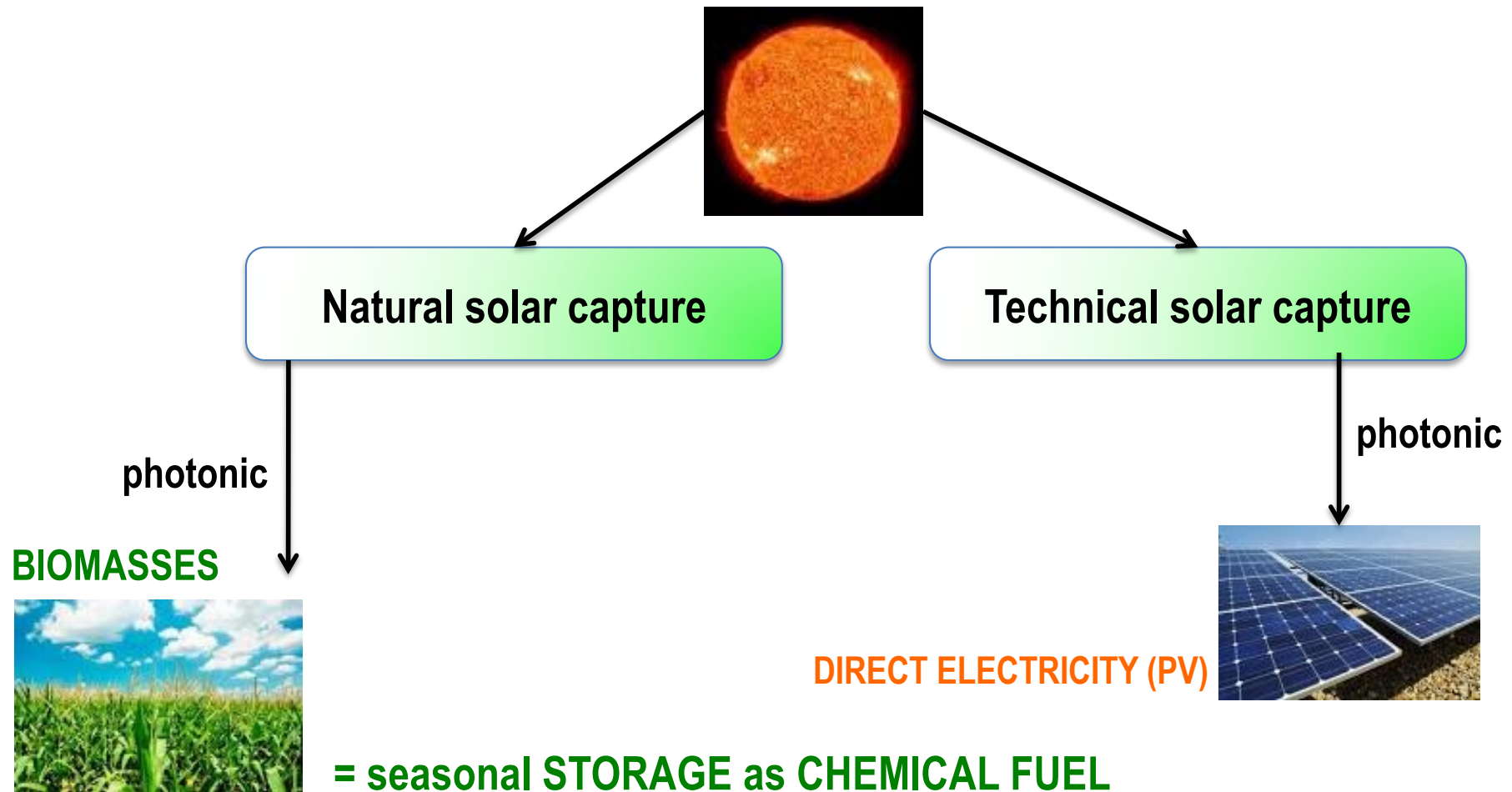


Biomass: resources & conversion technologies



Biomass overview

- Definitions
 - Photosynthesis, compositions, structure
- Potential
- Conversion technologies
 - 1. Solids** (wood; energy crops)
 - combustion
 - pyrolysis
 - gasification
 - 'secondary' fuels
 - 2. Liquids** (bioethanol; biodiesel)
 - fermentation
 - extraction
 - application as motor fuels
 - 3. Gas** (biogases)
 - anaerobic digestion
 - bio(electro)catalysis

Learning objectives

- Distinguish the types of biomasses
(and the appropriate conversion route per biomass type)
- Theoretical potential (photosynthesis efficiency) and estimates of real biomass potential
- Awareness of 'energy vs. food' competition
- Advantages & drawbacks of biomass as energy carrier
 - especially 'residual' biomass
- ~know the chemical structure of biomass (ligno-cellulose)
- Estimate the LHV of a biomass from its composition

Biomass and its solar origin

- indirect solar:
 - hydro power (potential energy; high density 1000 kg/m^3)
 - wind power (kinetic energy; low density 1.2 kg/m^3)
- direct solar:
 - thermal capture:
 - flat collectors (=> hot water)
 - concentrated collectors (parabolic mirrors, parabolic troughs, heliostats) => for power generation
 - **photonic capture**:
 - photovoltaic power
 - biomass

Definition of biomass

*Organic matter from **biological** origin, on an immediate or 'recent' timescale.*

(though trees may grow hundreds of years old...)

*The typical timescale is **weeks to years**.*

Fossil fuel ('CH₂') is decayed biomass ('CH₂O') that has lost the oxygen.

Theoretical solar capture potential

PHOTOSYNTHESIS



Solar radiation arriving at the outer atmosphere:

5.5 E+24 J/yr (1368 W/m², solar constant)

Solar radiation on Earth's surface (where vegetation can capture it)

averages out on a yearly basis to **5.1 E+23 J/yr**

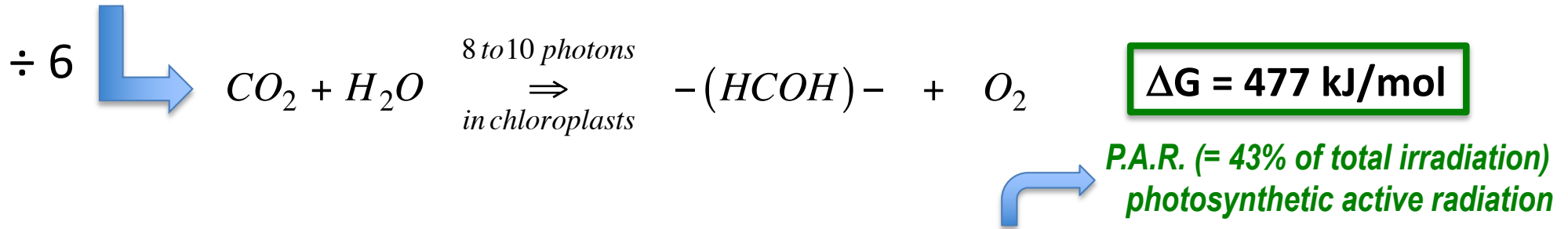
(~160 W/m², 5 GJ/m².yr ≈ 1400 kWh/m².yr)

Compared to world annual primary energy:

6 E+20 J/yr (= 600 EJ = 14 Gtoe)

→ theoretical potential ≈ **850 times** the human primary energy need

Theoretical photosynthesis efficiency



Considering red (660 nm), blue (450 nm) or white light (400-700 nm visible spectrum), and Planck's formula,

$$E_{\text{photon}} = h \cdot \nu = h \cdot \frac{c}{\lambda} \quad \begin{array}{l} h = 6.62 \cdot 10^{-34} \text{ Js} \\ c = 3 \cdot 10^8 \text{ m/s} \end{array} \quad \begin{array}{l} \text{Planck's constant} \\ \text{speed of light} \end{array}$$

photon energy amounts to $\frac{2 \cdot 10^{-16}}{\lambda \text{ (in nm)}} \text{ J/photon}$

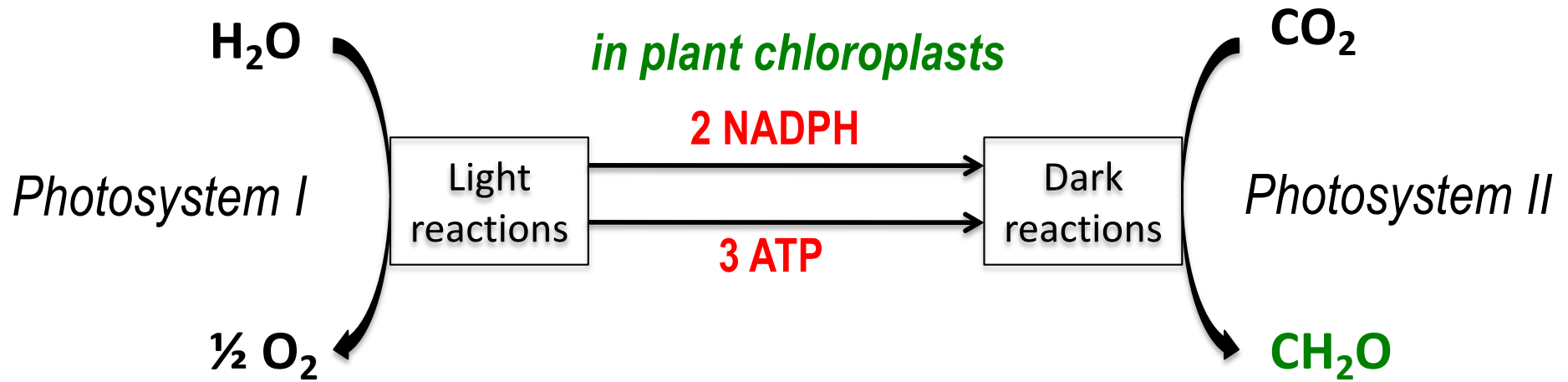
Hence for 1 mol of photons ($\times 6.02 \cdot 10^{23}$) $\rightarrow \frac{120}{\lambda \text{ (in nm)}} \text{ MJ/mol}$

- \rightarrow red (660 nm): 181.2 kJ/mol
- \rightarrow blue (450 nm): 265.6 kJ/mol
- \rightarrow white (577 nm): 208.1 kJ/mol

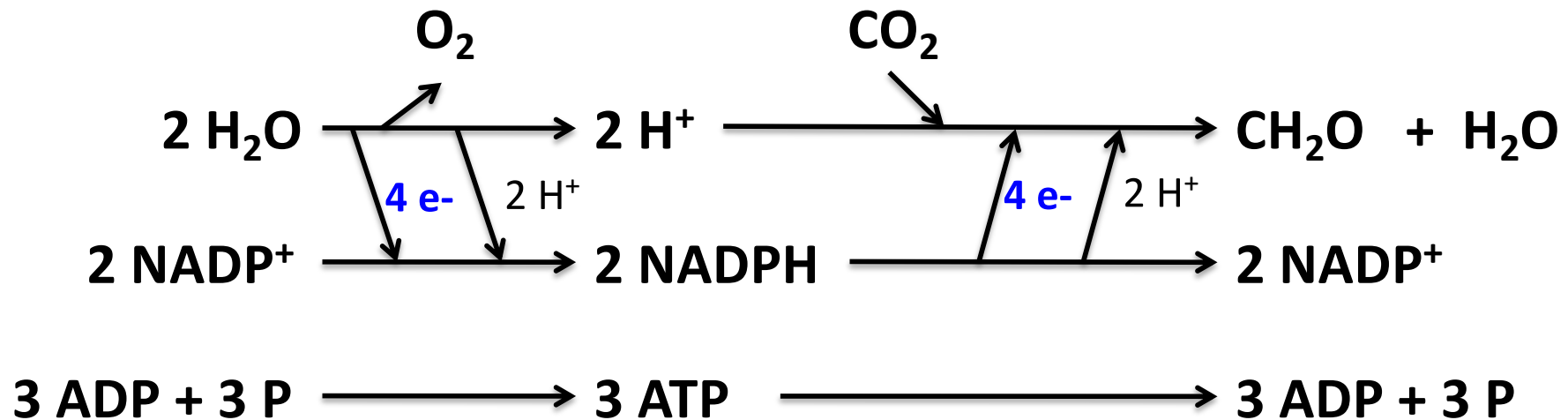
Theoretical P.S. efficiency (white light) is then, considering 8 photons for -HCOH- synthesis:

$$\frac{\text{glucose output}}{\text{photonic input}} = \frac{477 \text{ kJ/mol}}{8 \text{ photons} \cdot 208.1 \text{ kJ} / 1 \text{ mole of white light photons}} = 28.6\%$$

“Light” & “dark” reactions in plants

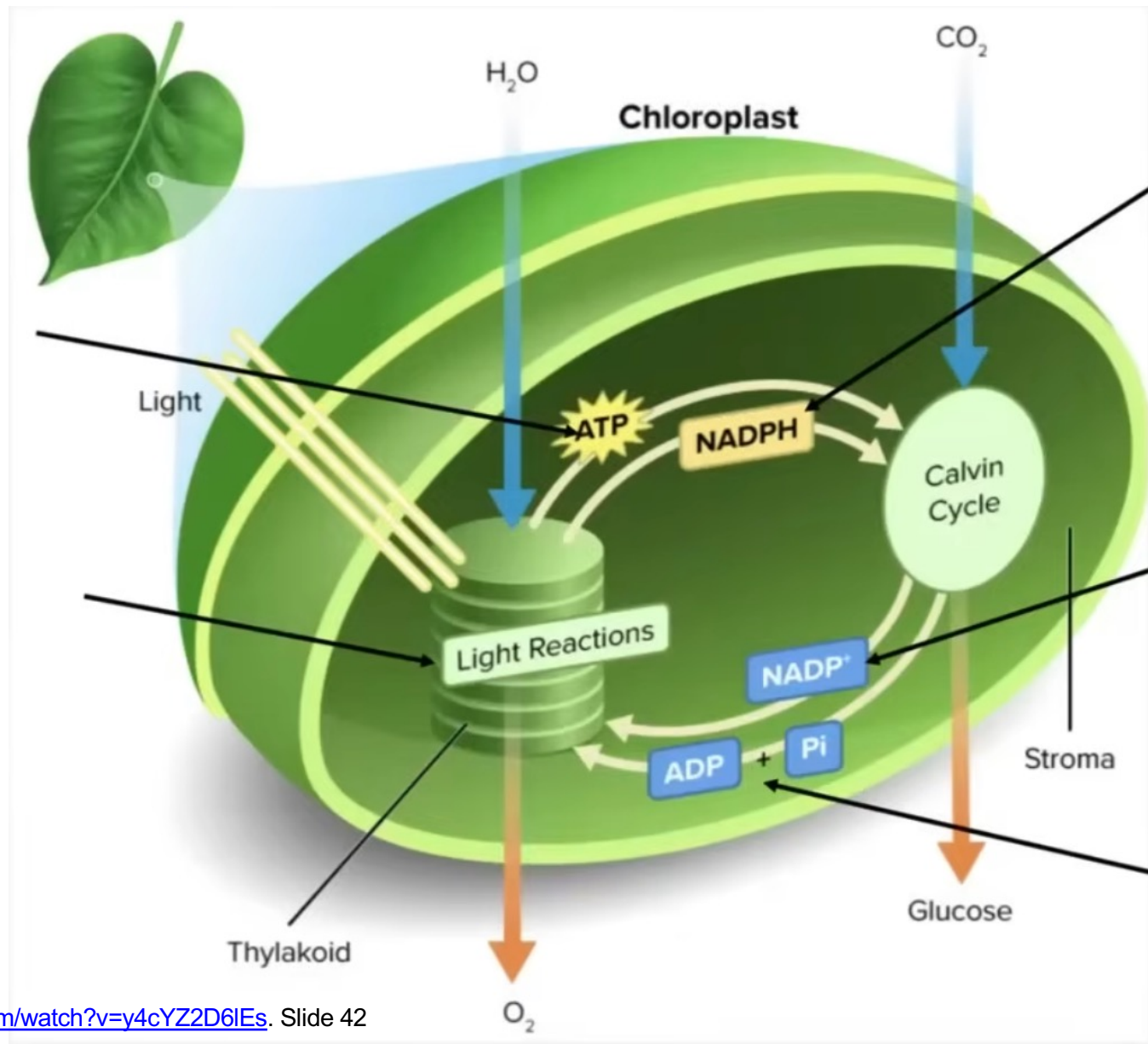


enzymatic fixation of CO_2 to glucose sugar by reduction by **NADPH**
 (8 electrons transfer = 8 photons)



electrons energy requirement for the reaction : $1.42 \text{ eV} = 137 \text{ kJ/mol}$

Chloroplasts where photosynthesis occurs

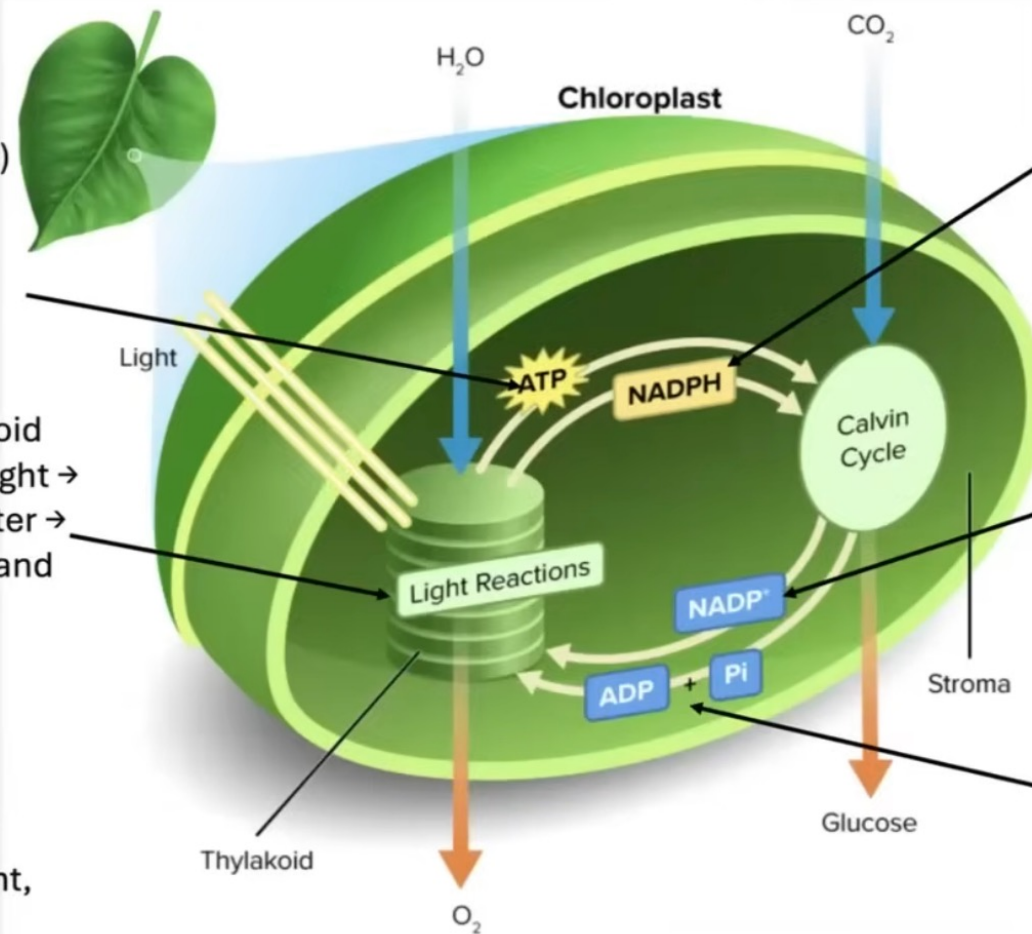


<https://www.youtube.com/watch?v=y4cYZ2D6IEs>. Slide 42

ATP (Adenosine Triphosphate)
The cell's energy currency -
produced in the light
reactions and used to power
the Calvin cycle

Chlorophyll sits in the thylakoid
membranes. It absorbs sunlight →
excites electrons → splits water →
releases O₂ and powers ATP and
NADPH formation.

Chlorophyll absorbs light
(energy) mainly in the blue
(≈430 nm) and red (≈660 nm)
parts of the visible spectrum
It absorbs *very little* green light,
which is why plants appear
green (they reflect it).



NADPH High-energy electron
carrier - delivers reducing
power (electrons + hydrogen)
to build sugars in the Calvin
cycle

NADP⁺ The empty electron
carrier - returns from the
Calvin cycle to the light
reactions to be re-energised
into NADPH

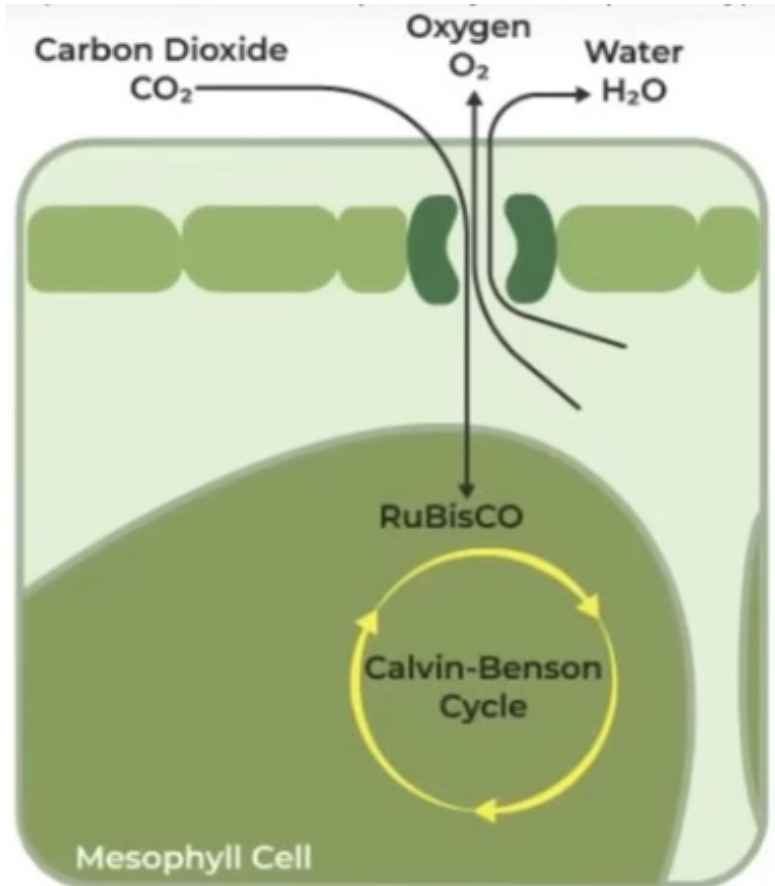
ADP + Pi Is a low-energy
form of ATP - recycled in the
light reactions to make fresh
ATP using sunlight

Evolution pathways of photosynthesis

- The enzyme Ru-bis-Co* evolved 3 bio yrs ago, when CO₂ ≈1% (very volcanic Earth, no plants). 'Rubisco' and the Calvin cycle already started in cyanobacteria
- Cyanobacteria, which generated O₂ in the atmosphere, became the chloroplasts in plants
- C3-plants evolved 400 mio yrs ago : trees, grasses, wheat, rice, when CO₂ ~3000 ppm. They removed huge amounts of CO₂ and became the coal deposits (Carboniferous)
- C4-plants evolved 30 mio yrs ago when CO₂ became scarce (400 ppm) : energy plants corn, sugarcane, sorghum
- CAM-plants (cacti, that conserve H₂O) evolved 20-25 mio yrs ago in deserts at low CO₂ 250 ppm

**Ribulose 1,5-biphosphate carboxylase / oxygenase*

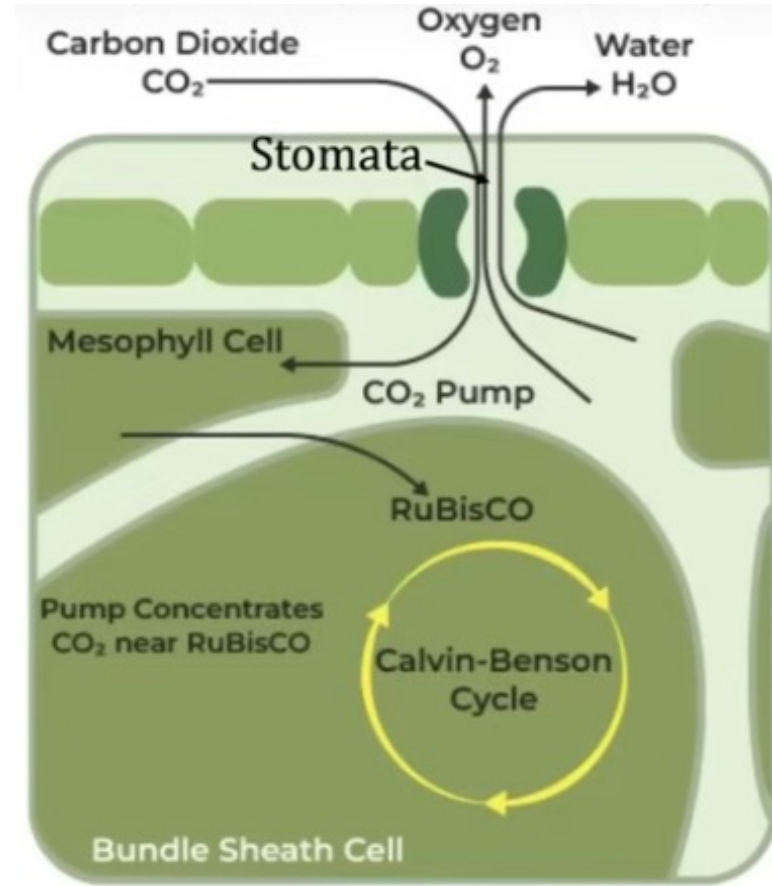
C3-pathway



In high CO_2 atmosphere

Instead of transferring CO_2 directly to RuBisCo (C3 plant), which also binds O_2 to photorespiration (CO_2 release), a C4 plant first concentrates CO_2 internally before transferring it to RuBisCo

C4-pathway



In low CO_2 atmosphere.

Geological time scale : CO₂ globally falling

From >2000 ppm 65 Myr ago, CO₂ started to drop steadily, which caused the emergence of **C4** plants, less sensitive to CO₂ level than **C3** plants.

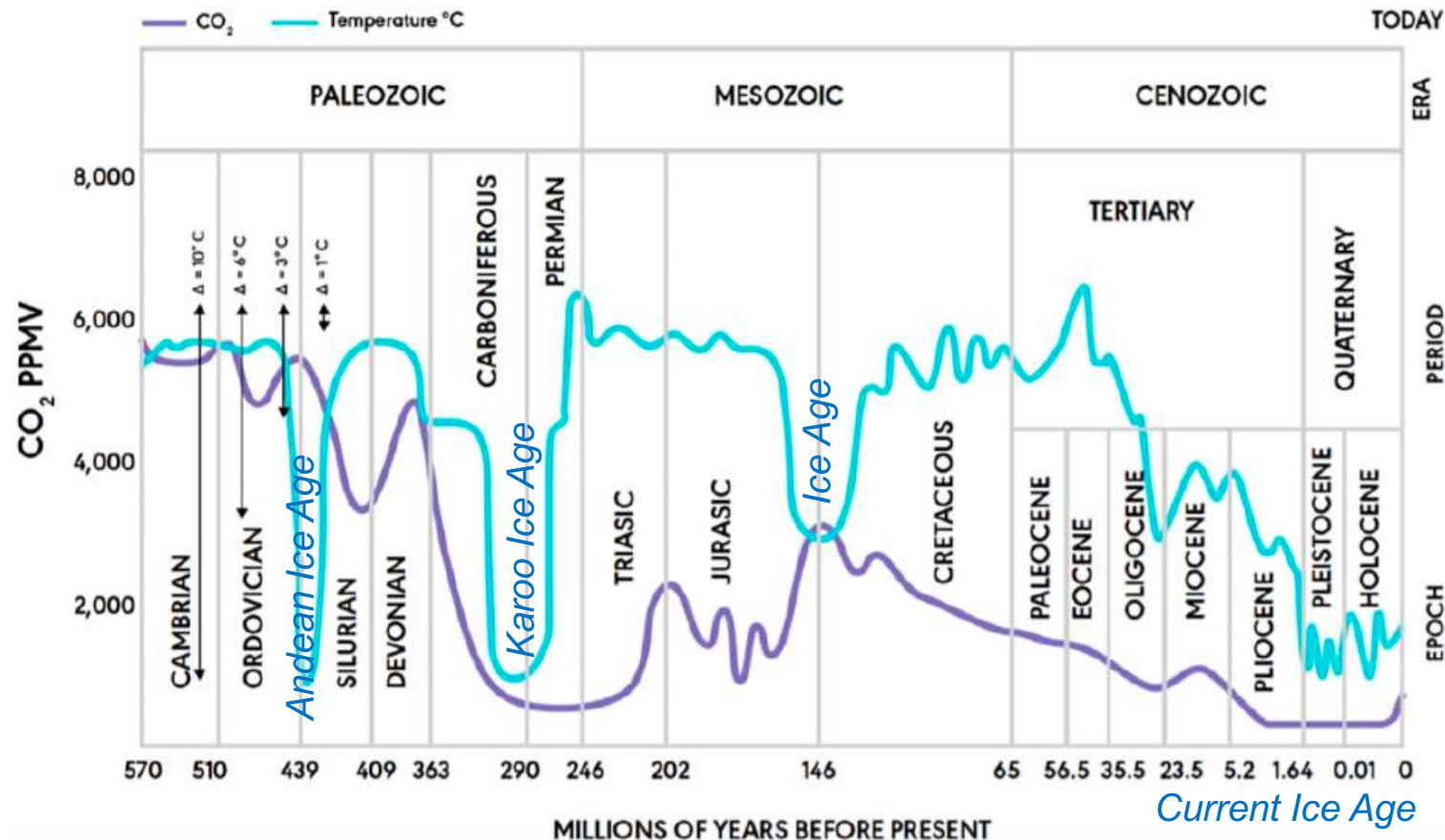


Figure 51. Global temperature and atmospheric CO₂ concentration over the past 570 million years. Purple line is CO₂ concentration (ppm); blue line is change in temperature ($\Delta^{\circ}\text{C}$). **Horizontal scale is not in constant units.** CO₂ scale derived from ratios to levels at around 1911 (300 ppm) calculated by Berner and Kothavala (2001). Source Idso et al. (2019) adapted from Nahle (2007), referencing Ruddiman (2001), Scotese (2003), Pagani et al. (2005).

Real biomass photosynthetic efficiency

Process / Maximal solar input on ground level: 1400 kWh/m ² .yr or 160 W/m ² = ↓	100%
Solar radiation energy → photosynthetic active part, PAR (400-700 nm)	43%
Maximum capture by leafs (canopy) = 80%	34.4%
Maximum photonic energy capture efficiency into glucose = 28.6%	9.8%
1/3 on average of the glucose energy is used for the plant metabolism (respiration)	6.6%
Max. practical efficiency of 'C-4' 'energy' plants (corn, sorghum, sugar cane), daily basis (24h)	5%
Max. practical efficiency of 'C-3' common plants (=95% of biomass, e.g. wheats, rice, trees,...), daily basis (24h)	3%
→ from the available 5.1 E+23 J/yr radiation (1400 kWh/m ² .yr), thus 3% is theoretically captured by common biomass (42 kWh/m ² .yr = 150 MJ/m ² .yr)	1.5 E+22 J/yr (4.8 W/m ²)
Climate factors, shading, and biomass density per m ² drop this capture efficiency by another factor 5 (→ 1 W/m ² = 8.4 kWh/m ² .yr = 30 MJ/m ² .yr ≈ 2 kg wood/m ² .yr)	0.6% 3 E+21 J/yr

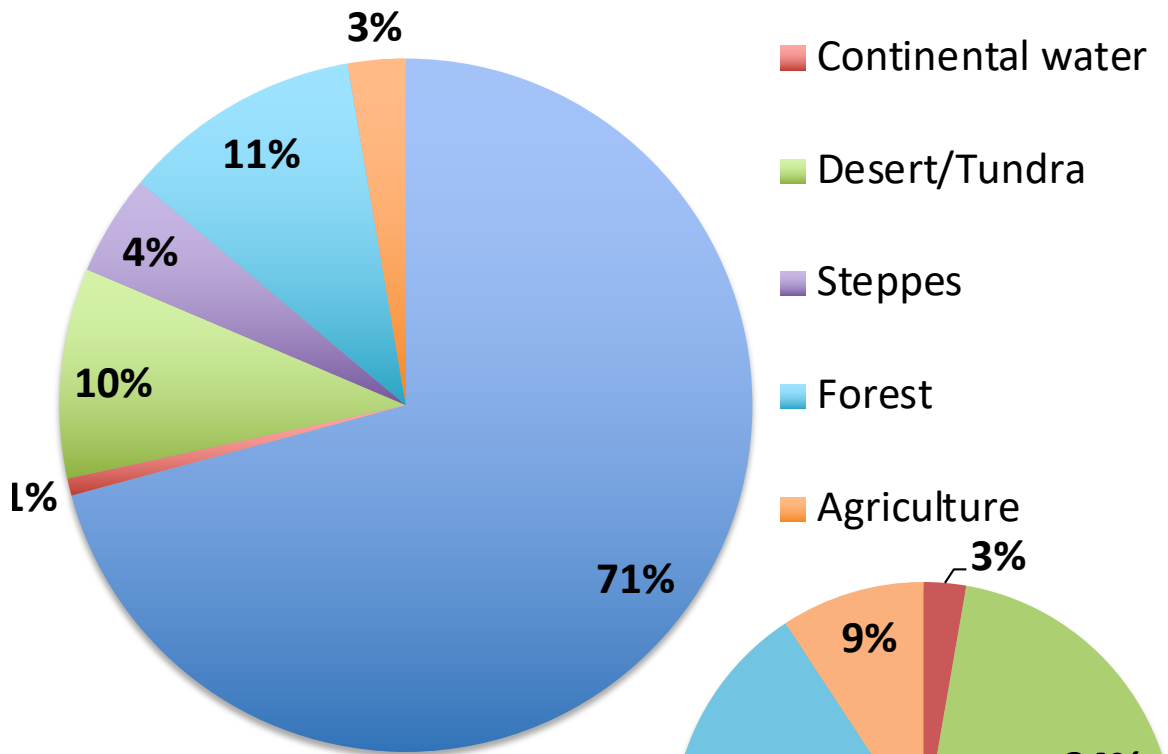
1 W/m² is a rather poor storage density !

Even for the '2 kW-society', every citizen would then need his personal 2000 m² 'storage'

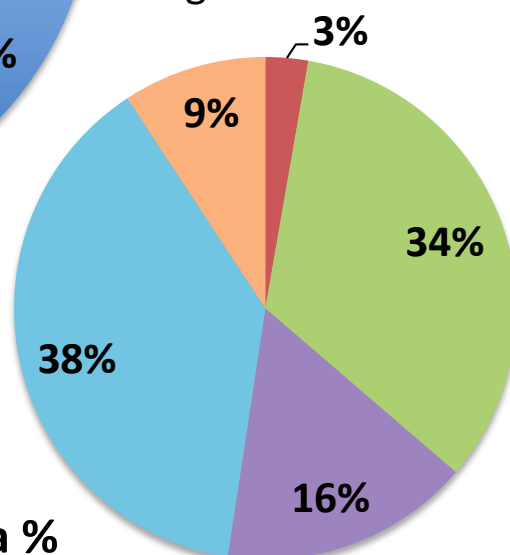
Biomass production of the biosphere

$3 \cdot 10^{21}$ J/yr = 3000 EJ \approx 70 Gtoe \approx 95 TW \approx 5 x the world annual primary energy

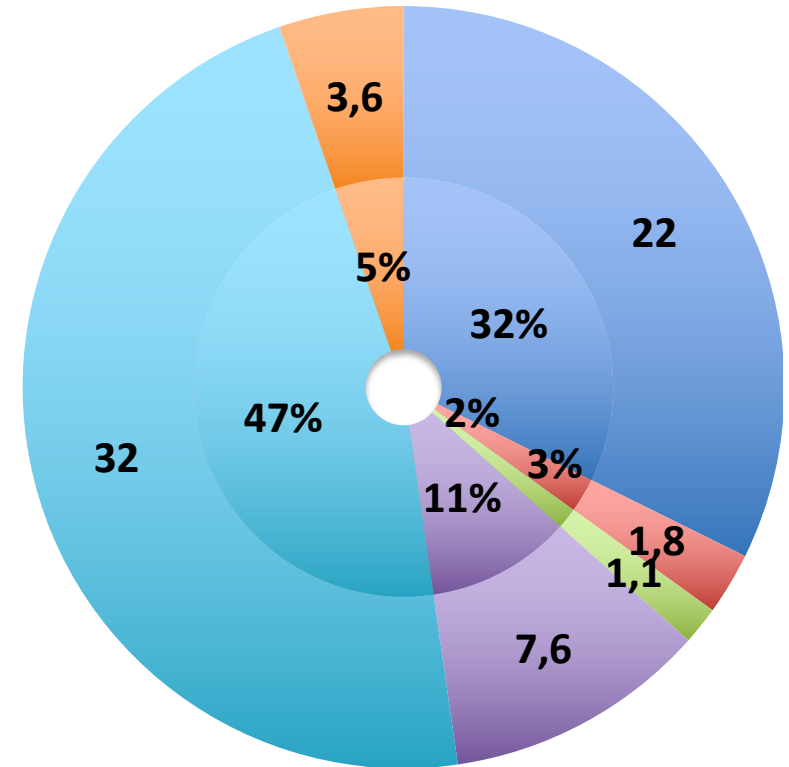
GLOBE AREA (%)



Land area %



in Gtoe



\Rightarrow 'wood': >2 x the world annual energy

\Rightarrow 'food': $\frac{1}{4}$ the world annual energy

Sustainable biomass potential

- Primary production of biomass in the biosphere ($3 \cdot 10^{21}$ J)
 $\approx 200 \cdot 10^9$ t (dry) /yr (assuming 15 MJ per kg dry biomass)
- Theoretically exploitable : 57% (w.o. oceans, desert,..)
- **Technically sustainable*** : ca. **9%**
= **agriculture (5%)** + ca. 10% of forestry (47%), cf. previous slide
($\approx 4\%$ of the Earth's total surface, or $\approx 13\%$ of the emerged lands)

= $18 \cdot 10^9$ t (dry) / yr

= $270 \cdot 10^{18}$ J = 270 EJ (6.4 Gtoe)

= **40% of world annual primary energy (620 EJ)**

(half of which (150 EJ) is used/meant for food, mainly)

Influence factors: :

↙ ca. 20% could be recovered as energy from the residues

nutrition, moisture, CO₂ concentration, light, temperature, leaf anatomy,..

On practical terms, the sustainable biomass energy potential might be estimated to $\approx 30\%$ (180 EJ) of the present human energy needs, itself composed mostly from wood (>120 EJ) and the remainder from other biomass sources.

Examples of real biomass yield

(in case of 0.6% efficiency = 30 MJ/m².yr = **300 GJ/ha.yr**; 1 ha = 1 hectare = 10'000 m²)

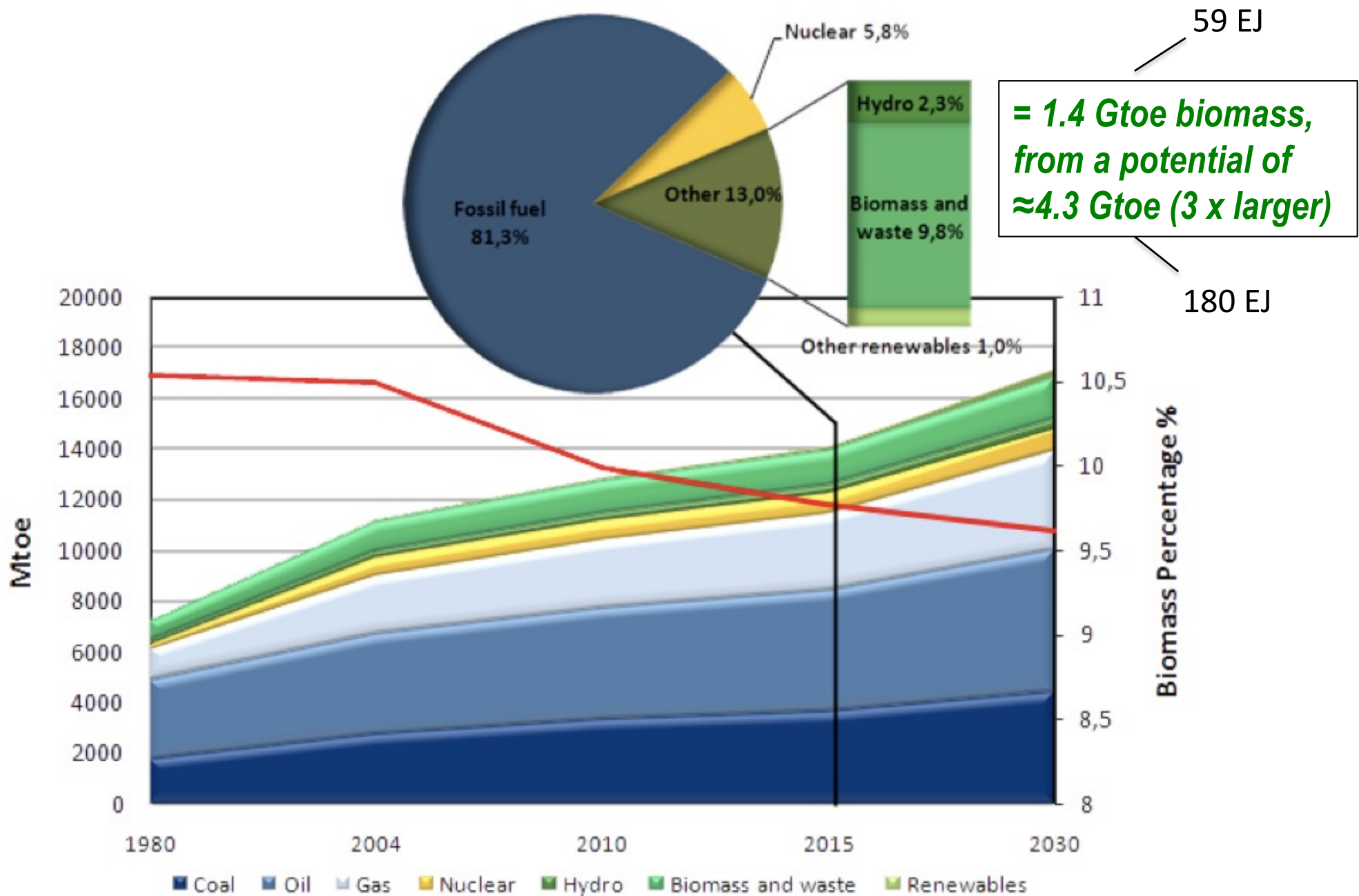
Plant	Energy output (GJ/ha/year)
1. Switchgrass	185...215
2. Miscanthus	Up to 785 (calc. with LHV=17,8 MJ/kg)
3. Sugar beet	62...96
4. Rape seed	14...78
5. Sweet sorghum	54...58
6. Wheat	23...47
8. Wood (forest)	100 (calc. on 50% dm with 10 t/ha yield)

*real yield ≈
typically
10-30%
only of the
possible yield!
(i.e. ≈0.1%
photosynthetic
efficiency)*

Sources:

- 1) 1: I.C. Madakadze et al.:Light interception, use-efficiency and energy yield of switchgrass (*panicum virgatum* L.) grown in a short season area. Biomass and Bioenergy, vol 15, No. 6, pp. 475-482, 1998
- 2) 2: I. Lewandowski et al.:Miscanthus: European experience with a novel energy crop, Biomass and Bioenergy 19 (2000) 209-227
- 3) 3-6: P. Venuri, G. Venuri: Analysis of energy comparison for crops in European agricultural systems. Biomass and Bioenergy 25 (2003) 235-255
- 4) Phyllis database available at <http://www.ecn.nl/phyllis/>

Biomass exploitation reality



Earth is **greening**: increase in **biomass**

Nature Climate Change vol 6, pp 791–795 (2016)

32 authors, 24 institutions, 3 different satellite data sets, over 35 years

LETTERS

NATURE CLIMATE CHANGE DOI: 10.1038/NCLIMATE3004

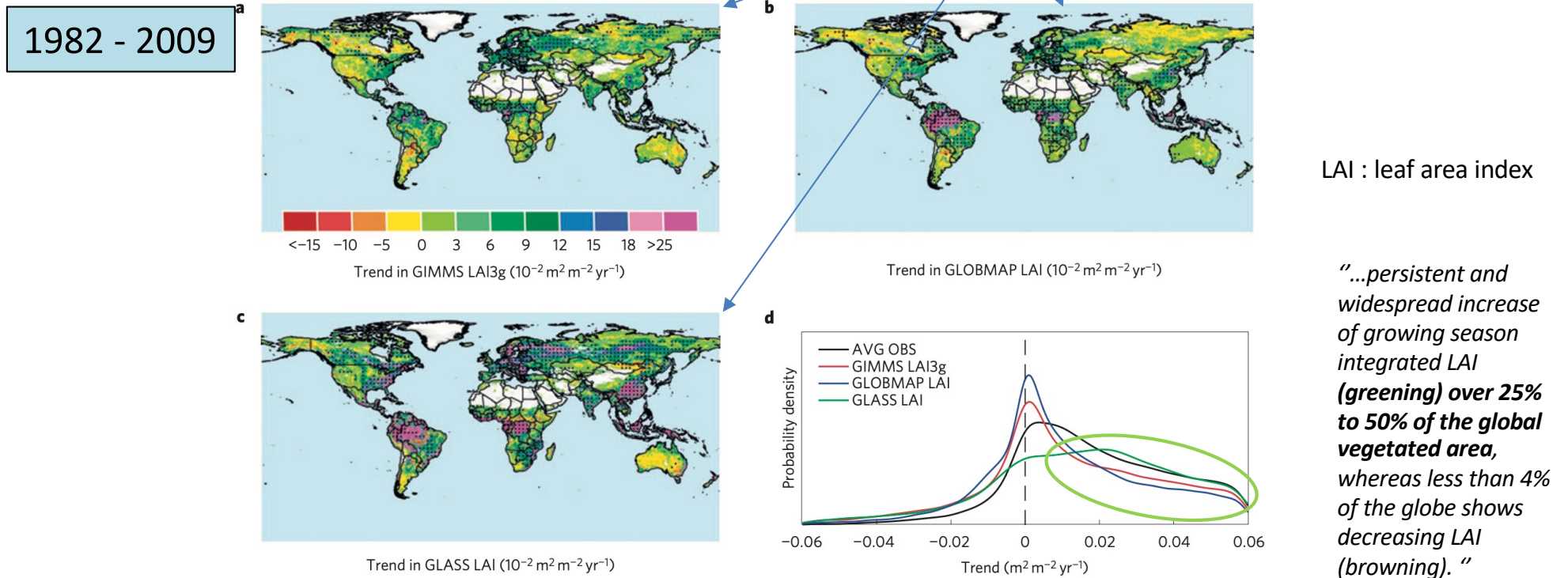
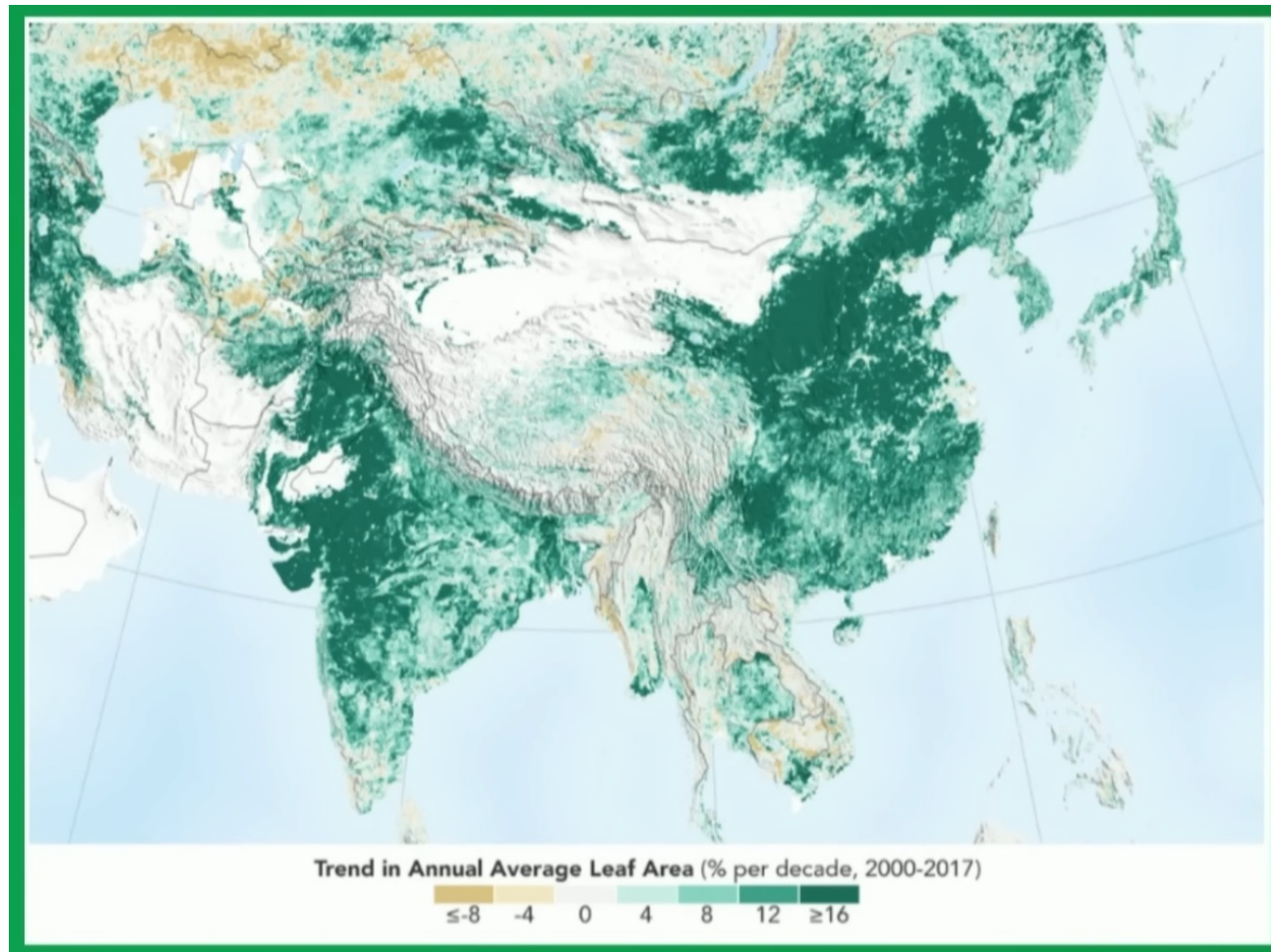


Figure 1 | Trend in observed growing season integrated LAI. a–c, Spatial pattern of trends in growing season integrated LAI derived from three remote sensing data sets. **a,** GIMMS LAI3g. **b,** GLOBMAP LAI. **c,** GLASS LAI. All data sets cover the period 1982 to 2009. Regions labelled by black dots indicate trends that are statistically significant (Mann-Kendall test; $p < 0.05$). **d,** Probability density function of LAI trends for GIMMS LAI3g, GLASS LAI, GLOBMAP LAI and the average of the three remote sensing data sets (AVG OBS).

Massive **greening** in India & China



P.Moore 28 AUG 2024 https://youtu.be/2H0OxmF7fak?si=7Bw_y45tBjpiD-1k

Photosynthesis : CO₂ increases crop yields



CO ₂ COALITION		
Carrots & turnips		+77.8%
Fresh fruit not elsewhere specified		+72.3%
Tropical fresh fruit not elsewhere specified		+72.3%
Grapes		+68.2%
Sugar beet	© 2017 Gregory Wrightstone	+65.7%
Dry beans	Idso 2013 The positive externalities of CO ₂	+61.7%
Oranges	Courtesy Monckton	+54.9%
Yams		+47.0%
Groundnuts with shells		+47.0%
Rapeseed		+46.9%
Soybeans		+45.5%
Bananas		+44.8%
Apples		+44.8%
Coconuts		+44.8%
Plantains		+44.8%
Cucumbers & gherkins		+44.8%
Pears		+44.8%
Millet		+44.3%
Watermelons		+41.5%
Pumpkins, squash & gourds		+41.5%
Fresh vegetables not elsewhere specified		+41.1%
Chillies & peppers		+41.1%
Eggplants		+41.0%

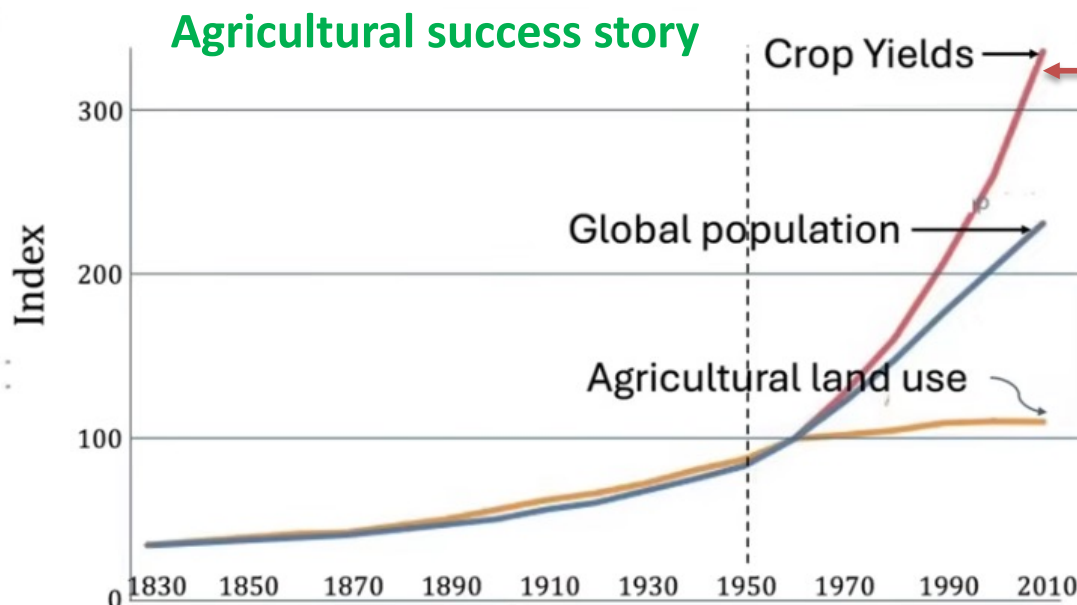
Idso 2013

% increase in crop biomass from additional 300 ppm of CO₂

<https://co2coalition.org/>

Cash benefit from CO ₂ fertilization, of crops, 1961-2010	\$150+ bn
	\$100-149 bn
	\$45-99 bn
	\$30-45 bn
	\$15-30 bn
	\$0-15 bn

2023 & 2024 saw 800 Mt record wheat production for the 1st time (=100 kg/person).



Crop yield increase due to

- CO₂
- fertilizer use (NPK)
- warming

<https://www.youtube.com/watch?v=y4cYZ2D6IEs>, slide 58
Our World in data. FAO & UN.

Greenhouses use 1000 ppm CO₂

Greenhouses use 1000 ppm CO₂ to maximize yield, an indication that plants evolved under such concentration for a long time.

The wide band is due to variation between crops and to conditions. This graph is based on data from about 60 publications of experiments worldwide in many greenhouse crops. (Source: Niderhoff, 1994). <https://ceresgs.com/growing-plants-with-carbon-dioxide/>

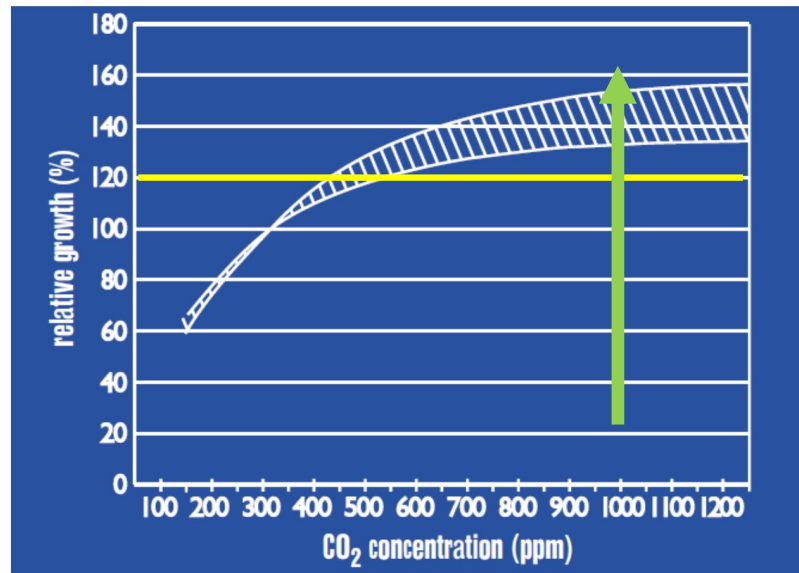


Figure 1. CO₂-curve. Crop production (%) at various levels of CO₂ (ppm). The production at the ambient CO₂ level (calc. 340 ppm in 1985) is assumed 100%.

- At **150 ppm** CO₂, plants dwarf and suffocate
- At **100 ppm** CO₂, photosynthesis stops => Earth +/- dies
- Positive coupling: more CO₂ => less plant stomata* => less water loss ✔

(*stomata = a proxy from fossilized plants for past atmospheric CO₂ content)

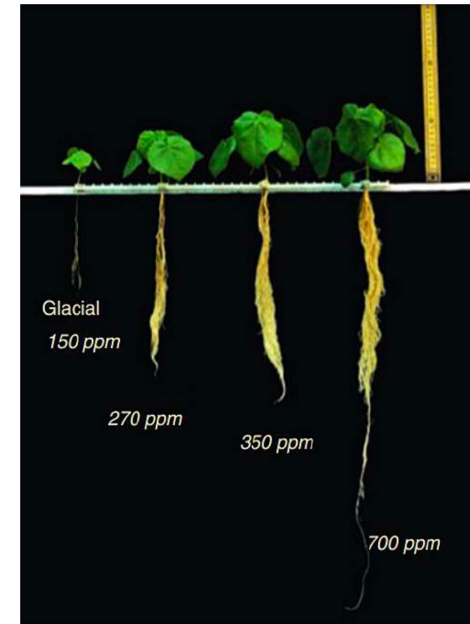
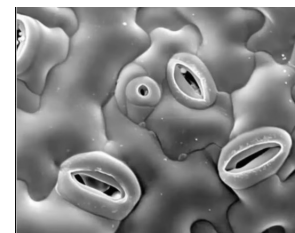
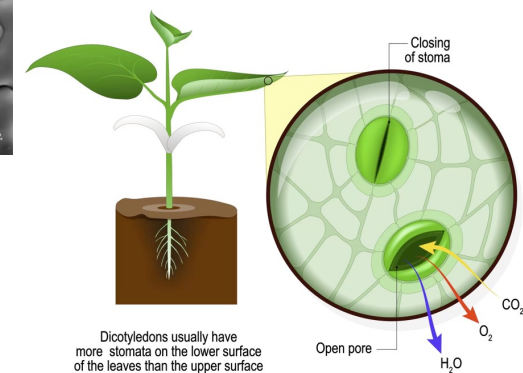


Figure 49. Representative plants of *Abutilon theophrasti* (C₃) grown at glacial through future [CO₂]. All plants were 14 days of age and were grown under similar water, light, and nutrient conditions. These plants were photographed during a study by Dippery et al. (1995). (Photograph is courtesy of Anne Hartley, Florida Gulf Coast University.). Modified after Gerhart and Ward (2010).



Function of a stoma



Carbon reservoirs

- Largest : limestone and rock, sediments (**Ca-carbonate**) >66'000'000 Gt-C
- **Fossil organic** : geological reserves vs today exploitable
 - 13'000'000 Gt-C kerogen (in rocks) / Exploitable : 6000 Gt-C => + 600 yrs
 - 1'000'000 Gt-C coal / Exploitable : 1000 Gt-C (Annual consumption : 5 Gt-C) => 200 yrs
 - 10'000'000 Gt-C oil / Exploitable : 800 Gt-C (Annual consumption: 4 Gt-C) => 200 yrs
 - 1'000'000 Gt-C gas / Exploitable : 500 Gt-C (Annual consumption: 2.2 Gt-C) => 200 yrs
- **Oceans** : 39'000 Gt-C (=38000 Gt-C dissolved inorganic, 700 Gt dissolved organic, 100 Gt-C colloids, 30 Gt-C particulate organic, 3 Gt phytoplankton, 0.1 Gt zooplankton, 0.2 Gt bacterial)
 - Ocean surface contains 900 Gt-C and exchanges 275 Gt-C between the deep ocean and surface ocean (tropics degas CO₂ and poles absorb CO₂)
- **Soil** organic 1500 Gt-C, **vegetation** 800 Gt-C, permafrost 1700 Gt-C
- **Atmosphere** : 1000 Gt-C (425 ppm)

Remarks on numbers

- Remark 1 : there is $38'000 \text{ Gt-C} / 1000 \text{ Gt-C} = 38$ times more dissolved CO_2 (90% as HCO_3^- , at pH 8) in the oceans than in the atmosphere.
 - the exchange of CO_2 between Oceans and atmosphere is in equilibrium and determined by ocean surface temperature (Henry's Law) : more CO_2 dissolves in cold waters (Poles), while warmer waters (Tropics) release CO_2 . Removing CO_2 from the atmosphere will make oceans gas out to restore equilibrium.
- Remark 2 :
 - warm tropical oceans degas CO_2 , cold polar oceans reabsorb it; about **90 Gt-C/yr**
 - soil organic matter decomposes to CO_2 and vegetation reabsorbs it (daytime photosynthesis); about **100 Gt-C/yr**
 - human-related emissions of 10 Gt-C/yr are then **5%** of the total (200 Gt-C/yr)
 - with 200 Gt-C/yr exchanged per year for a total atmospheric 1000 Gt-C, residence time is thus **5 yrs**
- Remark 3 : the CO_2 quantities in 'circulation' (39000 Gt-C in liquid (oceans), 1000 Gt-C in gas (atmosphere; 200 Gt-C/yr exchanged) and 2500 Gt-C in 'mobile' solid (soil + vegetation)), remain small compared to **H₂O** itself (Earth is a water-planet) :
 - 1'335'000'000 Gt-H₂O stock in oceans (liquid)
 - 13'000 Gt-H₂O in atmosphere (vapor; avg. concentration 0.4%; largely spread between 0 and several %)
 - 500'000 Gt-H₂O/yr 'exchanged' : = evaporated and reprecipitated (rain) = 1 m of ocean water per year

Exercise: competition with food?

- An adult human being is basically a **120 W** machine. Assume we get our energy from 80% vegetables (= '*direct*' biomass) and 20% from meat (= '*indirect*' biomass). (Assume efficiency from primary biomass-to-meat = 10%)
- How much MJ/day, and kWh/yr, do you need in food from primary biomass?
- How much primary biomass does the world consume in this way? (8.3 billion people)
- Discuss the result in view of the biomass potential for energy, and agricultural production.

Motivation for biomass use as **energy** resource

- the primary yearly biomass production (3000 EJ) is 5-fold the total world primary energy consumption (600 EJ)
- agricultural land <10% of total land area;
agricultural production = 5% of the biosphere production (150 EJ); this is enough for food, leaving a substantial residual
- optimised **cultivation** can raise the **effective photosynthetic efficiency** well above a 'usual' value of 0.6% (=30 MJ/m².yr); the theoretical limit is 3% to 5% for C3 and C4 plants (i.e. a multiple gain, up to 100-250 MJ/m².yr)
- **marginal land** areas can be used for energy cultures
- technologies for production and conversion are relatively well **established** or developed

Biomass use for energy

Advantages

- renewable
- $\approx 100\%$ use of collected matter
- rel. conventional technologies
- employment, labour intensive
- fuel import savings
- energy supply security

Drawbacks

- dispersed resource
- seasonal production
- low energy density
- requires transport and storage means
- some of the transformations involved are cumbersome (mechanical and chemical treatments,...)

Classification of biomass : general

- **aquatic** : algae
- **terrestrial** : different types, namely:
 1. **oil** producing plants, vegetable oils (=rapeseed, sunflower)
 2. **sugar**/starch crops (=sugar cane, beet, cereals)
 3. herbaceous (=grasses)
 4. wood : **lignocellulosic**
 - fast-growing 3-5 yrs
 - medium-growing 6-15 yrs
 - slow growing 15-50 yrs
- the biomass **chemical structure** defines the ease or difficulty of conversion

Classification: by **human** activity/influence

- **natural** biomass (=protected areas, no human interference)
- **residual** biomass (=organic **waste** from human activity)
 - **passive use**
 - agricultural residues
 - forestry
 - animal breeding / farming
 - industry (industrial solid and liquid wastes, e.g. food industry)
 - urban centers (municipal solid waste; sewage)
- **cultivated** biomass → **active use**
 - agriculture excesses
 - energy crops (non-food)

Classification: by origin

- *primary*: photosynthetic
- *secondary*: herbivorous species
- *tertiary*: carnivorous species



Classification : by **water** content

- 'dry' < 15 wt% humidity
- 'humid' anywhere between 15 and 90 wt% H₂O
- slurry 30-90 wt% H₂O (no structure)
 - typically: animal manure
 - also e.g. molasse (sirupy byproduct from sugar plants refining)
- liquid > 90 wt% H₂O (no structure)
 - waste waters
 - sewage
 - industrial effluents with high organic charge (e.g. food industry)

Classification: by chemical nature

- **lignocellulosic**
 - woods (lignin)
 - straws, grasses (herbaceous)
 - **amylaceous**
(=starch or inulin polysaccharide)
 - rice, corn, cereals
 - feed 4 billion people (half the world population)
 - 20 food plants feed 90% of the human population (out of 50'000 edible species)
 - **sugarous** (mono/di-saccharide)
 - glucosic, fructosic, sucrosic (sugar cane, beet)
 - **lipidic**
 - vegetable oils, greases (olives, sunflower, rapeseed)
 - **proteinic**
 - for food, not for energy
- carbohydrates (19 MJ/kg)*
- fats (39 MJ/kg)*
- proteins (22 MJ/kg)*

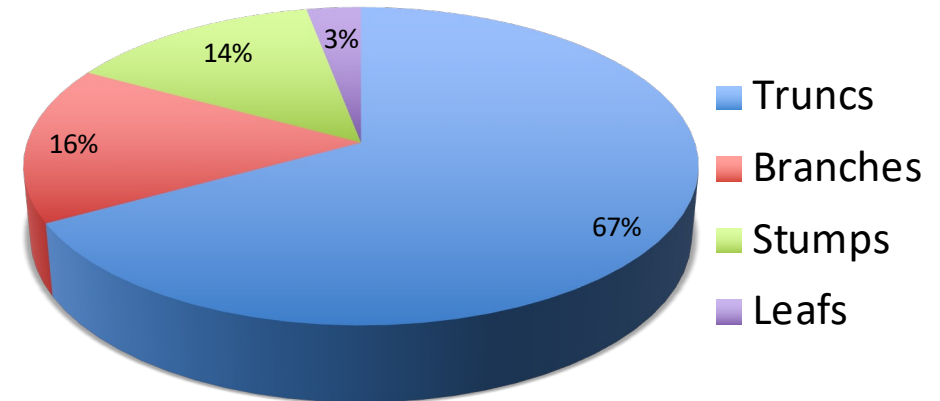
Residual biomasses

- **Agricultural**

- cereals
- fruit trees, vineyards, olive trees (lignic)
- industrial crops (oily plants)

- **Forestry**

- trimming residues
- wood industry
 - sawdust, bark, shavings
- forestry maintenance (1 kg/m²)



- **Breeding**

- slaughterhouses
- **manure**

- **Industry** (solids, liquids: effluents with organic charge)

- **Public waste** (municipal solid waste MSW; sewage)

(estimate for liq. wastes = 150-300 L/day/person containing 0.4 kg organic dry solids)

Exercise 2: estimate of residual biomass primary and final energy

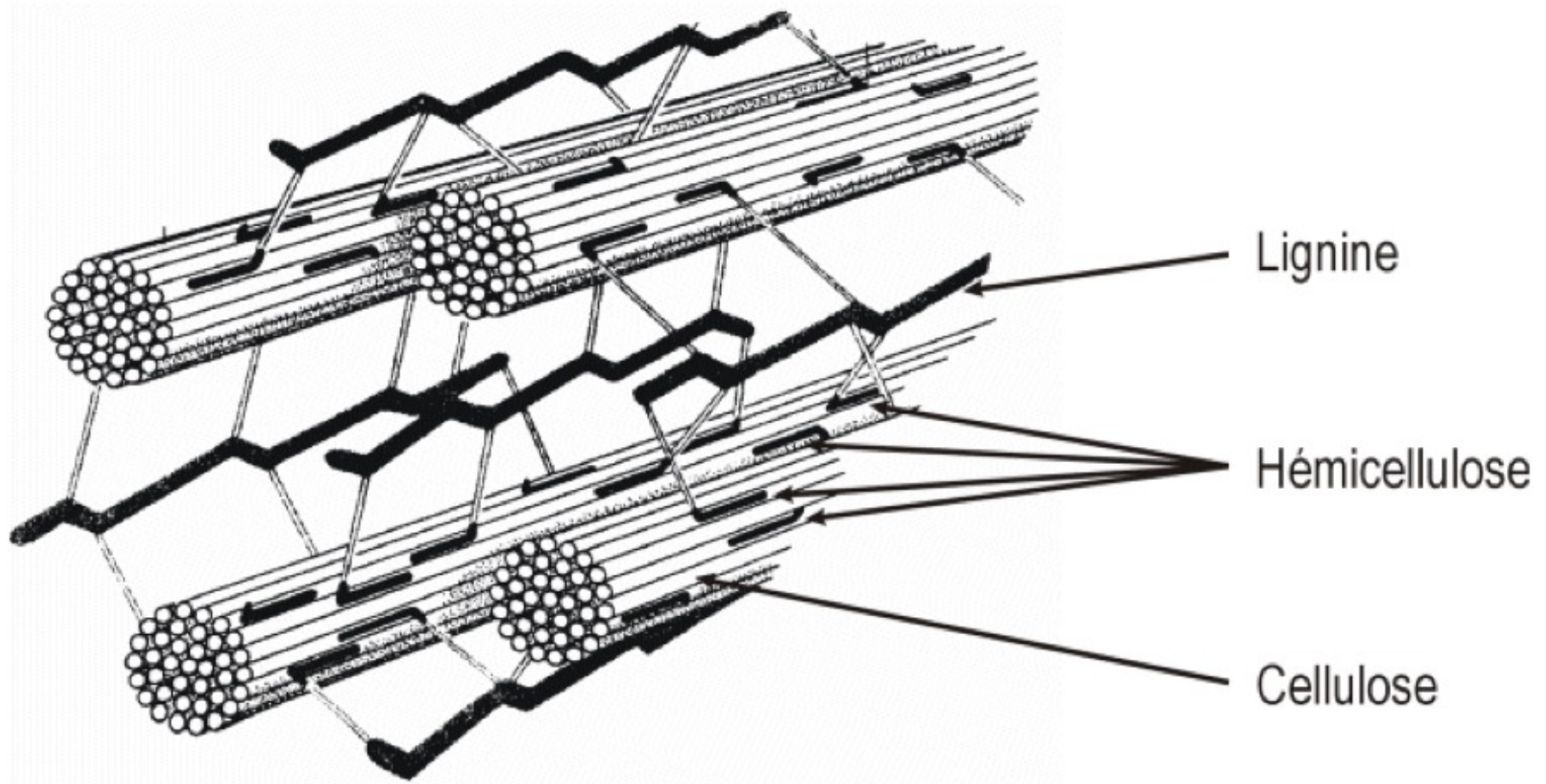
Assumptions:

1. **agriculture**: from total production (150 EJ), discount food requirement (cf. Exercise 1). Assume that from the remainder, $\approx 1/2$ is used to feed animals, $\approx 1/4$ is used for composting, and the rest (assume 10%) is recoverable as energy
2. **forestry**: 1 kg/m² per year (17 MJ/kg); assume 1% of the world's forests are in fact 'maintained' and trimmed
3. **animal manure**: assume 1 m³ of biogas per day (50% CH₄ content) per large farm animal (cows, pigs, horses, sheep,...) and there are half as many cattle farm animals as people.
4. **solid organic wastes** from human activity (kitchen waste, park&garden waste, food industry): 1 kg dry organic matter per week per person, converted to 500 L biogas per kg, with a CH₄ content of 60%
5. human **liquid organic waste** (sewage): assume 30 L biogas per day, with a CH₄ content of 65%
6. Finally, you need to assume realistic conversion efficiencies to final energy!

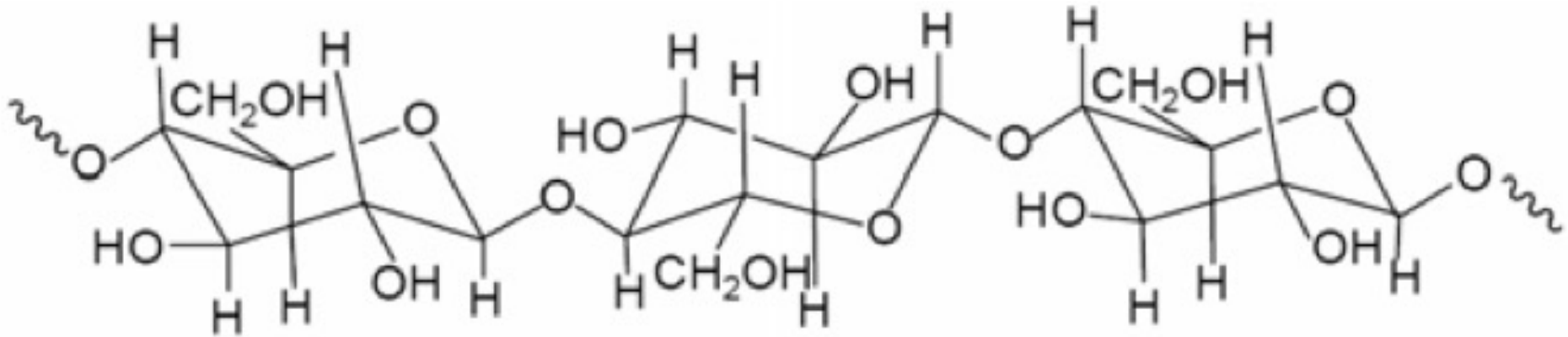
'Residual' biomass: advantages

- **low cost** production (can even be zero or *negative* cost fuel)
- closed cycle: minerals (inorganic part) are reused for **fertilising**
- **local** exploitation (= low transport cost)
- reduced contamination or load on waste management
- 'free' energy recovery, which amounts to at least several % (and up to 10%) of total energy needs
 - Swiss case : 56 PJ incinerated solid wastes (of which only 50% is in fact from renewable sources), 39 PJ wood use, 6 PJ of biogas (drastically *underexploited!*) = total of 100 PJ = 12% of primary energy

Ligno-cellulosic biomass structure



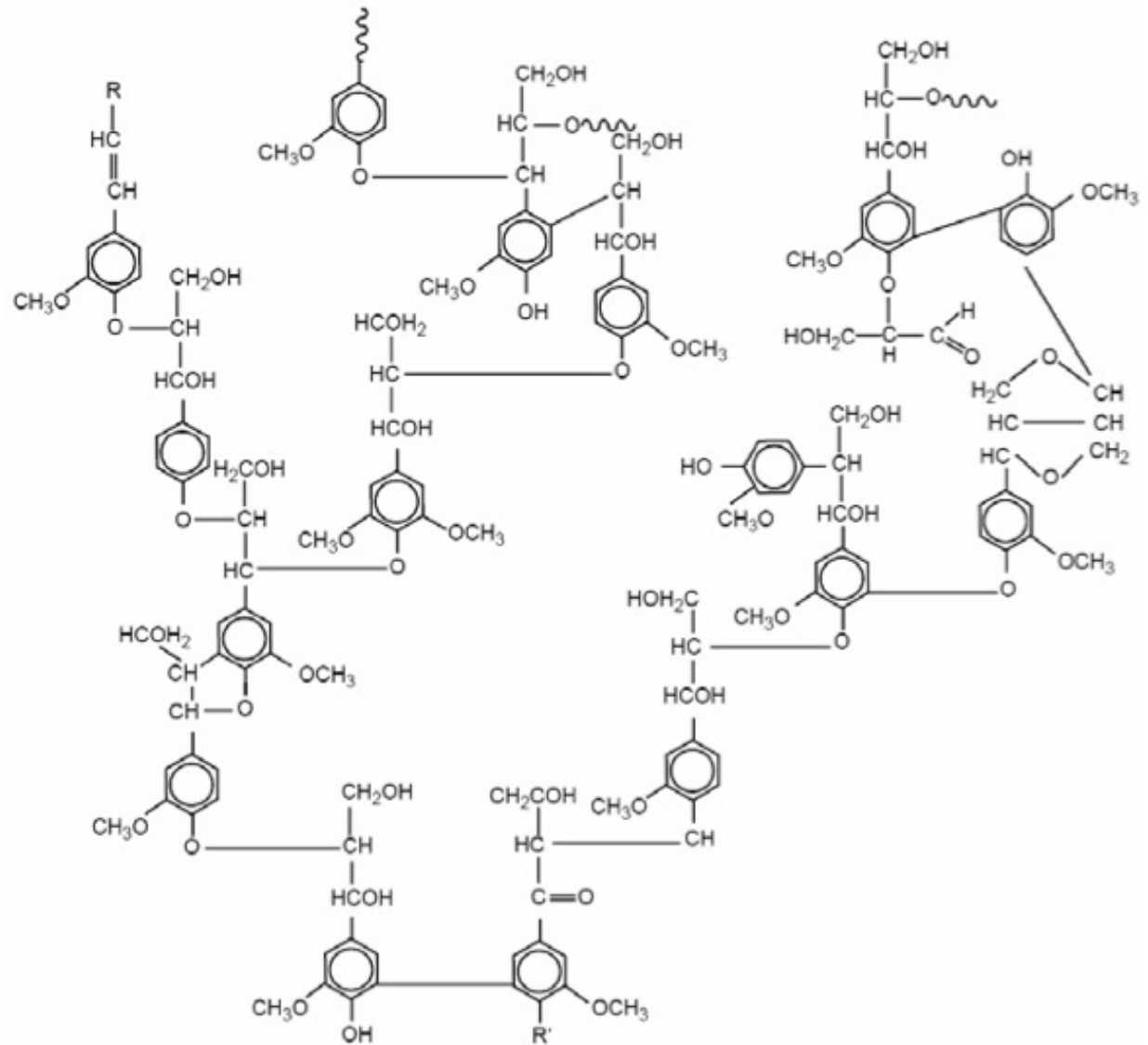
Cellulose



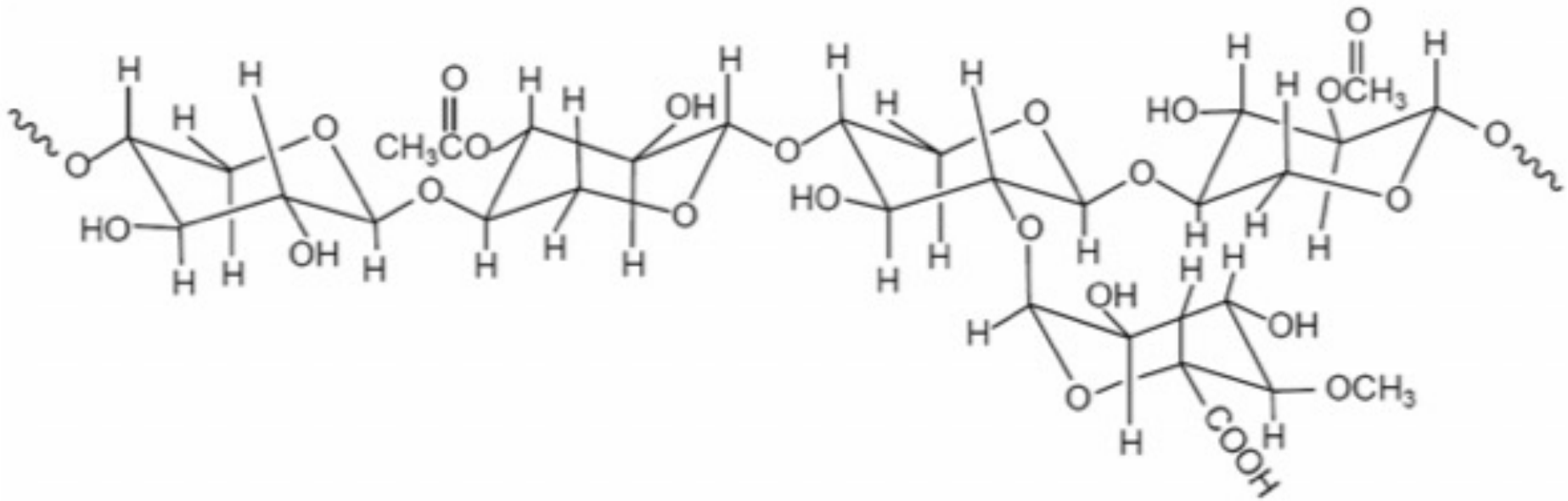
- 40-80 wt% in plants, **17.5 MJ/kg** (C:H:O \approx 30:45:25 at%)
- '**soft**' part in plants
- linear polymer of up to 10'000 glucose (C6) molecules:
 $(C_6H_{10}O_5)_n$

Lignine

- complex **aromatic** polymer
- ca. $(C_{10}H_{12}O_4)_n$
- 25-35 wt% in wood
- 10-25% in plants
- responsible for **slow growth and rigidity**
- **26.6 MJ/kg**
(C:H:O \approx 40:45:15 at%)



Hemi-cellulose (xylose)



- 15-30wt% of plants, $C_5H_8O_4$, **17.5 MJ/kg** (C:H:O \approx 30:45:25 at%)
- **'connects'** lignine to cellulose
- 'shorter' polymer of 50-200 sugar molecules (C5 structures)
- 5 sugars: xylose, arabinose, galactose, glucose, mannose

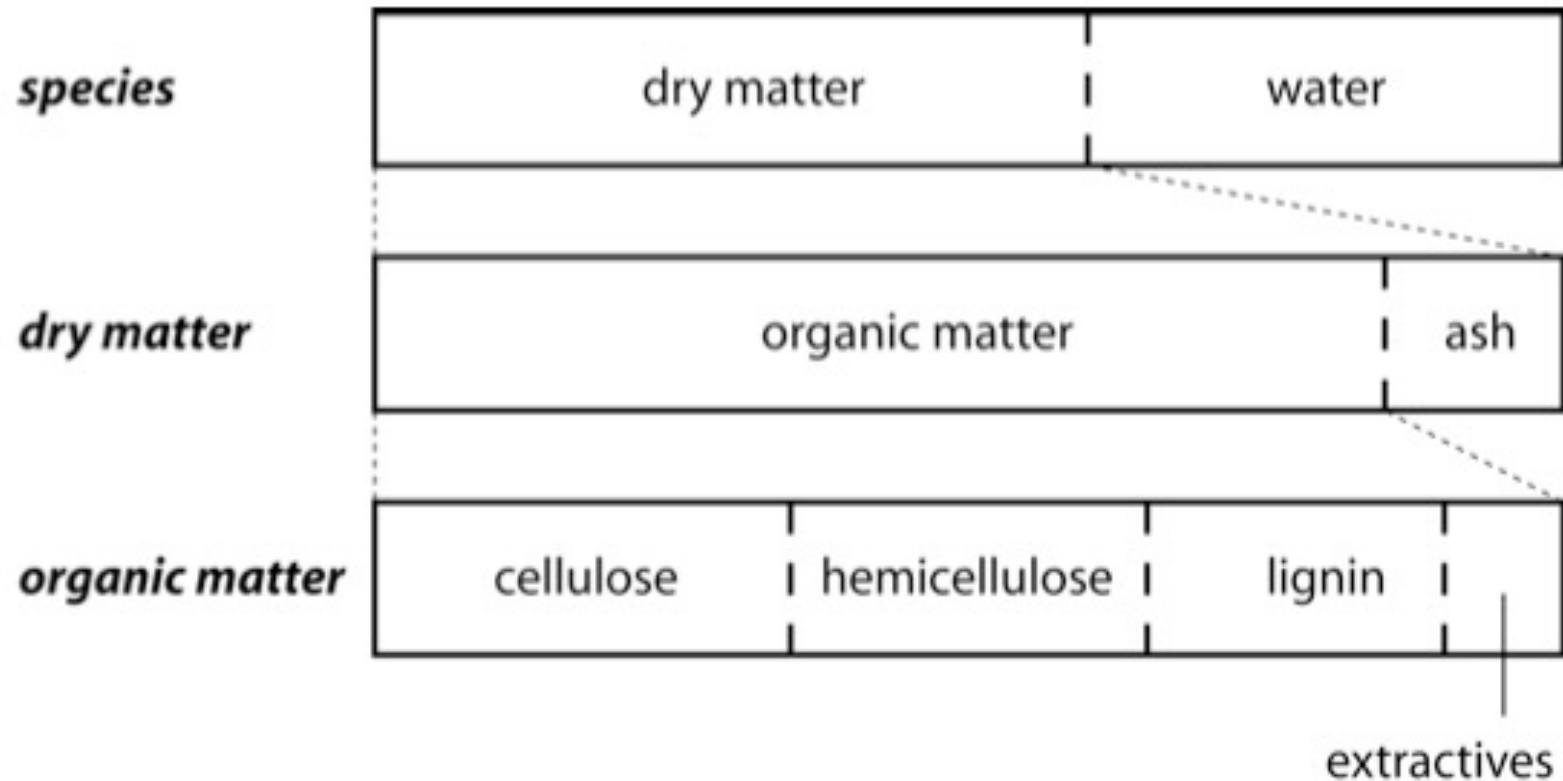
Composition examples

Dry fraction [mass-%]	Eucalyptus tree	Switchgrass	Corn stover	Corn grain
Cellulose	48	43	36	3
Hemicellulose	14	33	23	6
Lignin	29	9	17	2
Extractives	6	8	6	82
Ash	1	6	10	0
Residues	2	1	8	7

- lignocellulose usually 80-90%
- ash : inorganics (S, Si, Cl, alkali and other metals)
- extractibles (soluble in water or organic solvent)
- moisture : typically 20%
- on *average* : 60% carbohydrates, 25% proteins, 6% lipids, 9% minerals

Structural composition

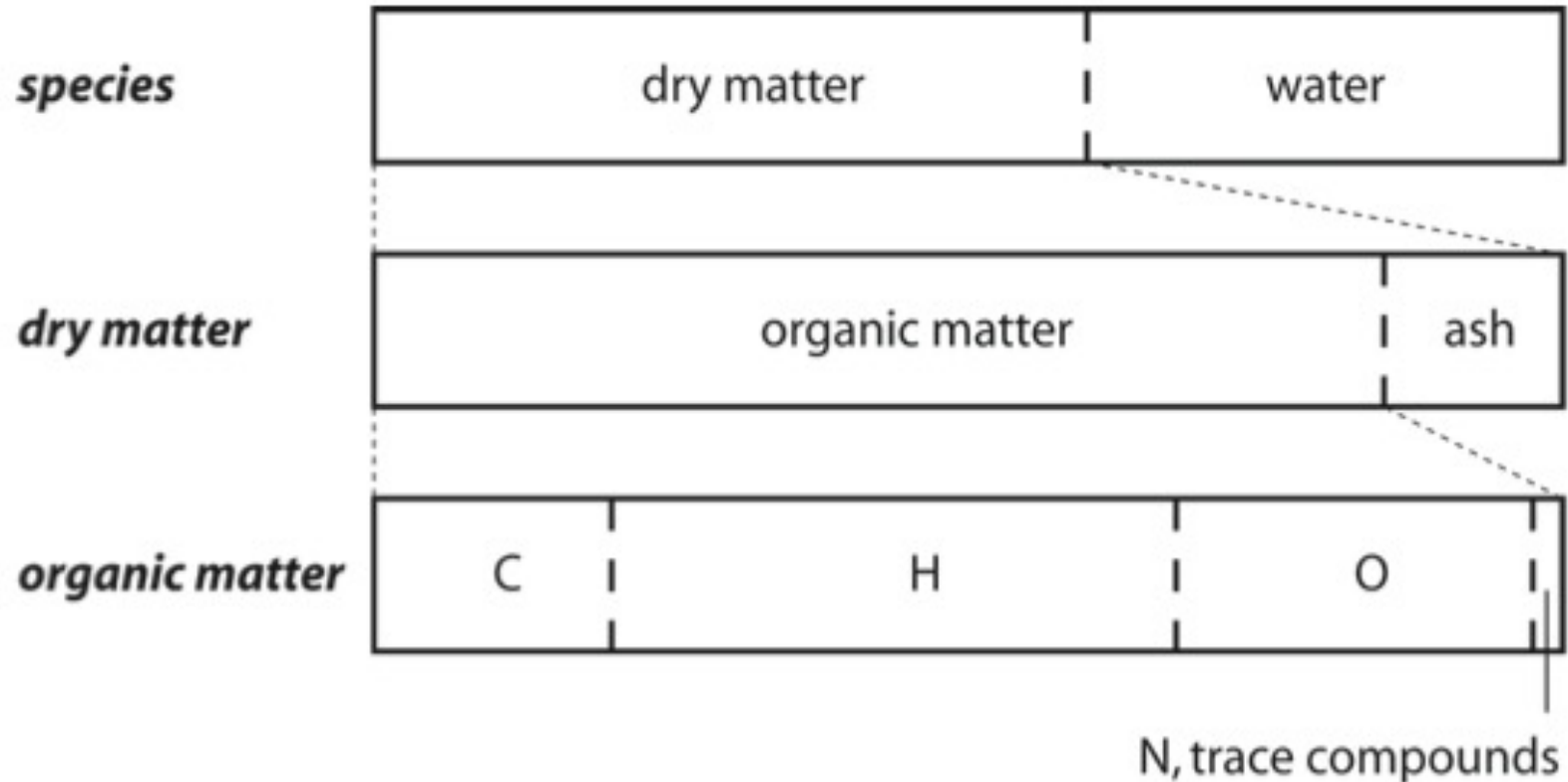
macromolecular description:



cellulose	31-47%wt	lignin	8-31%wt
hemicellulose	24-35%wt	extractives	1-31%wt

Chemical composition

atomic description:



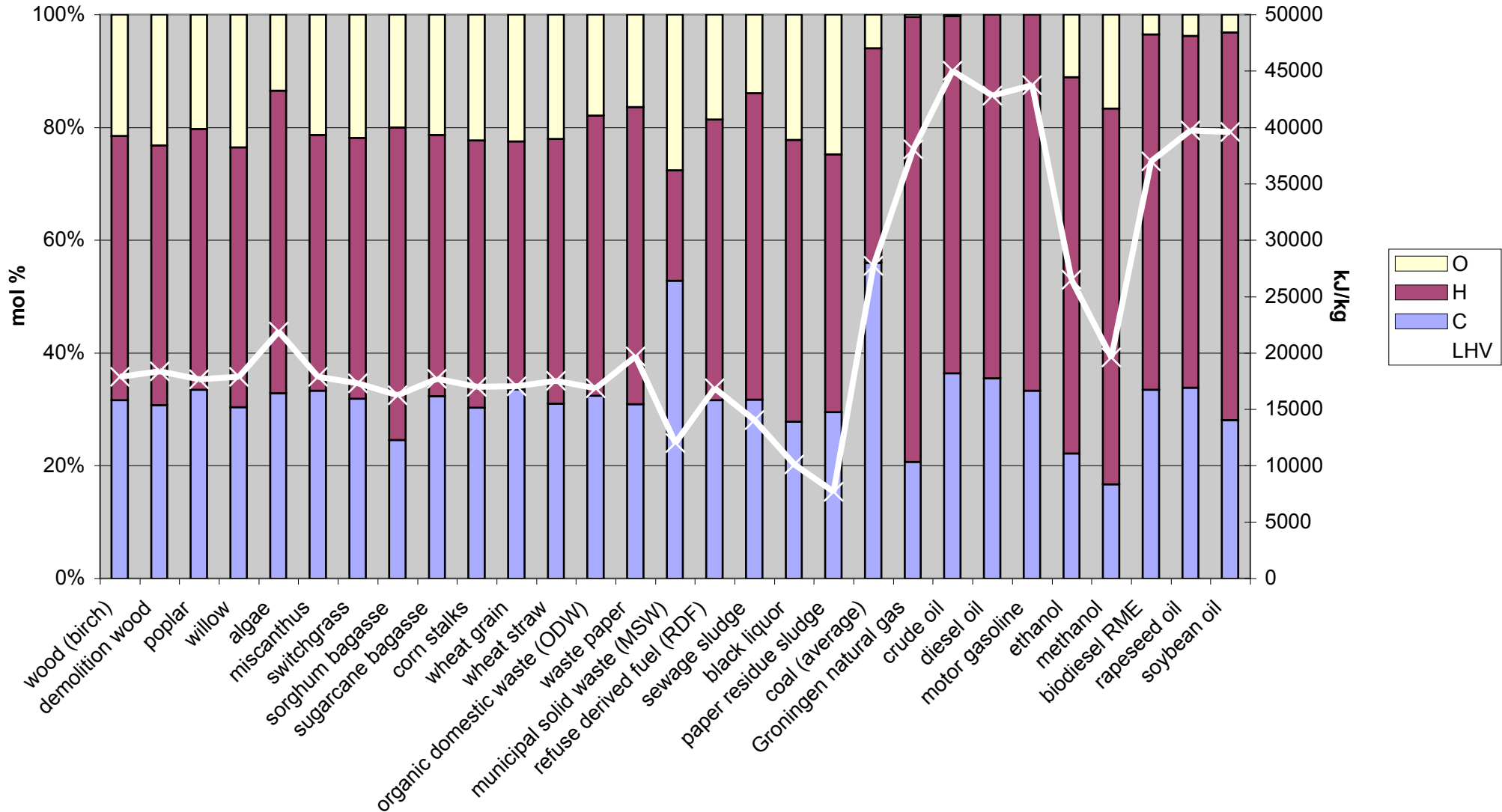
C ~ 30%mol O ~ 20%mol
H ~ 50%mol N ~ 1%mol

'Dry' wood (11% humidity)

Element	Weight %
C	47
H	6
O	35
N	0.1
S	0.0
Ash	1
Water	11

Composition and energy content of fuels

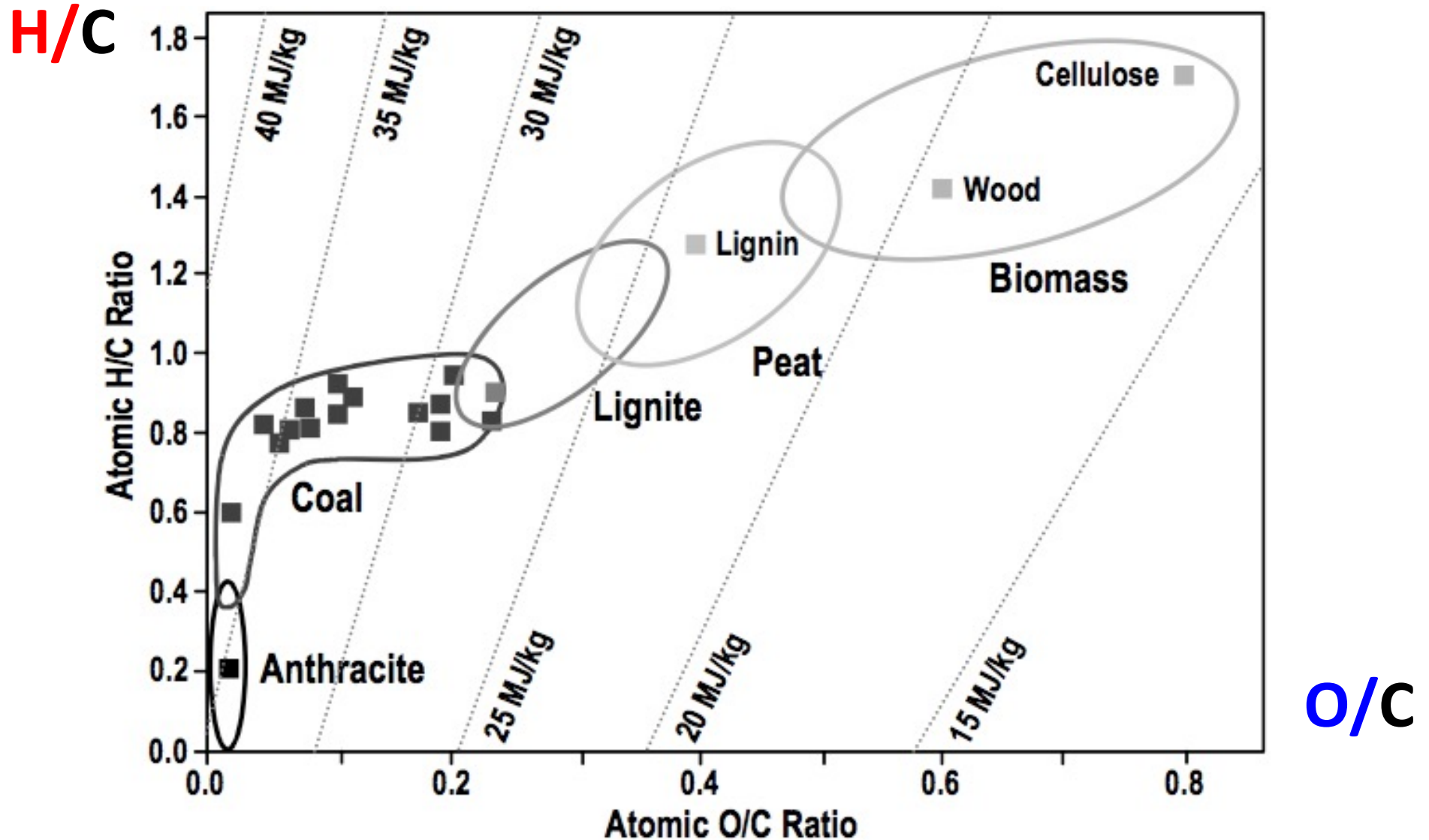
Elementar composition of biomass, fossil fuels and biofuels and lower heating value



The **OXYGEN** content in biomass fuels (=OXY-HYDROCARBONS) reduces the LHV to **<20 MJ/kg** compared to **>40 MJ/kg** for (fossil) HYDROCARBONS

Heating value and C/H/O composition

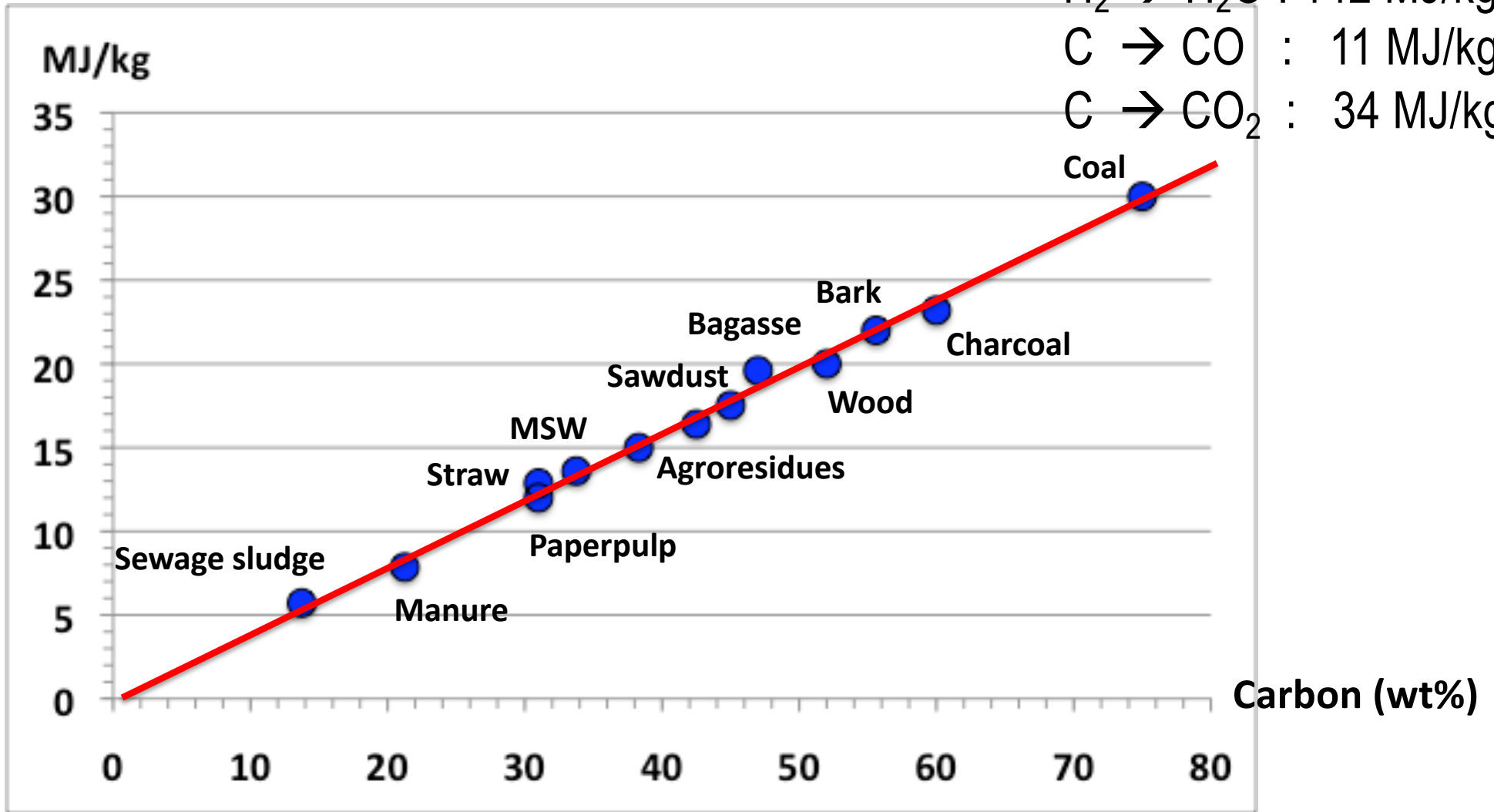
Van Krevelen diagram



Heating value vs. carbon content

Reminder:

$H_2 \rightarrow H_2O$: 142 MJ/kg
 $C \rightarrow CO$: 11 MJ/kg
 $C \rightarrow CO_2$: 34 MJ/kg



$LHV = 43.6 * C - 0.31 \quad MJ/kg$ where $C = wt\% \text{ carbon } (<80)$

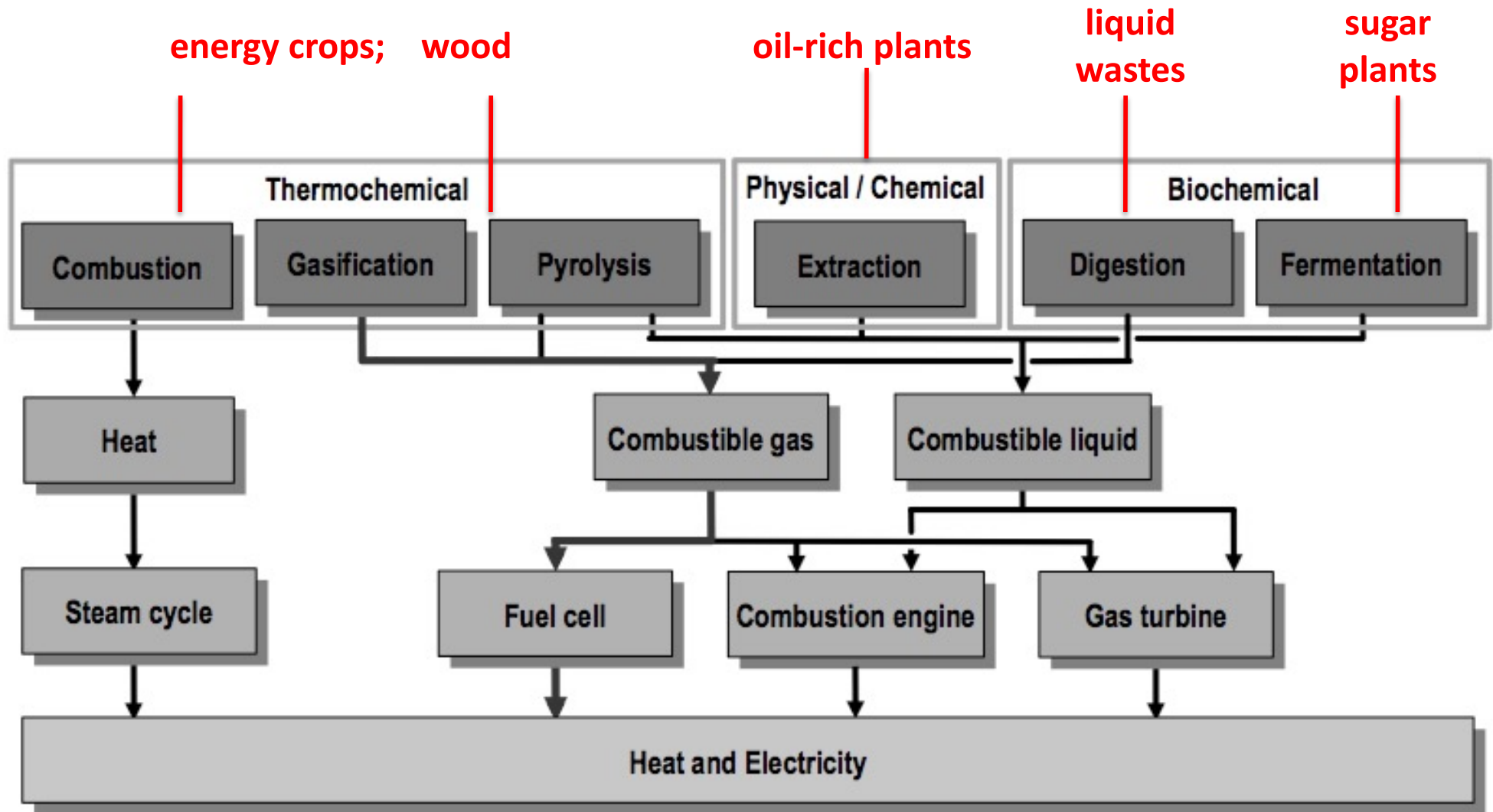
Compositions of biomasses

Source	C	H	O	N	S	Inorg.	LHV MJ/kg
carbon	100						29.3
coal	70-80	5	5-20	1-1.5	1-3	4-15	30-34
wood	52	6	40	0.1	0	1	21
bagasse	47	6	35	0	0	11	21
untreated sewage	45.5	7	26	2.4	0.5	19	16.4
cattle manure	42.7	5.5	31	2.4	0.3	18	17
rice residue	39	5.4	38	0.5	0	18	15
MSW	34	4.6	22	0.7	0.4	38	13
paperpulp	31	7	51	0.5	0.2	10	12
sewage sludge	14	2	11	1	0.7	71	5

$$LHV = 43.6 * C - 0.31 \text{ MJ/kg} \quad \text{where } C = \text{wt\% carbon } (<80)$$

The carbon content alone is a reasonable measure for the heating value.
 As if the LHV (expressed per kg fuel) gain due to H were 'lost' due to the presence of O mass in the fuel.

Biomass conversion overview



BIOMASS CONVERSION ROADMAP

