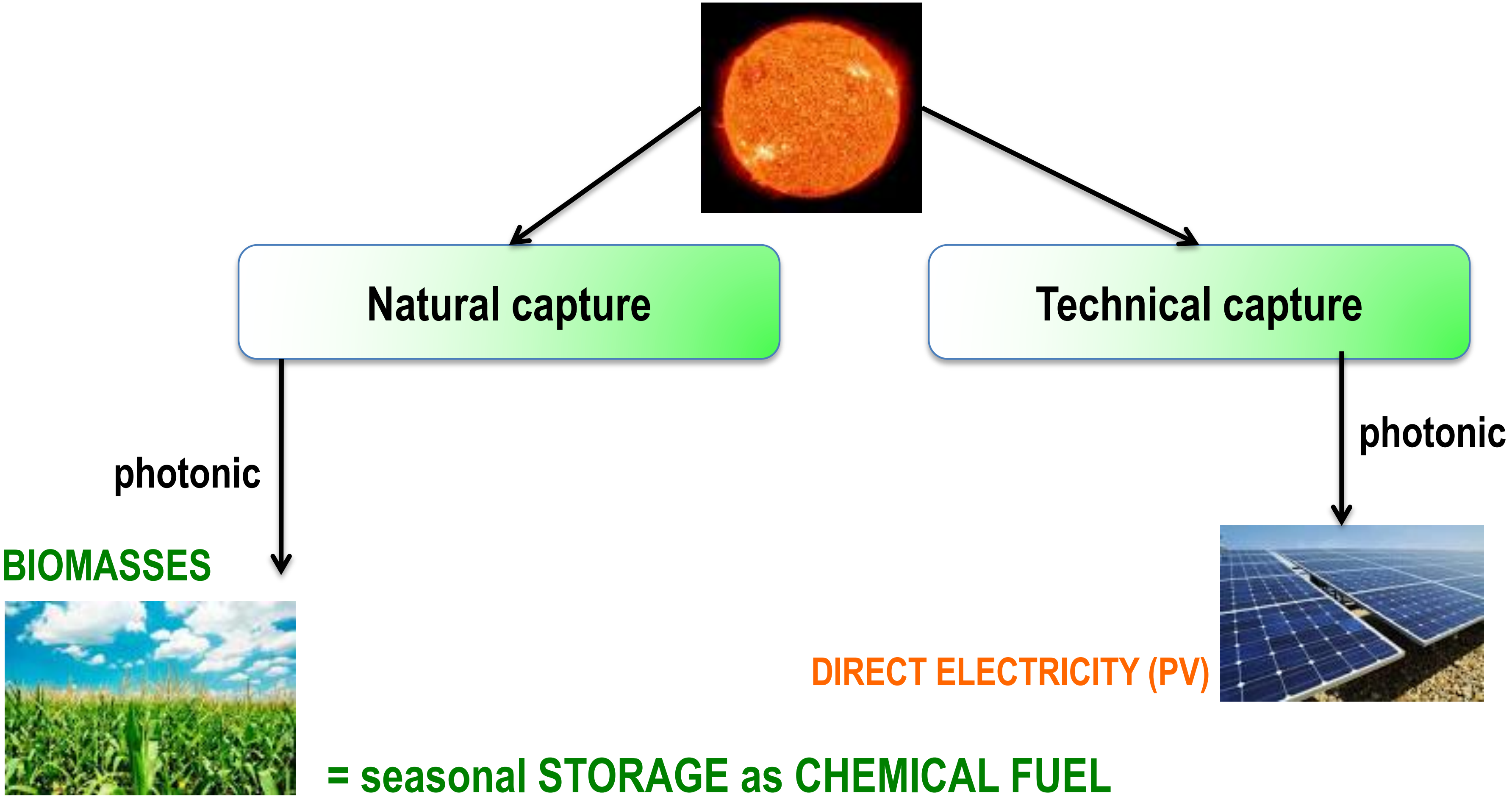
Biomass:
resources & conversion technologies



Natural capture

Technical capture

photonic

photonic

BIOMASSES

DIRECT ELECTRICITY (PV)

= seasonal STORAGE as CHEMICAL FUEL

Biomass course part: overview

- Definitions
  - Photosynthesis, compositions, structure
- Potential : theoretical vs. real
- Conversion
  1. **Solids** (wood; energy crops)
     - combustion
     - pyrolysis
     - gasification
     - solids-derived liquid/gaseous fuels (='secondary' biofuels)
  2. **Liquids** (bioethanol; biodiesel)
     - fermentation
     - extraction
     - application as 'primary' biofuels (engines)
  3. **Gas** (biogases)
     - anaerobic digestion

Learning objectives

- Know and distinguish the types of biomasses

  (as well as the appropriate conversion route per biomass type)
- Know theoretical biomass potential (photosynthesis efficiency) and the estimates of real biomass potential
- Quantify the ‘energy vs. food’ competition for biomass resource
- Explain advantages (& drawbacks) of biomass as energy carrier, in particular for residual biomass
- Know approximately the chemical structure of biomass (‘ligno-cellulose’)
- Estimate the LHV of a biomass from its composition

Theoretical photonic (solar) capture potential

PHOTOSYNTHESIS

$6\ CO_2 + 6\ H_2O + \text{photons} \rightarrow C_6H_{12}O_6\ \text{(glucose)} + 6\ O_2$

Extraterrestrial radiation arriving at the Earth's outer atmosphere:
5.5 E+24 J/yr (=1368 W/m^2, 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**
(which is ~160 W/m^2 or 5 GJ/m^2.yr ≈ 1400 kWh/m^2.yr)

Compared to the world annual primary energy:
5.4 E+20 J/yr (= 540 EJ = 13 Gtoe)

→ theoretical potential ≈ ***1000 times*** the human primary energy need

Theoretical **photosynthesis** efficiency

$$6\,CO_2 + 6\,H_2O \;\Rightarrow\; C_6H_{12}O_6 \;+\; 6\,O_2$$

glucose synthesis: ΔG = 2862 kJ/mol

divide by 6

÷ 6

$$CO_2 + H_2O \;\xrightarrow[\text{in chloroplasts}]{8\text{ to }10\text{ photons}}\; -(HCOH)- \;+\; O_2$$

$$\boxed{\Delta G = 477\ \text{kJ/mol}}$$

P.A.R. (= 43% of total irradiation)
photosynthetic active radiation

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

$$E_{photon} = h.\nu = h.\frac{c}{\lambda}$$

$h = 6.62 .10^{-34}$ Js : Planck's constant
$c = 3.10^{8}$ m/s : speed of light

photon energy amounts to $\dfrac{2\,.10^{-16}}{\lambda\,(in\ nm)}\ J/photon$

Hence for 1 mol of photons (x 6.02 10^{23}) → $\dfrac{120}{\lambda\,(in\ nm)}\ MJ/mol$

→ **red (660 nm)**: 181.2 kJ/mol
→ **blue (450 nm)**: 265.6 kJ/mol
→ **white (577 nm): 208.1 kJ/mol**

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

$$\frac{glucose\quad output}{photonic\quad input} = \frac{\boxed{477\ kJ/mol}}{\boxed{8\ photons \bullet 208.1\,{}^{kJ}\!/_{1\ mole}}\ of\ white\ light\ photons} = \boxed{28.6\%}$$

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% (effective square meters available)	34.4%
Maximum photonic energy capture efficiency into glucose = 28.6% (p. 5)	9.8%
⅓ 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), on daily basis (24h)	5%
Max. practical efficiency of ‘**C-3**’ common plants (=95% of biomass, e.g. wheats, rice, trees,…), on 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**

p.8

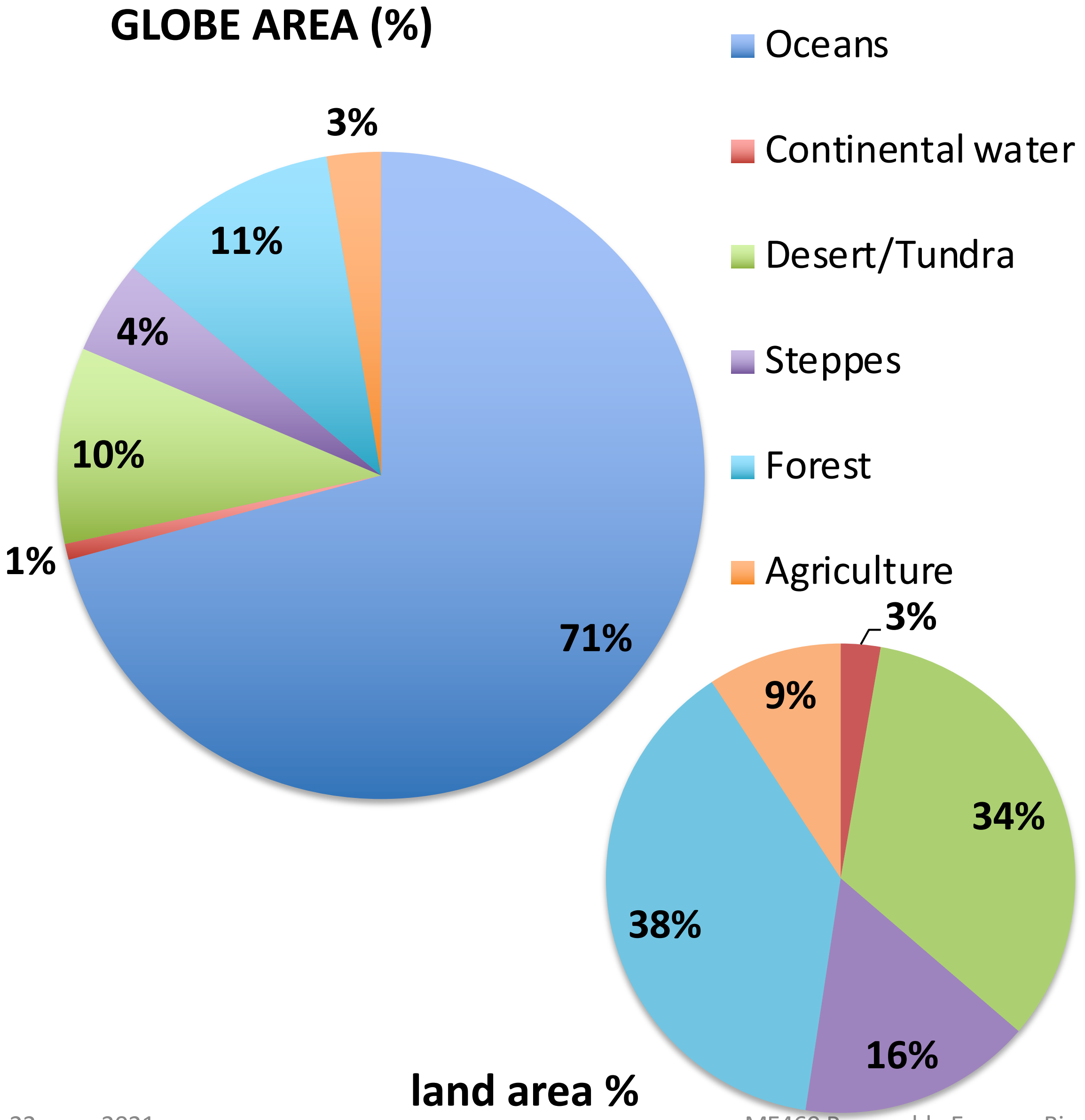
1 W/m^2 is a poor storage density ! *(20 tonnes (dry) / hectare.yr)*

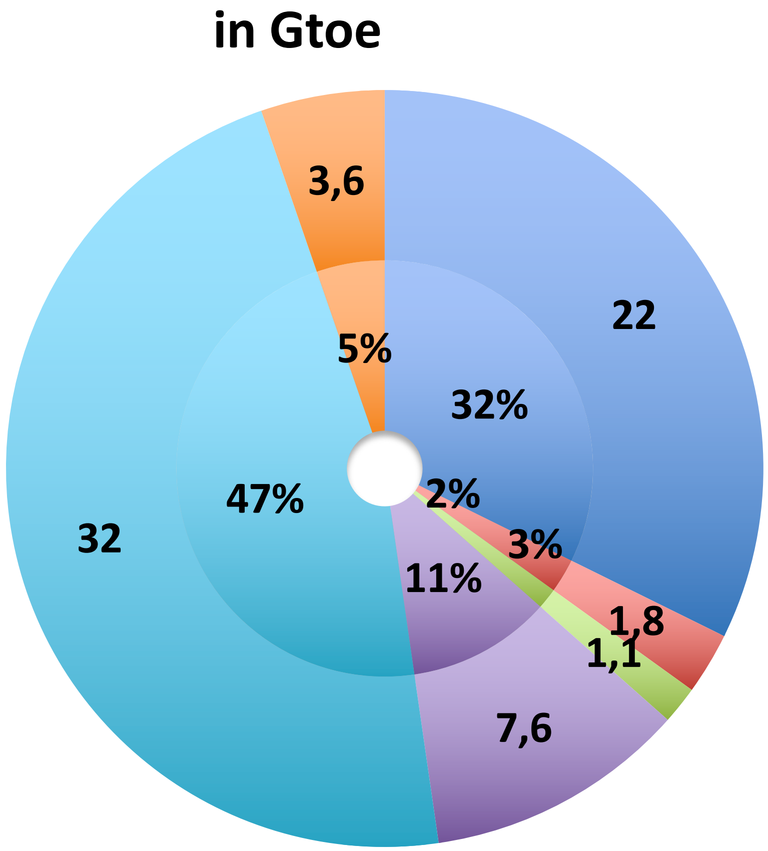
Even for a ‘2 kW-society’, every citizen would need his personal 2000 m^2 ‘storage’ surface

Biomass production of the biosphere

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

≈10 toe biomass energy per person on the planet!





=> *'wood': 2.5 x the world annual energy*

=> *'agro': 0.3 x the world annual energy*

Sustainable biomass potential

- Primary production of biomass in the biosphere (3×10^{21} J)
  ≈ 200×10^{9} tonnes (dry) /yr (assuming 15 MJ per kg dry biomass)
- Theoretically exploitable : 57% (without oceans, desert,..)
- **Technically sustainable*** : ca. **9%**
  = **agriculture (5%)** + ~10% of forestry (47%), cf. previous slide
  (≈ 4% of the Earth's total surface, or ≈ 13% of the emerged lands)
  = 18×10^{9} tonnes (dry) / yr
  = 270×10^{18}J = 270 EJ (6.4 Gtoe)
  = **50% of world annual primary energy (540 EJ)**
  (>half of which (150 EJ, 3.6 Gtoe) is used/meant for food, mainly)
  → *An important part can be recovered as energy from the residues*
  Influence factors: :
  nutrition, moisture, CO_2 concentration, light, temperature, leaf anatomy,..

→ *in practical terms, the sustainable biomass energy potential could amount up to ≈⅓ (180 EJ) of the present human energy needs.*
The main source is wood (>120 EJ) and the remainder from other biomass sources, an interesting source being ***residual*** *biomass (i.e. 'waste streams' – cf. further below)*

Examples of real biomass yield

(in case of 0.6% efficiency = 30 MJ/m^2.yr = **300 GJ/ha.yr**; 1 ha = 1 hectare = 10’000 m^2)

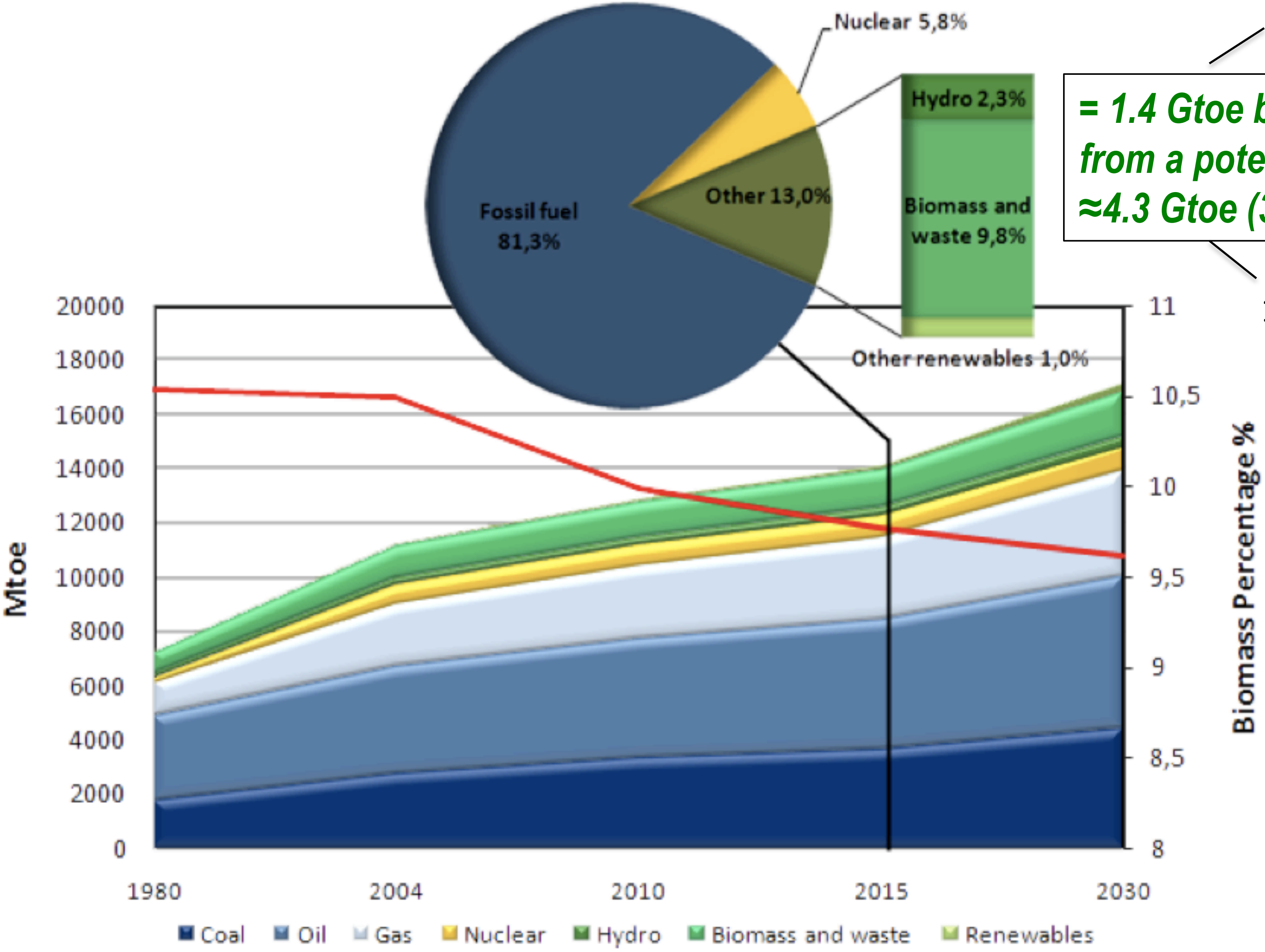
Plant	**Energy output (GJ/ha/year)**
1. Switchgrass	185…215
2. Miscanthus	Up to 785 (calc. with LHV=17,8 MJ/kg)
3. Sugar beet	62…96
4. Rape seed	14…78
5. Sweet sorghum	54…58
6. Wheat	23…47
8. Wood (forest)	100 (calc. on 50% dm with 10 t/ha yield)

real yield ≈ typically even only 10-30% of the raw photosynthetic yield !

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



59 EJ

= 1.4 Gtoe biomass, from a potential of ≈4.3 Gtoe (3 x larger)

180 EJ

Is there competition with food? (exercise)

- An adult human being is 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? (7.5 billion people)
- Discuss the result in view of the biomass potential for energy, and current agricultural production.

Motivation for biomass use as energy resource

- the primary yearly biomass production (3000EJ) is >5-fold the total world human primary energy consumption (550 EJ)
- agricultural land is <10% of the total land area;

  agricultural production = 5% of the biosphere energy production (152 EJ); this is enough to feed the planet, leaving residual energy
- optimised **cultivation** can raise the **effective photosynthetic efficiency** above the average value of 0.6% (=30 MJ/m^2.yr); the theoretical limit is 3% to 5% storage efficiency for C3 and C4 plants (i.e. a maximal potential up to 100-250 MJ/m^2.yr)
- **marginal land** areas can be used for ‘energy cultures’
- technologies for production and conversion are relatively well **established** or developed
- **CO_2 neutral**, and less overall polluting emissions (vs. fossil)

Biomass use for energy

Advantages

- renewable
- ≈100% use of collected matter
- rel. conventional technologies
- environmentally benign
- 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,…)

Biomass classification by **water** content

- ‘**dry**’ < 15 wt% humidity
- ‘**humid**’ 15-30 wt% H_2O
- ‘**slurry**’ 30-90 wt% H_2O (without ‘structure’)
  - e.g. animal manure
  - e.g. ‘molasse’ (=the sirupy byproduct from sugar plants)
- ‘**liquid**’ > 90 wt% H_2O
  - waste waters
    - sewage
    - industrial effluents with ‘high’ organic charge (e.g. food industry)

Biomass classification by human activity

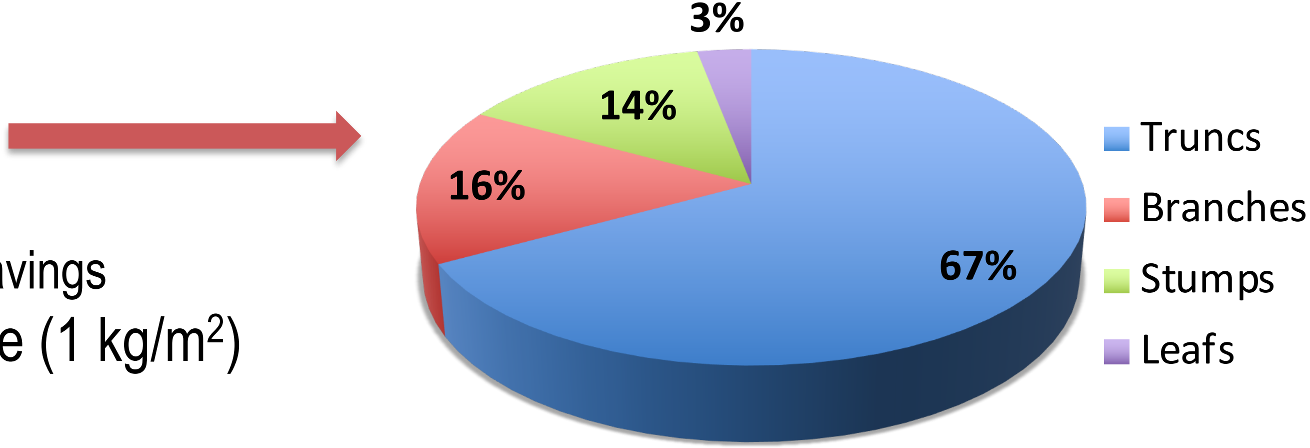
- natural biomass (=protected areas, no human interference)
- residual biomass (=organic **waste streams** from human activity)

  → **passive use** of biomass ('recovered' as energy resource)

  - agricultural residues
  - forestry maintenance
  - animal breeding / farming
  - industry (industrial solid and liquid wastes, e.g. food industry)
  - urban centers (municipal solid waste; sewage)
- cultivated biomass → **active use** of the land for energy
  - agricultural excess (e.g. non-edible parts of the harvest)
  - 'energy crops' (non-food)

Residual biomasses (='waste streams' from human activity)

- **Agriculture residues**
  - cereals
  - fruit trees, vineyards, olive trees (lignic)
  - industrial crops (oily plants)
- **Forestry**
  - trimming residues
  - wood industry
    - sawdust, bark, shavings
  - forestry maintenance (1 kg/m^2)



- **Animal 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)

Estimate of *residual* biomass, primary and final energy = energy recovered from waste streams *(exercise)*

Assumptions / Conversion factors:

1. agriculture residues: from total production (152 EJ), discount human food requirement (cf. exercise p.13). Assume that from the remainder, ≈½ is used to feed animals, ≈¼ is used for composting, and the rest (assume 10%) is recoverable as energy
2. forestry: assume 1 kg/m^2 per year of dry wood (LHV:17 MJ/kg); assume 1% of the world's forests area is trimmed (from where this 'waste wood' is recovered)
3. animal manure: assume a production of 1 m^3 of biogas per day (with 50% CH_4 content) per large farm animal and there are half as many large farm animal-'equivalents' as people.
4. solid organic **wastes** from our activities (kitchen waste, park&garden waste, food industry): assume 1 kg dry organic matter waste per week per person, converted to 500 L biogas per kg dry waste, with a CH_4 content of 60%
5. human liquid organic **waste** (sewage): assume a production of 30 L biogas per day per person, with a CH_4 content of 65%
6. Finally, you need to assume realistic conversion efficiencies from primary to final energy (whether heat or power) for the different sources!

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 !
  - e.g. for Switzerland: 56 PJ incinerated solid wastes (of which ≈50% is considered renewable), 40 PJ wood use and 5 PJ of biogas (both of which are much *under*exploited) = total of 100 PJ = 8% of Swiss primary energy need

‘Residual’ biomass energy: Swiss case

- 56 PJ incinerated solid wastes (MSW/ISW, waste wood; in part NG-assisted)

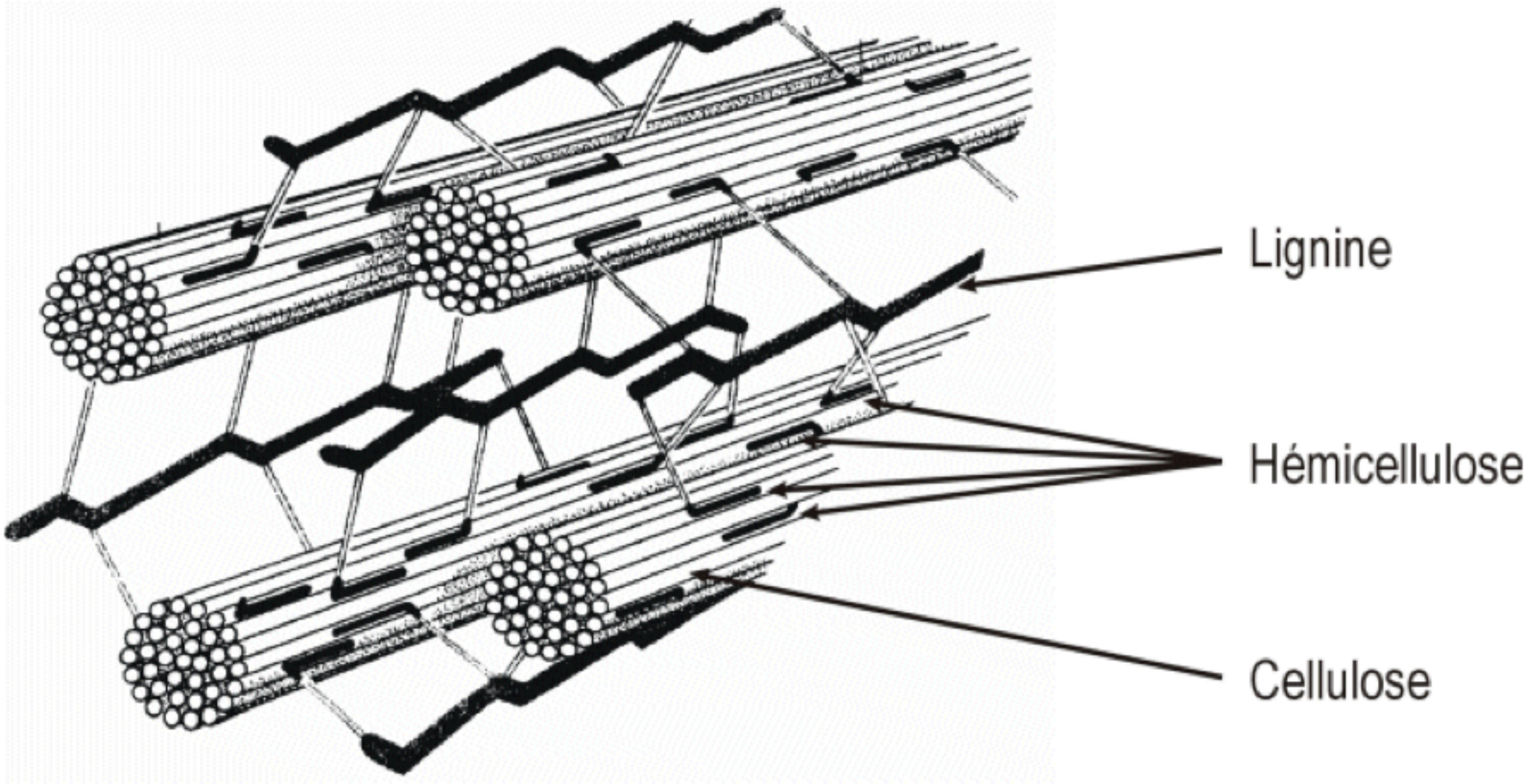
  ***(Remark:* only ≈50%** *of this is in fact* **renewable** *(rest = fossil origin, mainly plastics))*
- 40 PJ indigenous wood use (=> potential could be doubled)
- 5 PJ of biogas (largely *under*exploited)

  => could be increased >5-fold (≈30 PJ)

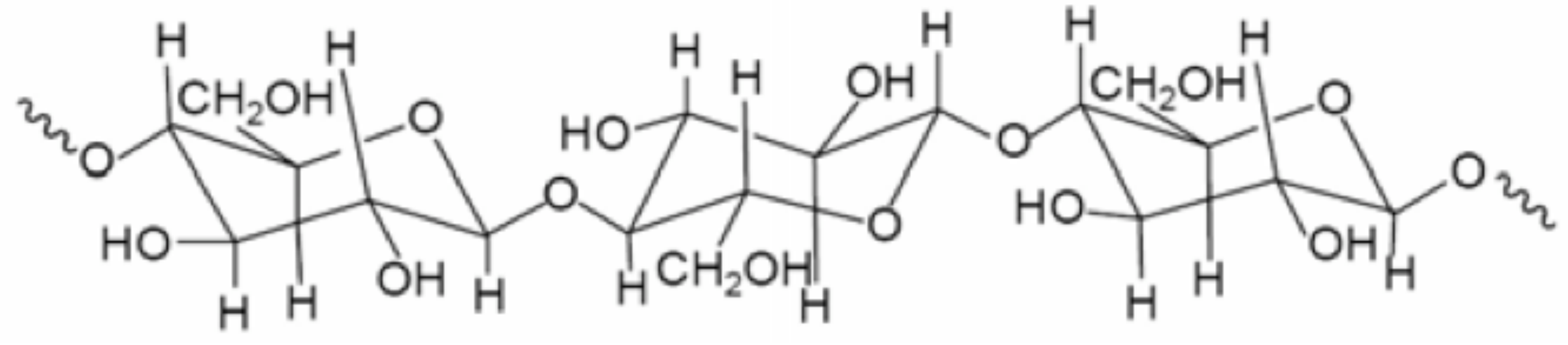
= present total of 100 PJ = 8% of Swiss primary energy

- ca. 6.5% of final energy; **5% of Swiss electricity** *(as renewable:* ***3%****)*
- electricity 10.2 PJ (20% efficiency) from incinerated solid wastes (2.85 TWh); in addition 30% heat is produced and distributed as district heat
- electricity 1.2 PJ (27% efficiency) from biogases (0.3 TWh) => 0.5% of total electricity
- electricity production from wood is negligible

Ligno-cellulosic biomass structure



Cellulose

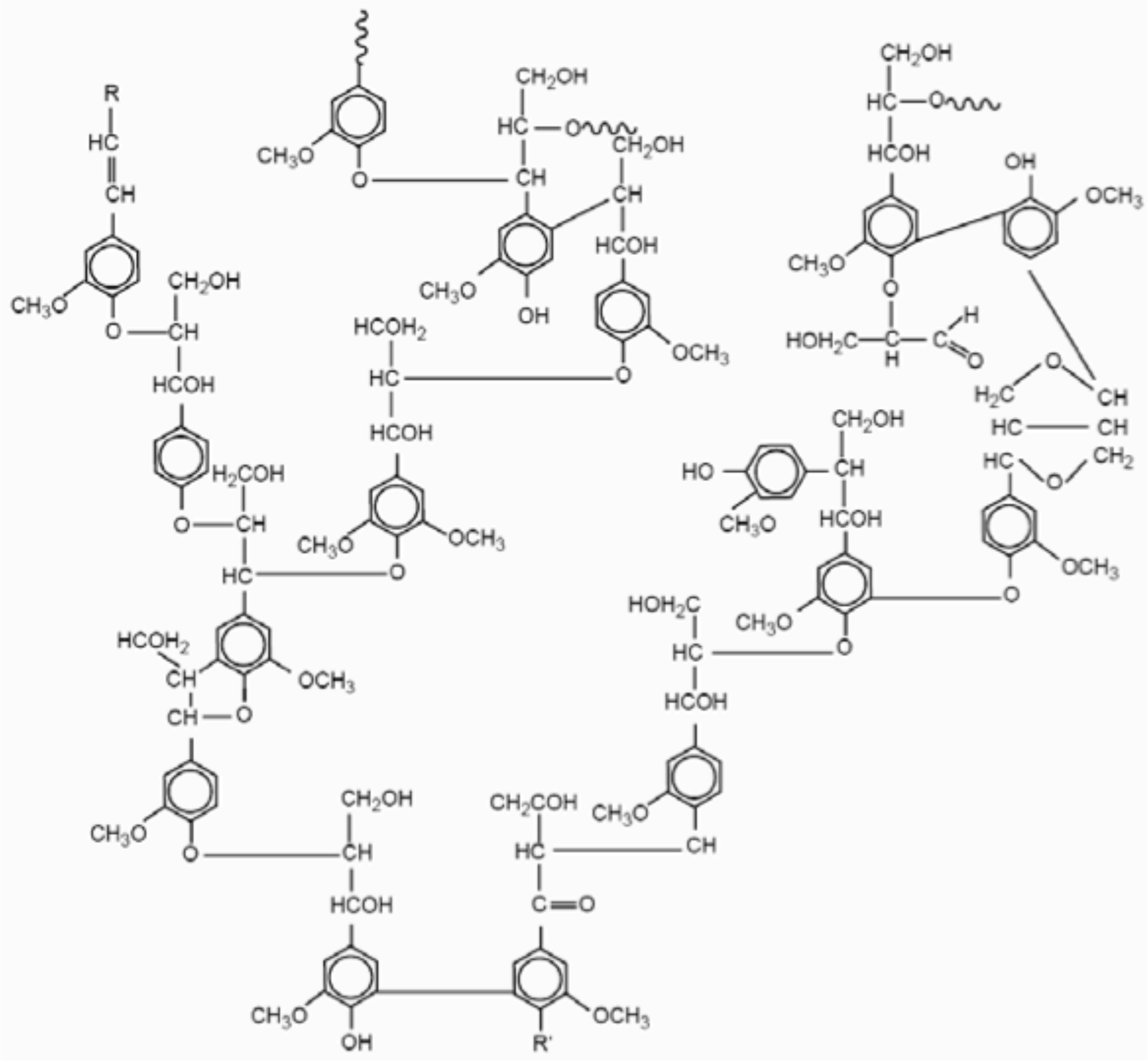


- 40-80 wt% in plants, **17.5 MJ/kg** (C:H:O ≈ 30:45:25 at%)
- ‘***soft***’ part in plants
- linear polymer of up to 10’000 glucose (C6) molecules: $(C_6H_{10}O_5)_n$

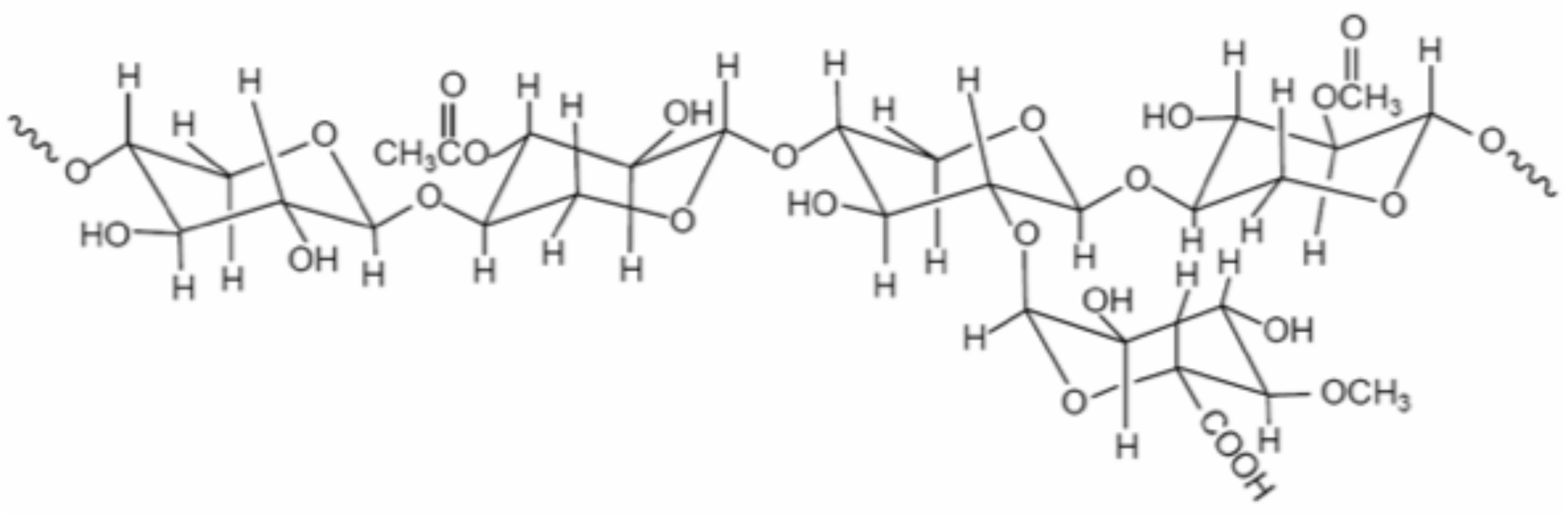
Lignine

- 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 ≈ 40:45:15 at%)



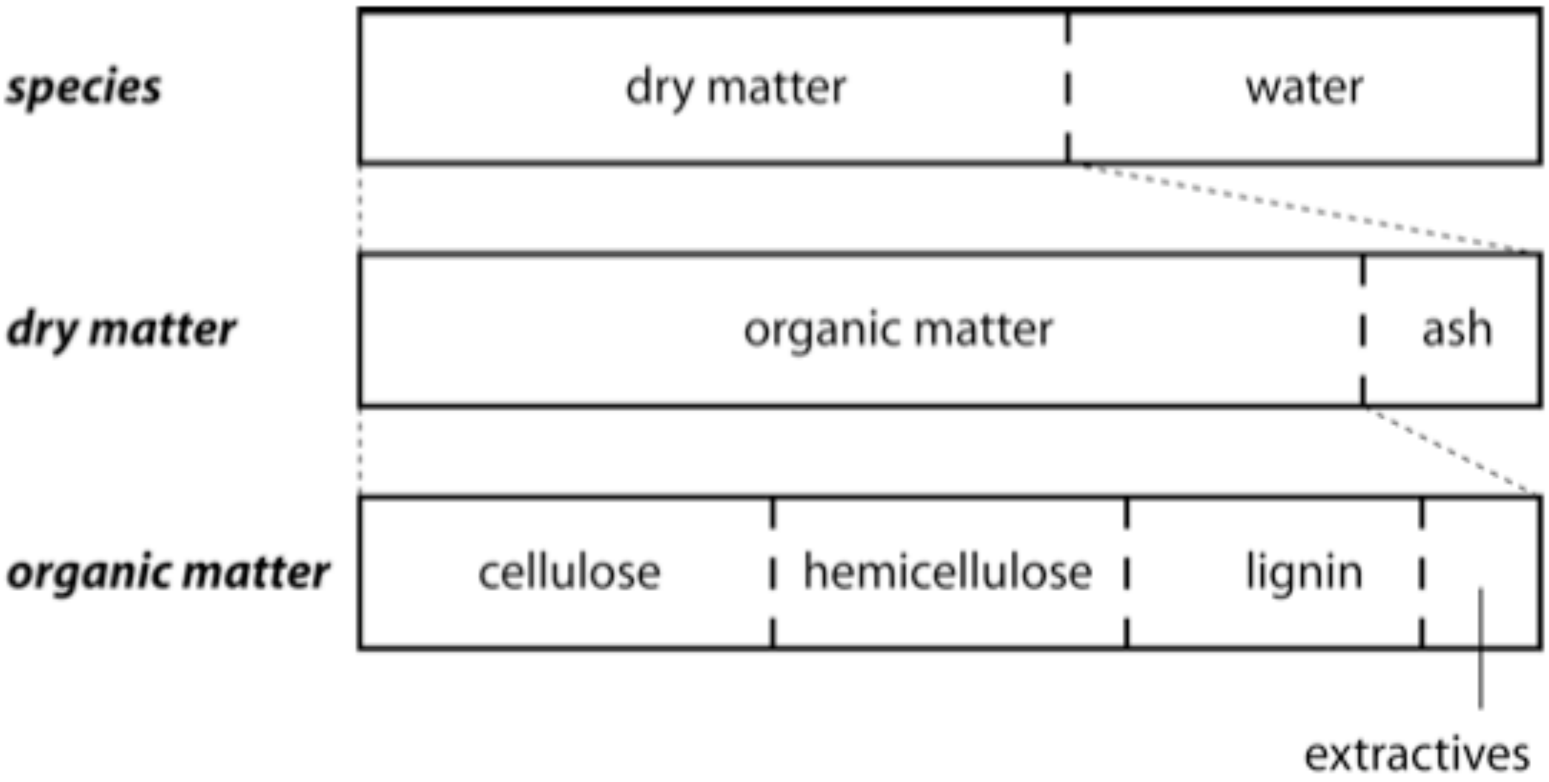
Hemi-cellulose (xylose)



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

Structural composition

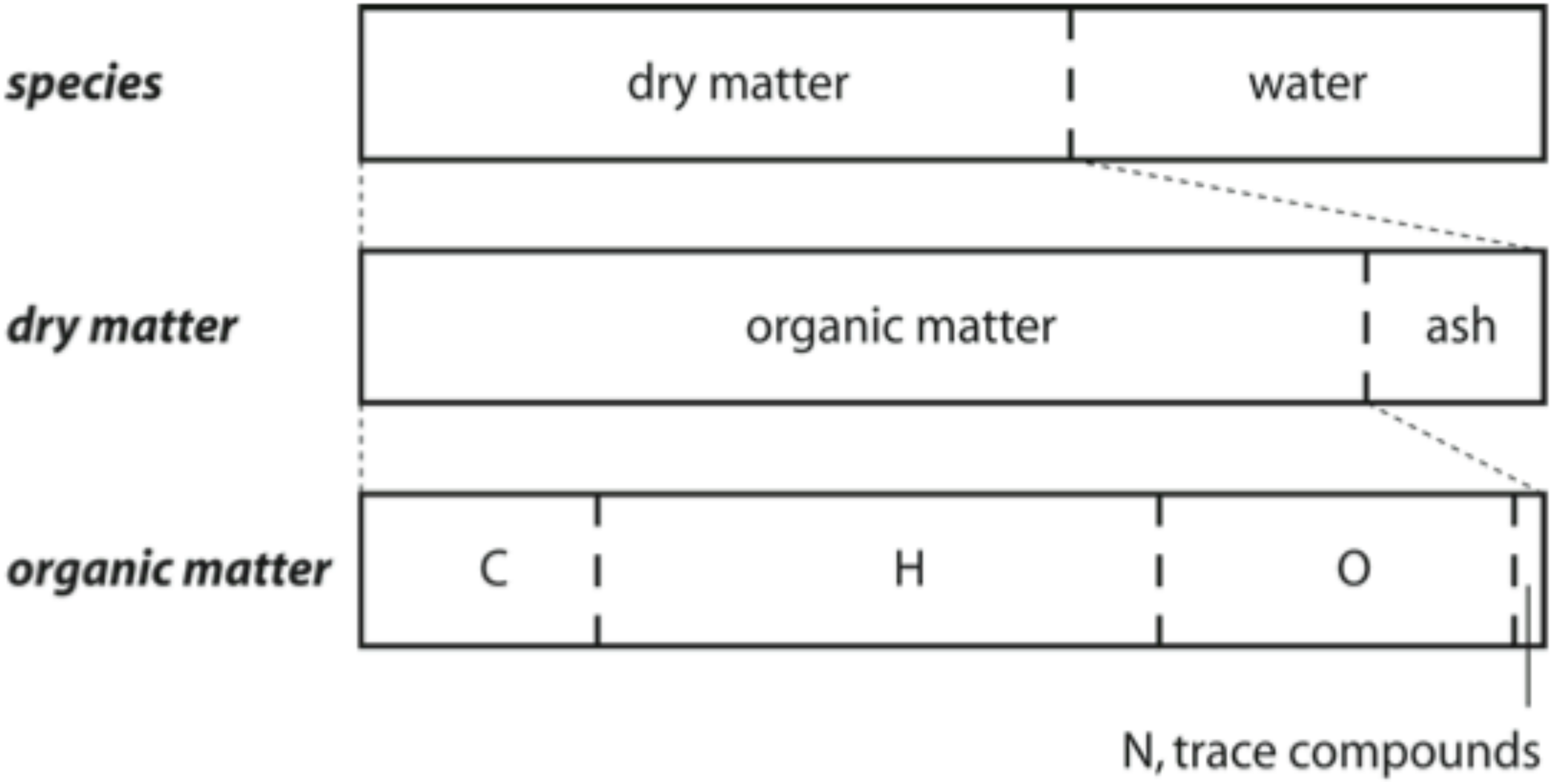
macromolecular description:



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

Chemical composition

atomic description:

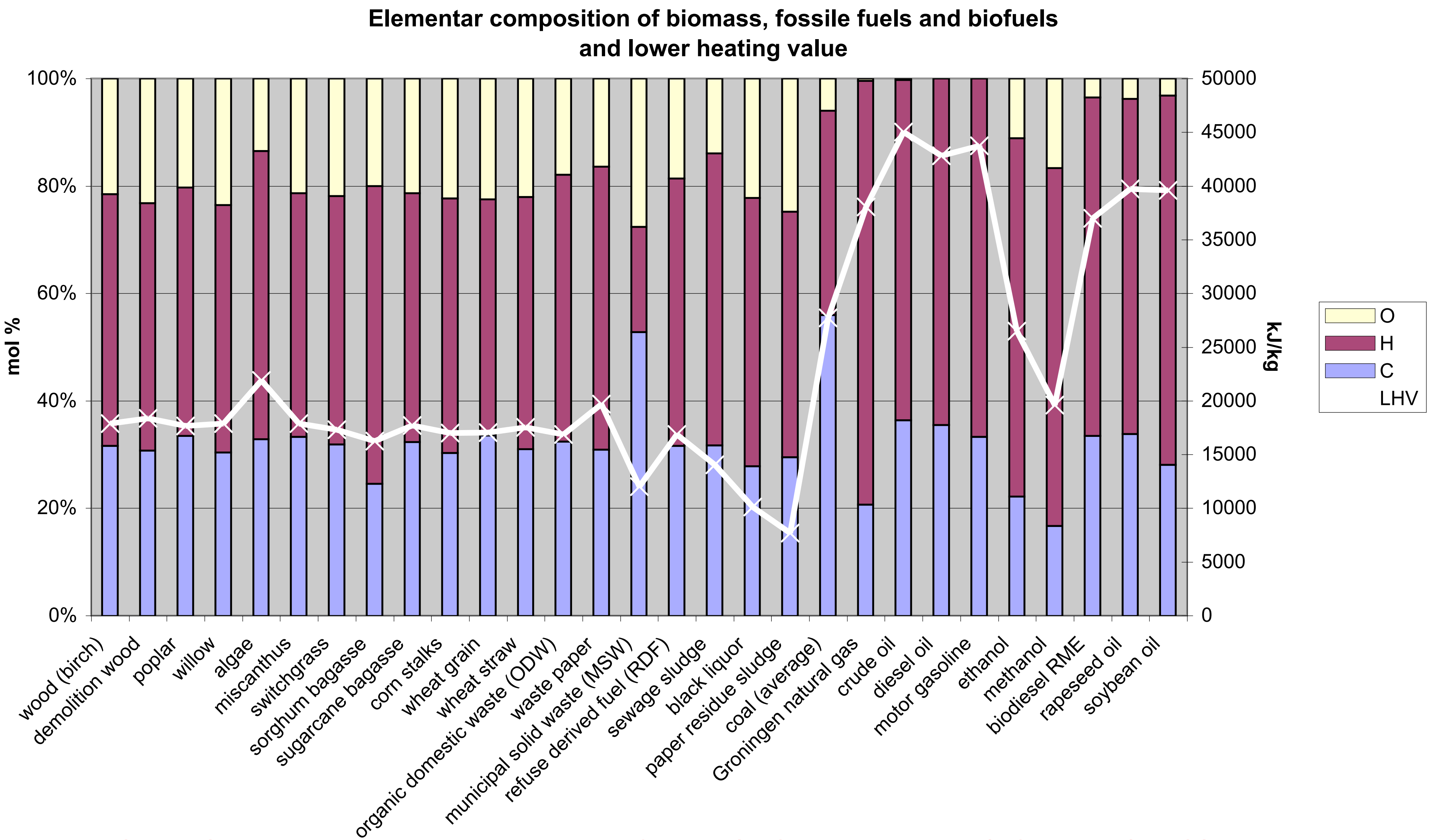


C	~ 30%mol	O	~ 20%mol
H	~ 50%mol	N	~ 1%mol

‘Dry’ wood (with 11% humidity)

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

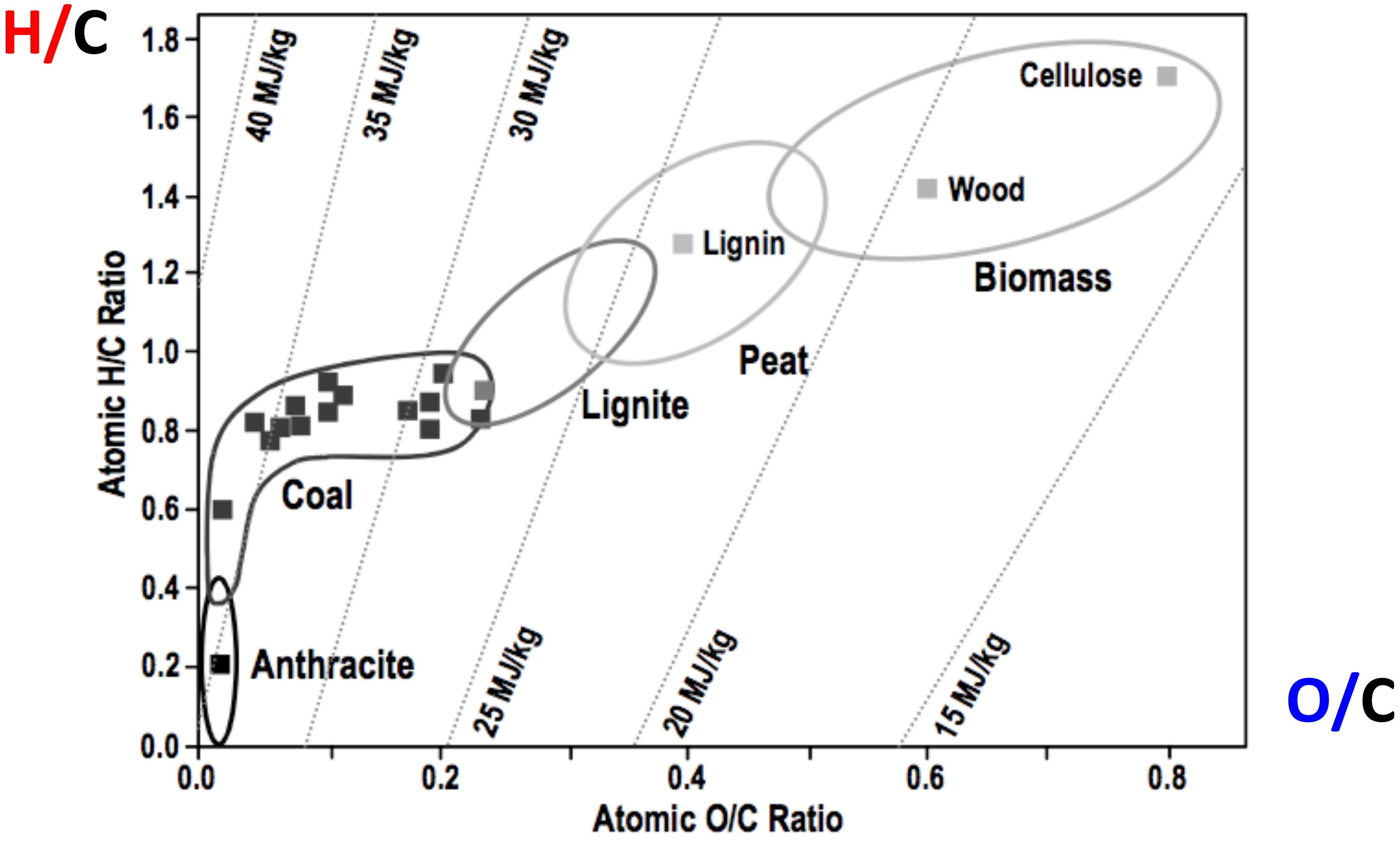
Composition and energy content of fuels


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

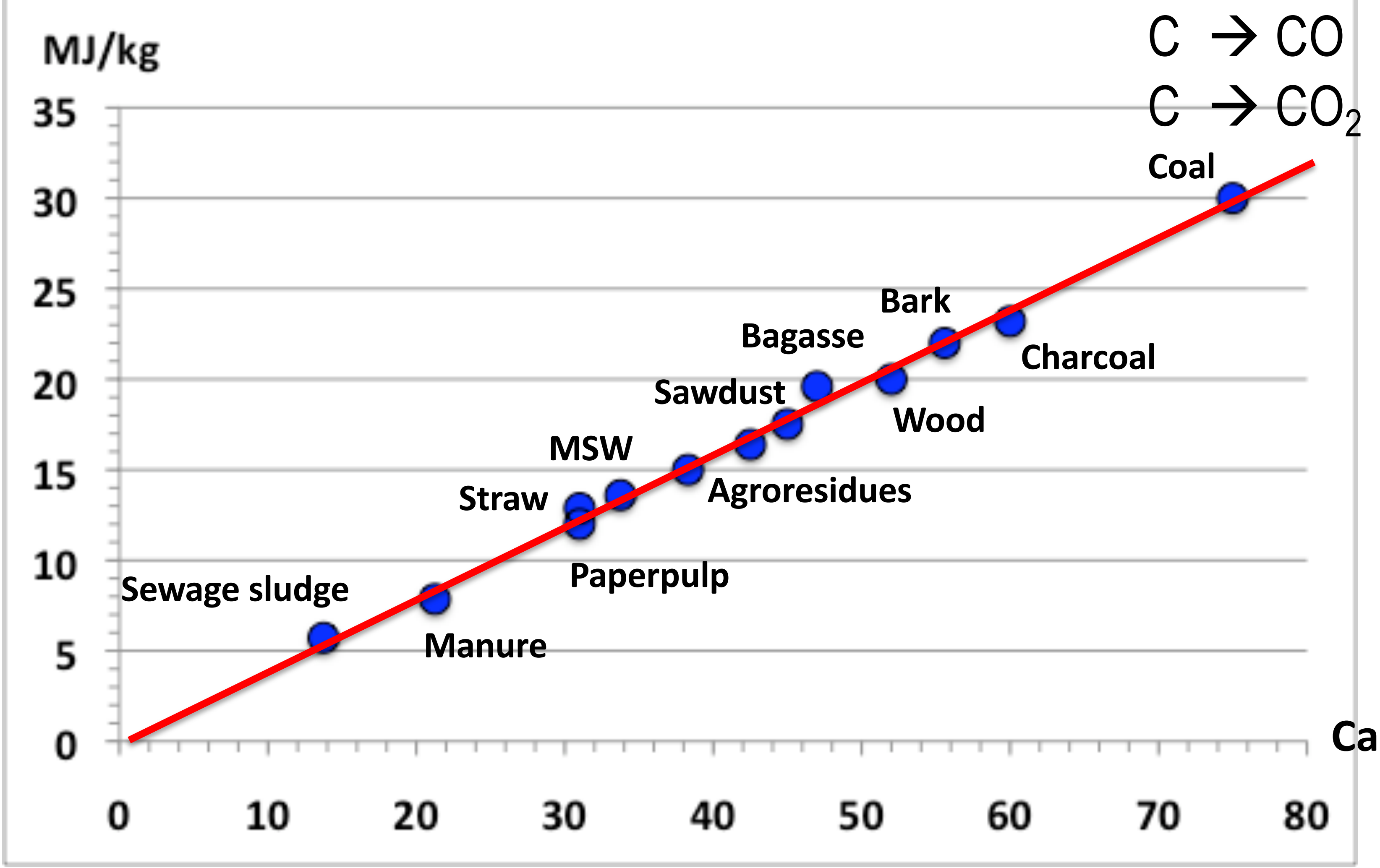
The **OXYGEN** content in biomass fuels (=**OXY**-HYDROCARBONS) reduces the LHV to **<20 MJ/kg** compared to >40 MJ/kg for (fossil) HYDROCARBONS

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% carbon (<80)

Compositions of biomasses

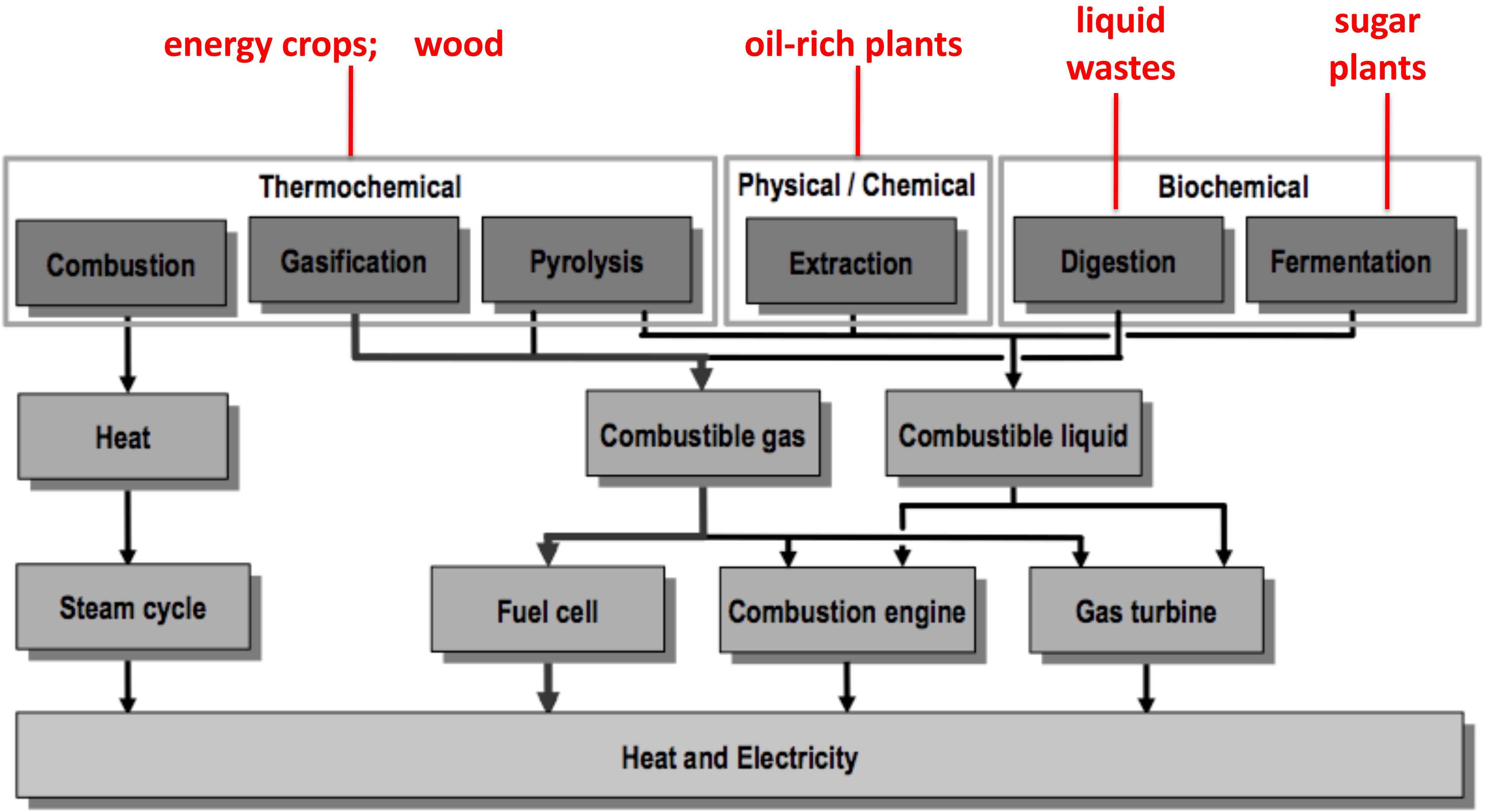
Source	C	H	O	N	S	Inorg.	LHV MJ/kg
carbon	100						29.3
coal	70-80	5	5-20	1-1.5	1-3	4-15	30-34
wood	52	6	40	0.1	0	1	21
bagasse	47	6	35	0	0	11	21
untreated sewage	45.5	7	26	2.4	0.5	19	16.4
cattle manure	42.7	5.5	31	2.4	0.3	18	17
rice residue	39	5.4	38	0.5	0	18	15
MSW	34	4.6	22	0.7	0.4	38	13
paperpulp	31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

$$\boxed{LHV = 43.6 * C - 0.31 \quad MJ/kg}$$

where C = 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 schemes overview



F. Nagel (PSI)

BIOMASS CONVERSION ROADMAP

Source

- Solid (wood, straw)
- Wet (waste, manure)
- Sugar/starch
- Oil crops

Process

- Combustion
- Gasification
- Pyrolysis
- Methanation
- Fermentation
- Extraction + esterification

Product

- Heat
- Woodgas
- Woodoil
- Biogas
- Bioethanol
- Biodiesel

Service

- Heat / CHP
- Electricity
- (Transport) Fuels
- Chemicals