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 CO₂ 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

\[ \text{CO}_2 + \text{H}_2\text{O} + h\nu \rightarrow \text{O}_2 + [\text{CH}_2\text{O}] \quad (h\nu = \text{photon}, \left[\text{CH}_2\text{O}\right] = \text{carbohydrate}) \]

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

Capture of CO₂ 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 CO₂
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 $\text{C}_6\text{H}_{12}\text{O}_6$
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\(^{-2}\),
- \( \varepsilon_i \) = fraction intercepted by leaves,
- \( \varepsilon_c \) = conversion efficiency,
- \( \eta \) = fraction of biomass harvested

Typically,

- \( S = 2000 \text{ kWh m}^{-2} = 72 \text{ TJ ha}^{-1} \)
- \( \varepsilon_i = 0.9 \)
- \( \varepsilon_c = 0.01 \)
- \( \eta = 1 \)

yielding

- \( Y = 160 \text{ GJ ha}^{-1} \approx 0.5 \text{ MWth km}^{-2} \)
- \( = 16 \text{ TJ km}^{-2} \)

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
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.

**Unregulated harvesting of wood** causes devastating environmental effects.

![Image](https://via.placeholder.com/150)

*Fig. 4.6* The Haiti Dominican Republic border. ©James P. Blair/ Getty Images

![Image](https://via.placeholder.com/150)

*Fig. 4.7* Developing world population by primary cooking fuel.
Traditional Cook stoves in Africa

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.
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

<table>
<thead>
<tr>
<th>Improved cook stoves</th>
<th>Clean cook stoves</th>
</tr>
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<tbody>
<tr>
<td>Legacy and basic</td>
<td></td>
</tr>
<tr>
<td>Small improvements in fuel efficiency, typically locally made</td>
<td>Rocket-style with improved combustion and fuel efficiency</td>
</tr>
</tbody>
</table>

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\textsubscript{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.
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*),

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

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.
Biofuels provide countries with **energy security** and have **lower CO₂ emissions** than fossil fuels.

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 CO₂.

The **fossil energy ratio** \( \text{FER} = \frac{\text{(energy supplied to customer)}}{\text{(fossil energy used)}} \) 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:

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

FER for bioethanol = 8. The waste gas, biogas, 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.
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

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.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>FER (location)</th>
<th>Biofuel (litre ha$^{-1}$)</th>
<th>Cultivation on degraded land?</th>
<th>Water requirement</th>
<th>Replacement of CO$_2$ (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>1.34 (USA)</td>
<td>3400</td>
<td>no</td>
<td>high</td>
<td>~50</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>8 (Brazil)</td>
<td>6000</td>
<td>no</td>
<td>high</td>
<td>~20</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>2.3 (EU)</td>
<td>1000</td>
<td>no</td>
<td>high</td>
<td>~50</td>
</tr>
<tr>
<td>Cassava</td>
<td>9 (Thailand)</td>
<td>~3000</td>
<td>yes</td>
<td>low</td>
<td>~0</td>
</tr>
<tr>
<td>Jatropha</td>
<td>6 (Thailand)</td>
<td>530</td>
<td>yes</td>
<td>low</td>
<td>~0</td>
</tr>
<tr>
<td>Palm oil</td>
<td>9 (Malaysia)</td>
<td>3750</td>
<td>no</td>
<td>high</td>
<td>~100</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>5 (USA)</td>
<td>2800</td>
<td>yes</td>
<td>low</td>
<td>~0</td>
</tr>
</tbody>
</table>

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 km²

- **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.