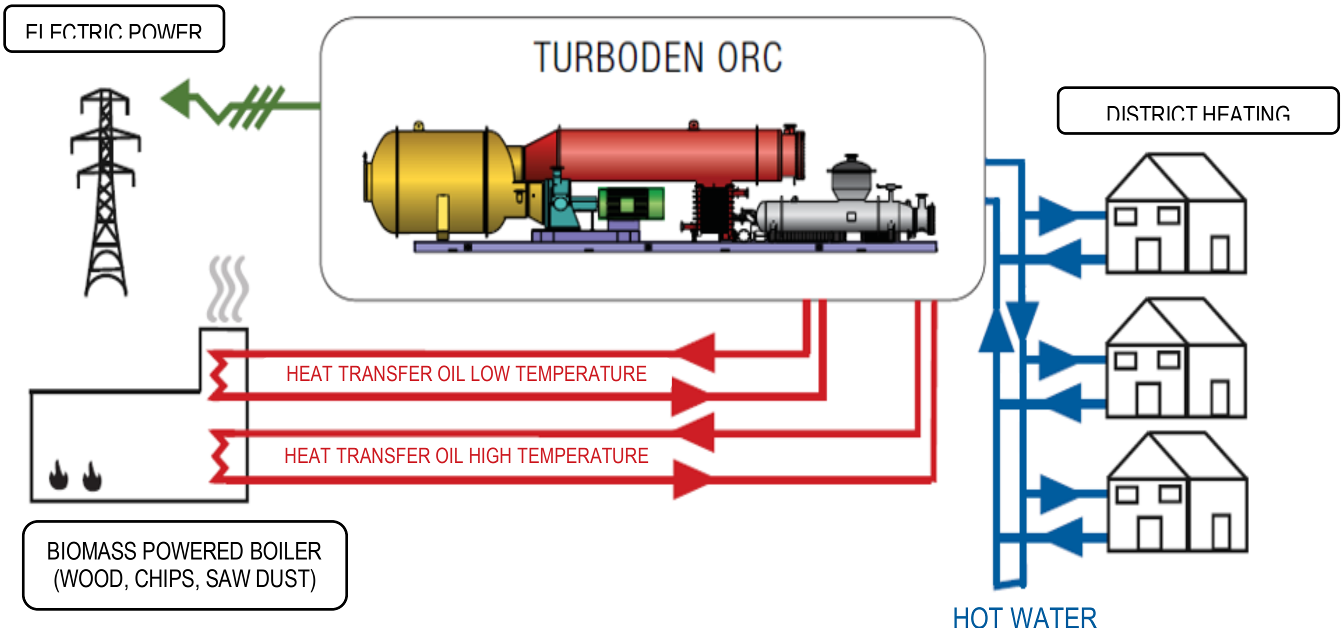
1) Power recovery from biomass combustion

Organic Rankine Cycle (ORC) technology is used to recover heat to electricity. One of the applications is for waste biomass combustion. The systems are flexible and can be used in district heating, pellet production factories, sawmills and tri-generation systems with absorption chillers.
An example of the technology is reported in the scheme below:



Data:

Input of woody biomass = 5254 kg/h
Wood biomass LHV = 9.36 MJ/kg
Heat transfer oil properties:

	Temperature	Enthalpy
Inlet Low Temp cycle	132 °C	200 kJ/kg
Outlet Low Temp cycle/ Inlet High Temp cycle	252°C	443 kJ/kg
Outlet High Temp cycle	312°C	578 kJ/kg

Mass flow of Low Temp cycle heating oil = 4.3 kg/s
Mass flow of High Temp cycle heating oil = 81.3 kg/s
Hot water outlet temperature from ORC system = 90°C
District heating water return temperature = 60°C
Water properties:

Temperature	Enthalpy
60°C	251 kJ/kg
90°C	377 kJ/kg

District heating water flow = 76.43 kg/s
Electric net power output of ORC Turboden plant = 2175 kW

Calculate

1) The boiler efficiency

Thermal oil total power = 4.3*(443-200) + 81.3*(578-443) = 12.02 MW
Wood Biomass input = 5254 kg/3600s*9.36 MJ/kg = 13.66 MW
Efficiency of boiler = 88%

2) The electrical efficiency of the ORC

Efficiency = output (electric power)/ input (thermal oil power)
Efficiency = 2175 kW / 12020 kW =18%

3) The cogeneration efficiency of the ORC

District heating power = 76.43*(377-251) = 9630 kW
Cogeneration efficiency on recovered heat = (2175+9630)/12020 = 98.2%
Cogeneration efficiency on woody biomass = (2175+9630)/13660 = 86.4%

2) Biomass CHP-plant from energy crops

A crop plantation yields 20 tons dry organic matter per year and per hectare (LHV: 17 MJ/kg). (Cf. corresponding to 2 kg/m^2, or also 1 W/m^2 storage efficiency, as seen in the course). Harvesting is in autumn. A CHP plant combusts the crop fuel during the heating season (6 months, 4000h). The idea is to supply as much as possible the local residents and their economic activity with heat and power from this plant. The power need averaged per person is taken as 0.8 kWel, the heat need (for the 4000h heating season) as 2.7 kW per person on average (values valid for Switzerland). The CHP plant drives a steam cycle with 21% efficiency, total cogeneration efficiency is 92%. A typical plantation size could be 1 km^2. How many people-equivalents could such a plant supply with heat and power (during the 4000h heating season)?
How many such plants (and therefore how many km^2 of energy crop plantations) would be needed to cover the whole population-equivalent? (8 million in CH)
Discuss the outcome.

Solution:
1 km^2 = 100 hectare = 2000 tons dry organic matter (at 17 MJ/kg) => 34 TJ of crop energy.
This amount is used during 4000h, which is equivalent to 34 TJ / 4000h = 2.36 MW total power equivalent of the plant. Electrical efficiency is 21%, or 2.36 MW * 0.21 = 496 kWel, and heat efficiency is 71% (92% total – 21% electrical), or 2.36 MW * 0.71 = 1.676 MWth.

With 0.8 kWel total average power need per person-equivalent, the 496 kWel power plant could thus supply an equivalent population of 496 kWel / 0.8 kWel = 620 people. The same result is obtained for heat need : 1.676 MW / 2.7 kW = 620; which is not a coincidence as the example was chosen in this way. It demonstrates however that the heat-to-power ratio of such a plant is well adapted for such a supply.
If we needed to cover the population-equivalent of 8 million people with such CHP plants, we thus would need 8’000’000 / 620 = 12900 of such plants, meaning 12900 km^2 of energy crop plantations. With a total agricultural area utilized of ~10’500 km^2, we see that we quickly run into land limitation with biomass-for-energy plants, but that they could give a partial contribution to the overall supply.

3) Biogas generation efficiency from manure

Manure biomass is transformed to biogas by anaerobic digestion (hydrolysis).
The manure's composition is, by weight (dry basis), 42% carbon, 6% hydrogen, 32% oxygen, 2.1% nitrogen, plus 18% of inorganics.
What will be the biogas composition ?
What is the energy balance of the process? I.e. how much energy is contained in the biogas compared with how much energy is contained in the manure?
(LHV CH_4 : 800 kJ/mole) (LHV NH_3 : 225 kJ/mole)
Hint: use the Buswell-Boyle formula

Solution

Transform the wt% composition into a molar composition :

100 g of dry manure contains

42 g C = 3.5 moles	(12 g/mole C)
6 g H = 6 moles	(1 g / mole H)
32 g O = 2 moles	(16 g / mole O)
2.1 g N = 0.15 moles	(14 g / mole)

The manure is thus of equivalent chemical formula
$C_{3.5}H_6O_2N_{0.15}$ with coefficients a = 3.5, b = 6, c = 2, d = 0.15

It is hydrolysed according to the Buswell-Boyle formula with
$0.25 * (4a - b - 2c + 3d)\ H_2O = 1.11\ H_2O$, to

$0.125 * (4a + b - 2c - 3d)\ CH_4 = 1.94375\ CH_4$, and
$0.125 * (4a - b + 2c + 3d)\ CO_2 = 1.55625\ CO_2$, and
$0.15\ NH_3$

or a total of 1.94375 + 1.55625 + 0.15 = 3.65 mole biogas = 82 NL biogas (22.4 NL/mole) from 100 g dry biomass (hence 820 L biogas or 436 L methane from 1 kg dry biomass).

Therefore, the product biogas is CH_4 = 53.25%, CO_2 = 42.64% and ammonia = 4.1%

The formula $C_{3.5}H_6O_2N_{0.15}$ plus inorganics (18%) equals 100 g/mole.
The LHV of the manure is estimated with LHV = 43.6 * wt%C – 0.31 = 18 MJ/kg where C =42wt%
One mole of 100 g (0.1 kg) thus contains 1.8 MJ.

It delivers 1.94375 mole CH_4 (LHV : 800 kJ/mole) or 1.555 MJ, plus 0.15 mole NH_3 (LHV 225 kJ/mol) or 33.75 kJ, hence in total 1.555 + 0.03375 = 1.58875 MJ
The process energy balance is thus 1.58875 MJ output/ 1.8 MJ input = 88.3%

- ⇨ conclusion : efficient process, decent yield, if all of the manure were digested. In reality, however, a considerable amount of (undigested) carbon may remain into the digestate. This is why digestates may still be incinerated. On the other hand, the digestate is usually restituted to the soil as natural fertilizer, as it contains the inorganic nutrients N, K, P, and the carbon is then also restituted to the soil in a positive and durable fashion (terra petra).