Exercise 1: competition biomass/food

An adult human being is a 120 W machine. We get our energy 80% from vegetables (= 'direct' biomass) and 20% from meat (= 'indirect' biomass), assuming an efficiency from primary biomass-to-meat of 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)
- assess the results in view of the biomass energy potential and agricultural production.

Solution:
→120 J/s * 3600 s/h * 24 h/day = 10.4 MJ/day (2500 kcal/day)* 365 d/yr = 3.8 GJ/yr = 1052 kWh/yr
80% as vegetables = 842 kWh/yr primary biomass
20% as meat = 210 kWh/yr secondary biomass ≈ 2100 kWh/yr primary biomass (assuming 10% efficiency)
Total primary biomass per person = 842 + 2100 = 2942 kWh/yr = 10.6 GJ/yr
→World population (7.5 billion) → 10.6 GJ * 7.5E+9 = **79 EJ**
→Comparison with:
– Yearly biomass production: 3000 EJ
– Yearly sustainable production (9%): 270 EJ
– Yearly agricultural production (5%): **152 EJ**
Hence the current agricultural production is roughly in two-fold excess to feed all people.
Rem1: many people, and children, do not eat 2500 kcal/day, and less meat.
Hence the 79 EJ is likely well exaggerated, and the excess thus larger.
Rem2: from the agricultural production we feed domestic animals too

Exercise 2: estimate of residual biomass primary and final energy

Assumptions:

a) Agriculture: from the total yearly human production (152 EJ), discount food requirement (79 EJ, exercise 1). Assume that from the remainder, ≈½ is used to feed animals, ≈¼ is used for composting, and the rest (10%) is recoverable as 'residual energy'.
b) Forestry: take 1 kg/m^2 new wood growth per year (LHV: 17 MJ/kg); assume 1% of the world's forests area is trimmed (from where this waste wood is recovered as energy)
c) Animal manure: assume a production of 1 m^3 of biogas per day (50% CH_4 content) per large farm animal and there are half as many large farm animal-equivalents as people.
d) Solid organic wastes from our activities (food waste, park and garden waste, food industry): assume a waste of 1 kg dry organic matter per week per person, converted to 500 L biogas per kg, with a CH_4 content of 60%

e) Human <u>liquid</u> organic waste (<u>sewage</u> – waste water treatment plants): assume a production of 30 L biogas per person per day, with a CH_4 content of 65%

From all this data, compute the total residual biomass primary energy potential and how this relates to the total human yearly <u>primary energy</u> consumption.

For the conversion to <u>final energy</u>, make realistic choices for the conversion technology (for power) and the conversion efficiencies.

<u>Solution</u>:

<u>Agroresidues</u>: 152 EJ total production
food for people: ≈50%, food for animals: 25%, compost: 15%
residue: 10% = **15 EJ**
<u>Forestry</u>: 1 kg/m^2 (17 MJ/kg). Forests cover 11% of the Earth surface (Earth surface = 5.1 E+14 m^2). Assume 1% energy use of the forests = 5.6 E+11 m^2 → multiplied with 1kg/m^2 sustainable wood production with energy content of 17 MJ/kg → **9.5 EJ**
(this figure is likely a strong underestimate)
<u>Manure</u>: 1 m^3 biogas/day (50% CH_4) with LHV(CH_4) = 36 MJ/m^3
18 MJ/m^3.day per large farm animal* 365 days * ~3.75 billion large animal-equivalents (estimate!) gives **24.6 EJ**
<u>Solid waste</u>: 1 kg dry matter/week → 52 kg/yr, converted to 500 L biogas/kg (with 60% CH_4)
52 kg/yr * 0.5 m^3/kg * 0.6 * 36 MJ/m^3 = 0.56 GJ/yr.person
for 7.5 billion people: **4.2 EJ**
<u>Sewage</u>: 30 L/day.person (65% CH_4)
0.03 m^3/d * 365 d/yr * 0.65 * 36 MJ/m^3 = 0.26 GJ/yr.person
for 7.5 billion people: **1.9 EJ**

⇒ **Total: 15+9.5+24.6+4.2+1.9 = 55.2 EJ** (10% of world primary energy!)

When valorised to electricity :
20% efficiency for solids (15+9.5=24.5 EJ) → 2.9 EJ → 0.8 PWh
30% efficiency for biogases (24.6+4.2+1.9=30.7 EJ) → 9.2 EJ → 2.55 PWh

=> total 3350 TWh (world: 22'000 TWh), i.e. 15% of world electricity!

<u>Rem</u>: in 2017 <u>all</u> biomass electricity was only ≈500 TWh

Exercise 3: wood pyrolysis energy balance

Input:

- 1 kg dry wood with LHV 17 MJ/kg
- heat supply for the pyrolysis (endothermal): 2.4 MJ
  (=delivered from burning the liberated gases)

Products:

- 200 L gas (with LHV equal to 1/3rd of that of NG (36 MJ/m^3))
- 0.45 kg liquids (with LHV equal to 1/3rd of oil (42 MJ/kg))
- 0.3 kg charcoal (with LHV equal to that of coal (24 MJ/kg)

Compute the total energy balance of the pyrolysis process.
Compute the energy balance only for the solid output (charcoal).

Solution:
Products:

- 200 L gas (LHV 1/3rd of NG (36 MJ/m^3) = 12 MJ/m^3) => 2.4 MJ
- 0.45 kg liquids (LHV 1/3 of oil (42 MJ/kg) = 14 MJ/kg) => 6.3 MJ
- 0.3 kg charcoal (LHV of coal (24 MJ/kg)) => 7.2 MJ

Total: 15.9 MJ
Balance: (15.9-2.4) / 17 = 79% (total)
7.2 / 17 = 42% (carbon basis only)

Exercise 4: wood gasification energy balance (downdraft gasifier, air)

Input:
1 kg 15% humid wood (with LHV of wood with 0% H_2O = 17.8 MJ/kg)
⇨ compute the LHV of the humid wood
Products:
2 m^3 ‘producer gas’ of :
18% CO / 16 % H_2 / 2 % CH_4 / 14% CO_2 / 50% N_2
(LHV (CO): 305 kJ/mole; LHV (H_2) : 241 kJ/mole; LHV (CH_4) : 800 kJ/mole)

Compute the energy balance of this gasification process (‘cold gas efficiency’).

Indication:

Producer gas type	**Main compounds**	**Process**
Poor : ≤ 5 MJ / m^3	N_2, CO, H_2	pulsed **air**
Medium : 10 MJ / m^3	CO, H_2	pulsed **oxygen**; mixed air/steam reforming
Rich : ≥ 15 MJ / m^3	CH_4	**steam** reforming, hydrogenation

Input: 1 kg 15% humid wood (17.8 MJ/kg 0% H_2O)

=> LHV(15% water) = 17.8*(1 – 1.14*15%) = 14.75 MJ/kg

2 m^3 producer gas of :
18% CO / 16 % H_2 / 2 % CH_4 / 14% CO_2 / 50% N_2
= 360 L CO / 320 L H_2 / 40 L CH_4
= 16 moles CO / 14.3 moles H_2 / 1.8 moles CH_4 (22.4 L/Nm^3)
(LHV (CO): 305 kJ/mole; LHV (H_2) : 241 kJ/mole; LHV (CH_4) : 800 kJ/mole)

=> 4.88 MJ CO + 3.45 MJ H_2 + 1.44 MJ CH_4 = 9.77 MJ
(= 4.9 MJ/m^3) = ‘poor’ gas (air-pulsed) – see the above table

Balance: 9.77 MJ out / 14.75 MJ in = 66% (‘cold gas efficiency’)

Exercise 5: 25 MWe straw biomass plant

Data:

- 8000h / 200 GWh_el
- 160’000 tonnes / yr of straw
- 200’000 t CO_2 emissions / yr avoided
- assume a typical yield of 3 tonnes straw per ha

Questions:

- what is the electrical efficiency of the plant?
  (use the LHV for straw from the course slides)
- what would be the straw collection area needed for the plant?
- what is the CO_2 emission value based on?

→ What is the electrical efficiency of the plant?
(use the LHV for straw from the course slides p. 35) => 13 MJ/kg
(this straw is 20% wet)
Input : 160'000'000 kg straw * 13 MJ/kg = 2.08 PJ

Electricity produced : 200 GWh_el = 0.72 PJ
⇨ efficiency = 0.72/2.08 = 34.6%. This is a particularly efficient (optimised) plant, due to the fairly large steam turbine size (25 MWe) - cf. the course slides p.33

→ What would be the straw collection area needed for the plant?
With 3 tonnes/ha straw, we need 160'000 tonnes/3 = 53333 hectare = 533.3 km^2, or a square of 23 x 23 km. This is a huge area, for a comparatively small power plant.

→ What is the CO_2 emission value based on?
200'000 t CO_2 avoided for 200 GWh_el produced => the emission assumption of 1 kg per 1 kWh_el produced has been assumed, which is typical for coal plants.