John Andrews & Nick Jelley

Lecture 4:

Biomass

Overview

- Plants derive energy from Sun's radiation, which converts carbon dioxide and water into carbohydrate and oxygen by **photosynthesis**
- Traditional biomass provides **10% of global energy needs**, as wood, charcoal, dung, crop residues.
- Provided CO_2 from land clearance, fertilizing, and harvesting is low, biomass can be a **sustainable low-carbon** source of energy. But large areas of land required and there has been concern over competition with food production.

Photosynthesis

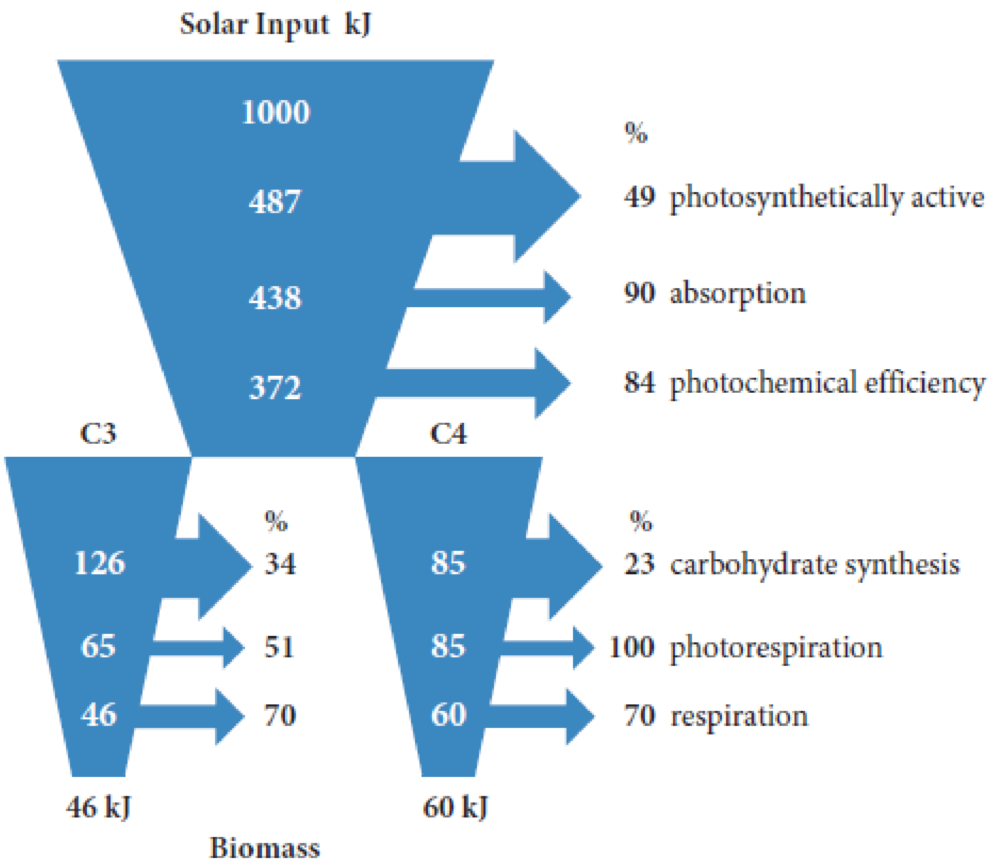
$$CO_2 + H_2O + h\nu \rightarrow O_2 + [CH_2O] \qquad (h\nu = \text{ photon, } [CH_2O] = \text{carbohydrate})$$

Photons used in photosynthesis is in **visible** part of the spectrum (400-740 nm)

Capture of CO_2 is by Calvin or **C3 cycle,** or by **C4 cycle,** or by **CAM**, an adaption to arid conditions. Only 3% of plants are C4 but they include **maize** and **sugarcane**, which have high energy yields.

Plants use the energy to grow, by **respiration** (= reverse of photosynthesis), which releases CO_2

Energy conversion



49% of sunlight is used in photosynthesis, of which

- 10% is reflected off leaves
- 16% is lost as heat

Simplest carbohydrates are **sugars**, e.g. glucose $C_6H_{12}O_6$

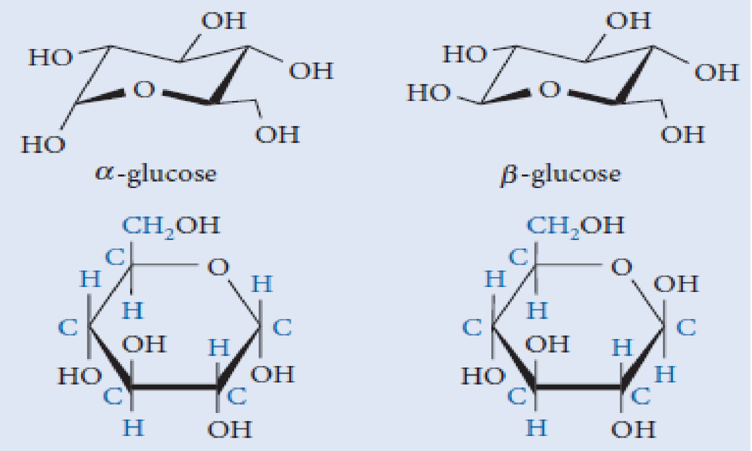


Fig. 4.2 α-glucose and β-glucose.

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Crop yield

Annual dry weight yield is given by

$$Y = S \times \varepsilon_i \times \varepsilon_c \times \eta$$

where

S = solar energy per unit area kWh m^{-2},
ε_i = fraction intercepted by leaves,
ε_c = conversion efficiency,
η = fraction of biomass harvested

Typically,

S = 2000 kWh m^{-2} = 72 TJ ha^{-1}
ε_i = 0.9
ε_c = 0.01
η = 1

yielding

Y = 160 GJ $ha^{-1} \approx$ 0.5 MWth km^{-2}
= 16 TJ km^{-2}
so **1 EJ** requires ~ **65000** sq km

Traditional biomass for heating and cooking for 3 billion people in developing countries is the main use biomass, typically 3 kg a day per person, corresponding to 50 EJ per annum. Biomass used for cooking is **polluting and inefficient** (10-20%).

In 2012, **bioenergy for heat** in buildings = 5 EJ, for industry = 8 EJ
c.f. ~400 EJ final energy demand

Biofuel production has grown from 16 billion litres in 2000 to 110 billion litres in 2013, but only expected to be ~ 140 billion litres in 2020

Cooking in the developing world

About **3 billion people use traditional biomass** (wood, charcoal, dung, agricultural waste) for cooking on open stoves or fires.

The resulting **air pollution** causes 4.3 million premature deaths a year.

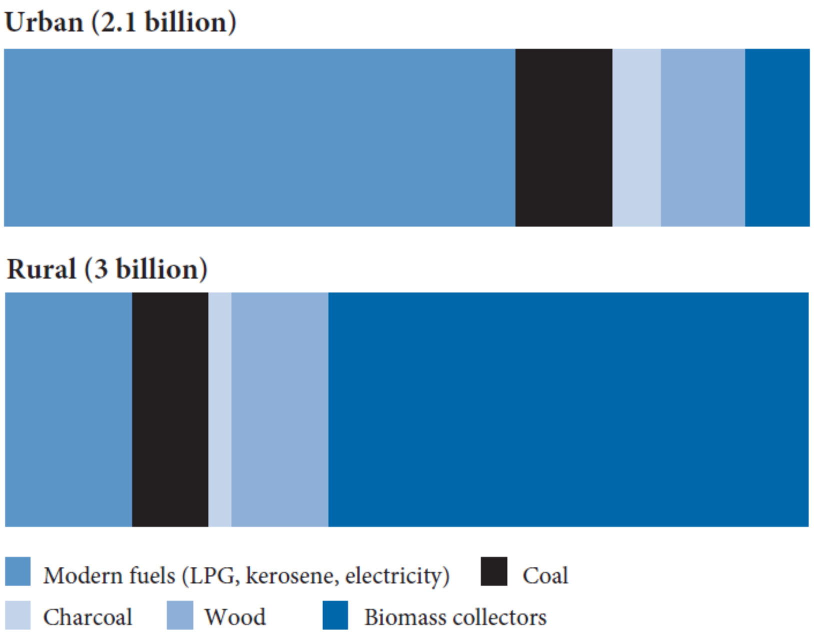

Fig. 4.7 Developing world population by primary cooking fuel.

Unregulated harvesting of wood causes devastating environmental effects.

Fig. 4.6 The Haiti Dominican Republic border.

Traditional Cook stoves in Africa

Fig. 4.8 (a) Traditional cooking pot. (b) Women collecting firewood.
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In rural areas, the traditional 3-stone wood heated stove is widely used.

Only about 15% of the heat is transferred to the cooking pot and the smoke is very damaging to health.

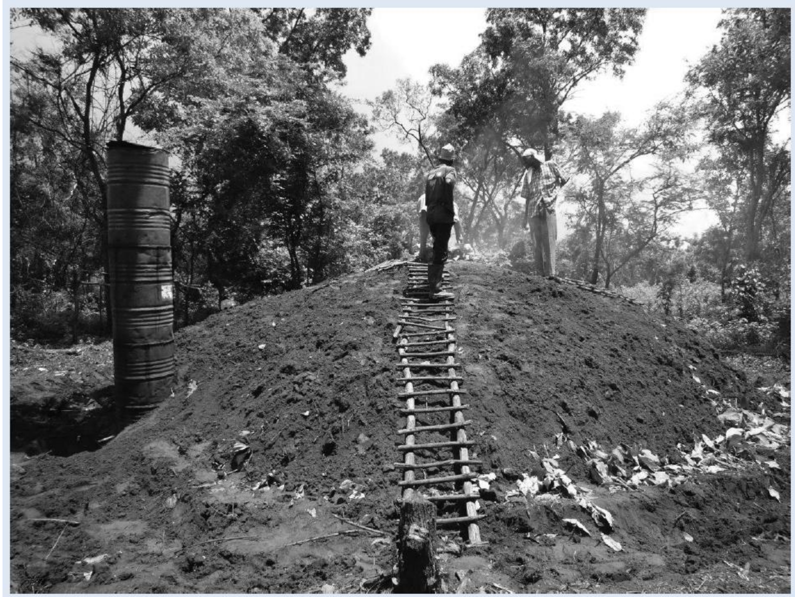
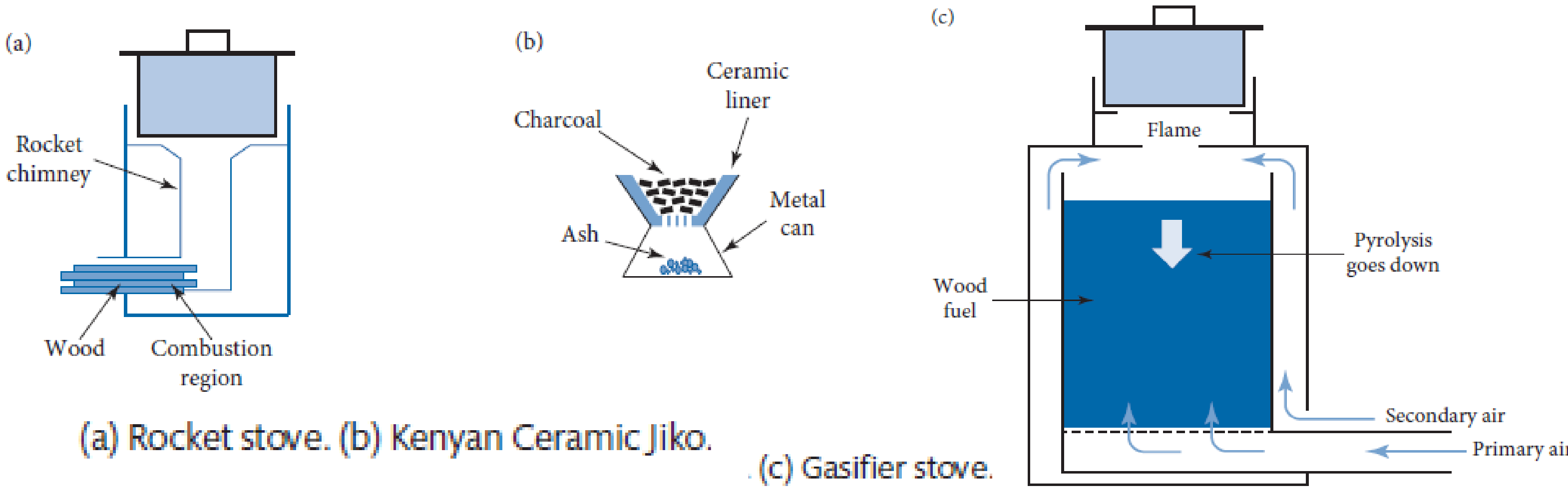


Fig. 4.9 Casamance charcoal kiln.

Improved cook stove designs



(a) Rocket stove. (b) Kenyan Ceramic Jiko. (c) Gasifier stove.

Table 4.1 Improved and clean cook stoves; emissions decrease from left to right

Improved cook stoves			Clean cook stoves	
Legacy[1] and basic	Intermediate ICS	Advanced ICS	Modern fuel	Renewable fuel
Small improvements in fuel efficiency-, typically locally made	Rocket-style with improved combustion and fuel efficiency	Fan or natural-draft gasifiers with good fuel and combustion efficiency	LPG, kerosene,[2] or electric stoves with high fuel efficiency and low emissions	Bio-gas, ethanol, solar, or retained heat stoves-, often used as supplementary

[1] Many probably perform below standard.
[2] There is evidence that in the field, kerosene stoves are often polluting.

Modern biomass for heat and power

Main use of modern biomass is to provide heat, e.g. in **CHP systems (80% efficient)**.

High transport cost, so **small local biomass plants** tend to be more economic.

For heat and power, the main sources are **agricultural and municipal waste**.

Waste need to be processed before it can be used as fuel. **Life cycle analysis** calculates the mass of CO_2 produced per kWh of energy produced.

Municipal solid waste MSW (or energy from waste EfW) produces **360 g per kWh**, compared with **970 g per kWh** from coal and **450 g per kWh** from a natural gas CCGT plant.

By-product of **anaerobic decomposition** of organic waste is **biogas** (mainly methane), used in developing countries for cooking and heating - 50 million homes in China.

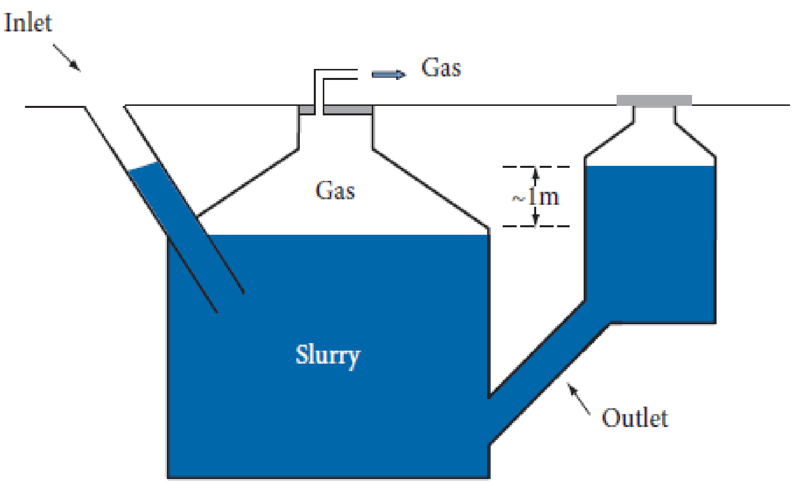


Fig. 4.11 A Chinese fixed-dome anaerobic digester.
Source: AD04.

CAM Biocrops

Useful biocrops have **large dry mass content,** which **reduces transport costs** for same energy generation.

e.g. **CAM plants** *Opuntia* 10%, *Euphorbia* 17%, which can grow on semi-arid land.

Typical yields: 12 t ha^{-1} y^{-1} (*Opuntia*),
20 t ha^{-1} y^{-1} (*Euphorbia*),

Fig. 4.12 *Opuntia ficus-indica.*

Global area of semi-arid land = 2.5 billion hectares. Assuming 10% of this area is used for energy crops, the electrical energy generated = 5 PWh

Table 4.3 Global energy potential from AD of CAM crops

Contributions	*Opuntia*	*Euphorbia*
Dry tonnes $ha^{-1}year^{-1}$	12	20
Equivalent thermal power ($W\ m^{-2}$)	0.68	1.14
Gas yield (biomethane litre kg^{-1})	325	260
Energy yield ($MJ\ kg^{-1}$)	11.59	9.28
Efficiency of AD	64%	52%
Efficiency of biomethane to electricity	41%	41%
Electrical power ($W\ m^{-2}$)	0.18	0.24
PWh from 10% semi-arid land ($2.5\ 10^8$ ha)	3.9	5.2

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Biofuels

Biofuels provide countries with **energy security** and have **lower CO_2 emissions** than fossil fuels.

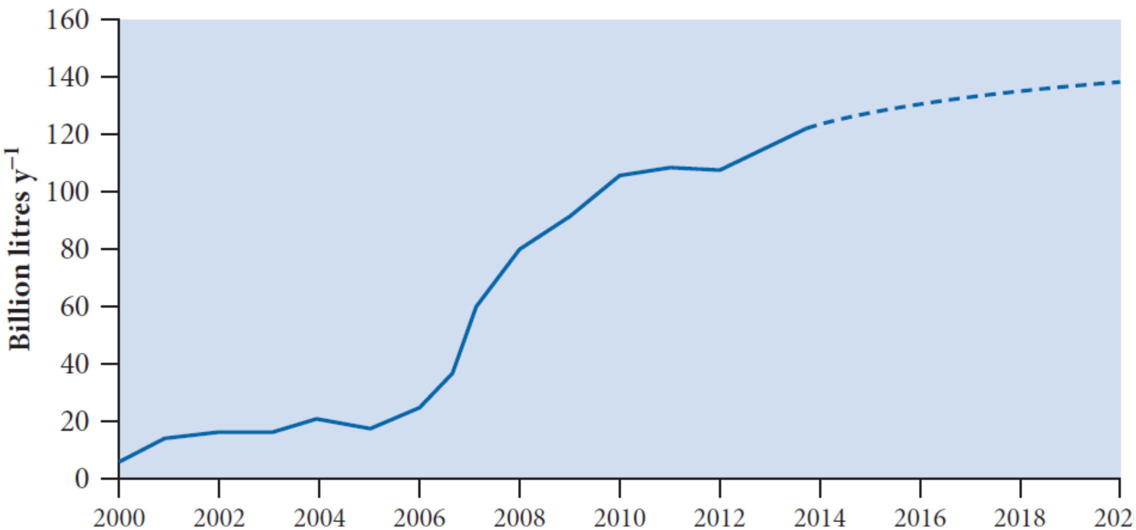

Fig. 4.14 Global biofuel production with estimate up to 2020 (IEA).
Source: Based on IEA data from Medium-Term Renewable Energy Market Report © OECD/IEA[2015], www.iea.org/statistics. Licence: www.iea.org/t&c; as modified by the author.

Slowdown in growth in last few years is due to concerns over their

- impact on food production and the environment
- cost relative to fossil fuels (due to fall in price of oil).

Note that **land clearance** for energy crops can release significant amounts of CO_2

The **fossil energy ratio** FER = (energy supplied to customer)/(fossil energy used) is a useful measure of the energy savings due to biofuels.

Biofuels contribute 15% of Brazil's domestic energy demand and 2.5% of the ~100 EJ global transport requirement.

Bioethanol from sugarcane

Sugarcane (or sugarbeet) contains glucose, which is easily extracted, and converted to **bioethanol** by fermentation by yeast or bacteria:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2, \quad \Delta H = -0.4\ \mathrm{MJ\ kg^{-1}}$$

FER for bioethanol = 8. The waste gas, **biogasse**, is used to provide heat and has a good FER.

These **first generation biofuels** need good-quality soil and lots of water, and compete for land with food crops.

USA (58%) and **Brazil (31%)** are the largest producers of bioethanol, which can be blended with gasoline.

Fig. 4.15 Sugarcane plantation (Sokari Ekine, sokariekine.me).

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Second generation biofuels

- In the US 15% of cropland would be needed to produce ~5 billion litres yr^{-1} bioethanol, equivalent to ~6% by energy of the gasoline consumed. Hence interest in starch rich plants, e.g. cassava and sweet sorghum, that will grow on degraded soil.

- The large group of cellulose-based plants such as switch grass will grow in marginal land unsuitable for food stocks.
- But extracting glucose from these second-generation biofuel plants has proved difficult. Enzyme hydrolysis not yet cost-effective and only ~40 million litres yr^{-1} is produced.

Biodiesel

- Biodiesel can be made from plant oils. In 2014 ~30 billion litres yr^{-1}, but only ~35 billion expected in 2020.
- Concern over food production when food crops such as palm trees planted. Hence interest in jatropha that grows on marginal land.
- Made by trans-esterification of vegetable oils with an FER of ~3.2. Can also be produced by hydroprocessing using hydrogen; then called renewable diesel.
- Microalgae typically contain 20-50% of their mass as oil and can produce up to 20 times more oil ha^{-1} than land crops. But after many years of R&D still not competitive.

Environmental impact of biomass

Feedstock	FER (location)	Biofuel (litre ha^{-1})	Cultivation on degraded land?	Water requirement	Replacement of CO_2 (y)
Corn	1.34 (USA)	3400	no	high	~50
Sugarcane	8 (Brazil)	6000	no	high	~20
Rapeseed	2.3 (EU)	1000	no	high	~50
Cassava	9 (Thailand)	~3000	yes	low	~0
Jatropha	6 (Thailand)	530	yes	low	~0
Palm oil	9 (Malaysia)	3750	no	high	~100
Switchgrass	5 (USA)	2800	yes	low	~0

Source: WorldBank2009.

Plants and soil contain about **2.7 times more CO_2** than in the atmosphere

Large scale biomass production needs **large areas of land**.

Land clearance and deforestation can release large amounts of CO_2

Bio-crops grown on cleared land can **replace the lost carbon** after some years (see Table).

Availability of water can be a major issue.

Global potential and economics of biomass

- **Large resources** of biomass **remain untapped**. Technical potential = 200-500 EJ (WEC2013)
- Traditional biomass provides about 10% of global primary energy demand, mainly in developing countries
- Biofuel production needs **large area**, currently 0.5 MW per km^2
- **Tax incentives** and **mandating the percentage share of biomass** in energy production (e.g. EU mandates) has helped development of biomass technologies. But **land clearance and low FERs** in production of some biofuel feedstock has had a negative impact on support for biofuels.
- Development of cost-competitive **second-generation** biofuels has proved much harder than anticipated

Key Points

- IEA estimate that modern biomass could provide an additional **15% of primary energy** demand by 2050, but growth has been such that **5-10%** more likely
- **Accessible potential** by 2050 for electricity generation = 200 GWe, 45 EJ for heat
- **Water availability** is a major issue for bioenergy crops – demand is already greater than sustainable supply
- Current **low cost of fossil fuels** and public misgivings over use of unsuitable land for bioenergy crops and over competition with **food production** has slowed the growth in biofuels.
- Biomass could contribute **15-20% of global energy needs** sustainably by 2050, given strong policy support.

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