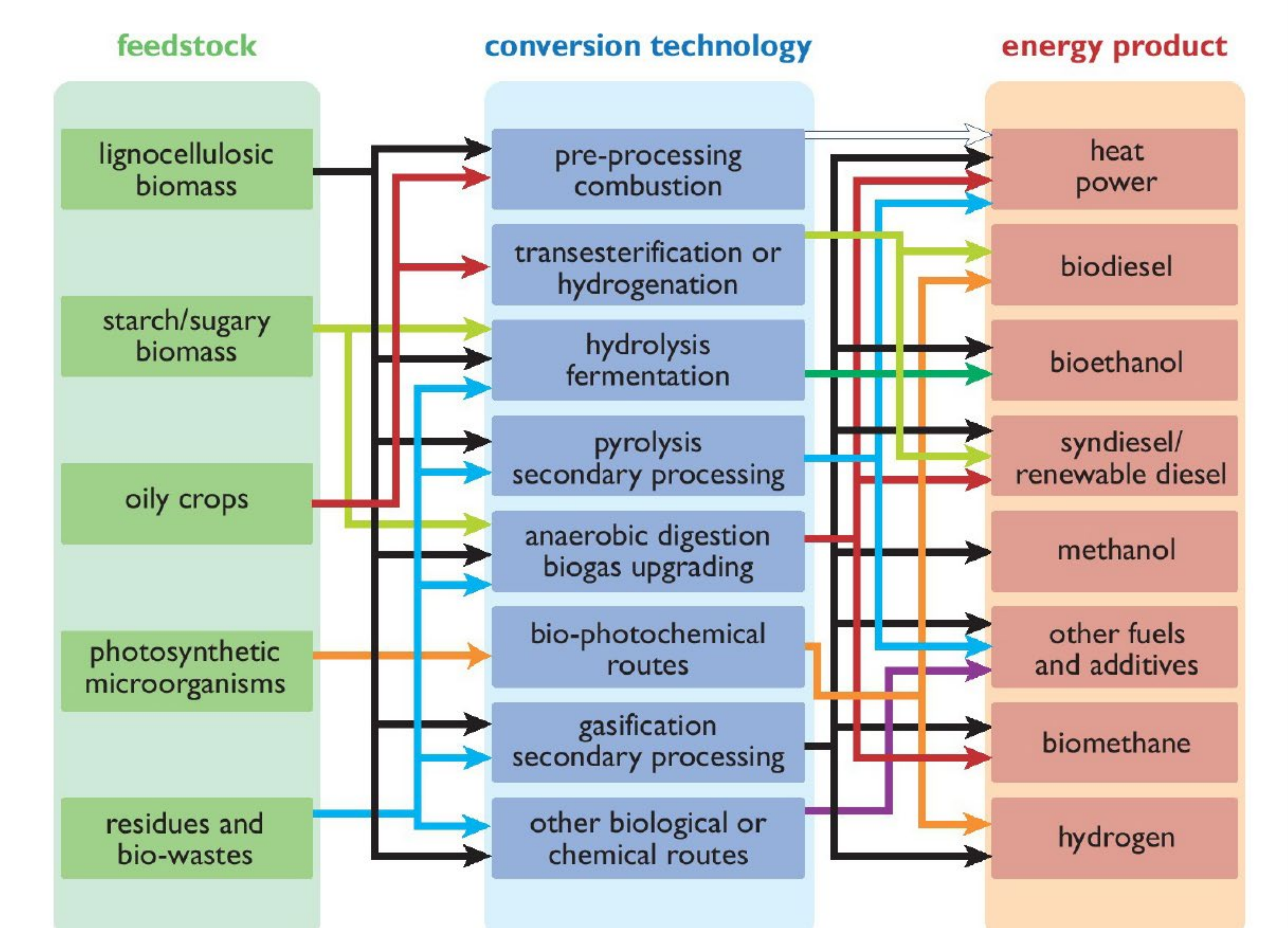
(7) Municipal solid waste

The average household in an industrialized country generates rather more than a tonne of solid waste per year



Bioenergy Processing & Conversion Technologies

Biomass Conversion Routes



Conversion Technologies for Solid Biomass

Firewood and chipped wood

40% of the world's population still relies on firewood for energy provision. Wood chips can be used alone as a power station fuel, or in a 15–30% co-firing mix with pulverized coal to yield an energy conversion of 33–37%.

Pelleting

Wood chips can be further refined to produce pellets, a process which requires further mechanical grinding before the resultant sawdust is compressed and extruded through 6–10 mm dies.

Charcoal and torrefaction

The development of charcoal through **pyrolysis,** wood materials are heated to 400 ˚C in the absence of air to make a product which is almost pure carbon. The consequent charcoal has an energy content of approximately 30 MJ kg^{-1}, can be burnt without flame or smoke and can reach temperatures of 2700 ˚C

Conversion Technologies for Liquid Biomass

Bioethanol

- Sugars are extracted from biomass feedstocks and converted to ethanol through fermentation.

- Fermentation is an anaerobic biological process where the simple sugars from the biomass feedstock are converted to alcohol and carbon dioxide via the action of microorganisms, such as yeasts.

- The ethanol product (C_2H_5OH) is then separated from other components using heat to distil the mixture; the ethanol boils off and can then be cooled and condensed back to liquid.

Anhydrous bioethanol is most commonly used as an extender in gasohol, which is gasoline containing a percentage of ethanol. Higher blends (typically 85% ethanol, 15% gasoline – designated E85) are used in flexible-fuel vehicles (FFVs).

The energy content of ethanol is about 30 GJ per tonne or 0.024 GJ per liter.

Conversion Technologies for Liquid Biomass

Table 5.7 Ethanol yield varies depending on feedstock type

Raw material	Litres per tonne*	Litres per hectare per year#
Sugar cane (stem)	70	400–12 000
Maize (grain)	360	250–2000
Cassava (roots)	180	500–4000
Sweet potatoes (roots)	120	1000–4500
Wood (stem)	160	160–4000

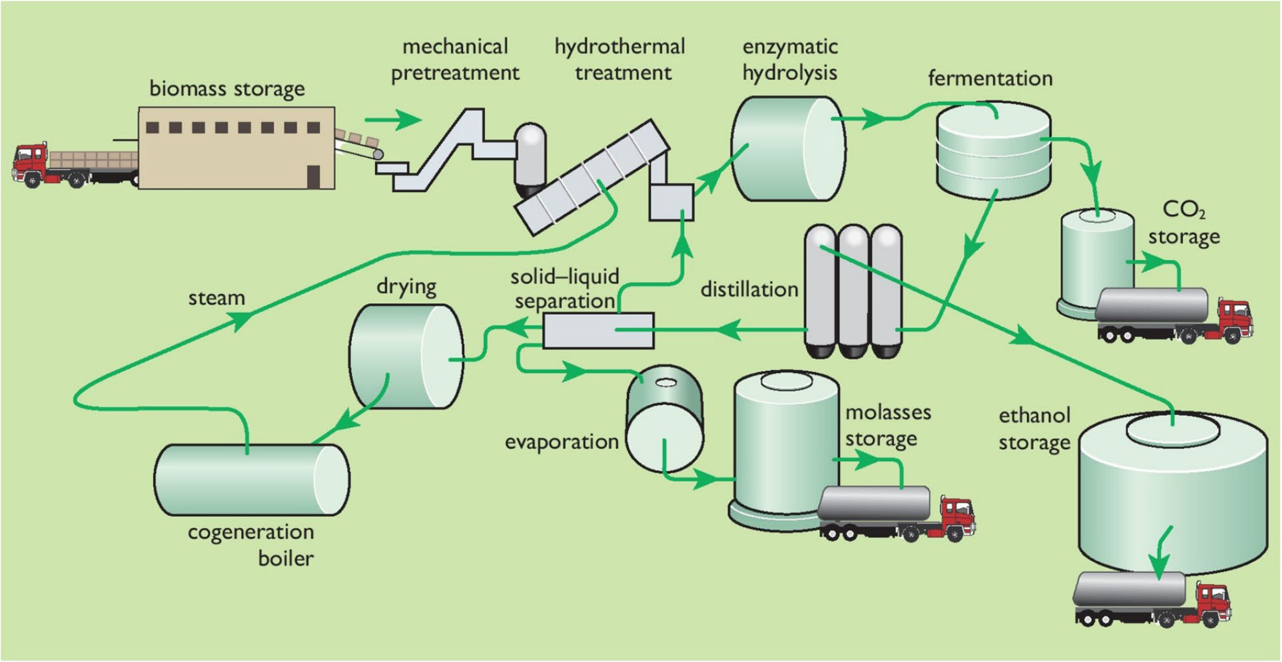


Figure 5.17 Schematic of the Inbicon integrated process for ethanol production from straw, where the co-generation boiler supplies steam for the hydrothermal treatment

Conversion Technologies for Gaseous Biomass

Anaerobic digestion for biogas

- Biogas can be produced through anaerobic digestion (AD) of organic wastes.

- It consists of 60–65 % methane and 30–35% of CO_2 plus smaller quantities of water vapor, H_2 and H_2S.

- The AD of biomass comprises four main steps, each of which is based on bacterial activity: (1) hydrolysis, (2) acidogenesis, (3) acetogenesis and (4) methanogenesis.

- Hydrolysis of large inorganic molecules such as carbohydrates, proteins and lipids yields relatively simple molecules of sugars, amino acids and fatty acids.

- These are then subjected to acidogenic bacteria that break them down into their basic compounds, some of which are organic acids, which are in turn acted upon by acetogenic bacteria to form acetic acid, along with H_2, NH_4 and CO_2.

- Finally, methanogenic bacteria facilitate the decomposition of acetic acid to methane and CO_2.

Conversion Technologies for Gaseous Biomass

- Worldwide electricity production from biogas in 2012 was in the region of 47–95 TWh, with China and Germany dominating the sector.

- Germany is the largest European producer of biogas, with nearly 9000 AD plants in operation in 2016, generating around 30 TWh or 5% of German electricity consumption

- China initiated large-scale programs for small-scale domestic AD starting in the 1970s. A later drive involving more commercial enterprises resulted in some 5 million domestic plants operating successfully by the mid-1990s, and tens of millions by the 2010s.

Conversion Technologies for Gaseous Biomass

- ***Gasification for syngas***
- Woody biomass undergoes three distinct transitions.

- Firstly, wood is dehydrated rapidly before temperatures exceed 200 ˚C, at which point pyrolysis is initiated and char and vapors are produced as previously detailed.

- At this stage, the presence of O_2 partially oxidizes the char and produces CO and CO_2, while the vapors are combusted to form CO_2 and H_2O.

- After further chemical reactions, a gaseous mixture of CO, H_2 and CO_2 is recovered, this is then known as syngas.

- The process of gasification, when applied to wood, gives an energy conversion rate of approximately 60%.

Discussion on Costs & Environmental Impact

Discussion Topics

- Atmospheric emissions of CO_2. methane, and nitrous oxide.
- Land use.
- Energy balance and efficiency.
- Economics of bioenergy.
- The future of bioenergy with carbon capture and storage.