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, and not all is edible. One sees the order of magnitude is OK.

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 2 kg/m^2 new wood growth per year (LHV: 17 MJ/kg); assume 2% 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 liquid organic waste (sewage – 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 primary energy consumption.

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

Solution:

Agroresidues: 152 EJ total production
food for people: ≈50%, food for animals: 25%, compost: 15%
residue: 10% = **15 EJ**
Forestry: 2 kg/m^2 (17 MJ/kg). Forests cover 11% of the Earth surface (Earth surface = 5.1 E+14 m^2). Assume 2% energy use of the forests = 1.12 E+12 m^2 → multiplied with 2kg/m^2 sustainable wood production with energy content of 17 MJ/kg → **19 EJ**
(this figure is likely a strong underestimate)
Manure: 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**
Solid waste: 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**
Sewage: 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+19+24.6+4.2+1.9 = 64.7 EJ** (11% of world primary energy!)

When valorised to electricity :
20% efficiency for solids (15+19=34 EJ) → 6.8 EJ → 1.9 PWh
35% efficiency for biogases (24.6+4.2+1.9=30.7 EJ) → 10.75 EJ → 3 PWh

=> total 4.9 PWh (world: 25 PWh), i.e. 20% of world electricity!

Rem: in 2017 all biomass electricity was only ≈500 TWh (1/10th of the potential)

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

<u>Questions</u>:

- 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 taken, which is typical for coal plants.