1) Biogas generation efficiency from manure

Manure biomass is transformed to biogas by anaerobic digestion (in essence a slow 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

$$
\begin{aligned}
C_aH_bO_cN_dS_e + \frac{1}{4}\left[4a - b - 2c + 3d + 2e\right]H_2O \\
\rightarrow \quad & \frac{1}{8}(4a + b - 2c - 3d - 2e)CH_4 \\
+ \quad & \frac{1}{8}(4a - b + 2c + 3d + 2e)CO_2 \\
+ \quad & dNH_3 \quad + \quad eH_2S
\end{aligned}
$$

with
¼ * (4a – b - 2c + 3d) H_2O = 1.11 H_2O, to

1/8 * (4a + b – 2c - 3d) CH_4 = 1.94375 CH_4, and
1/8 * (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 the formula :

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 : it's a rather efficient process, with a decent yield, if ALL of the manure were digested. In reality, however, a considerable amount of (undigested) carbon remains into the digestate. Often 20% to even 50% of the carbon !
This is why digestates are still incinerated.
On the other hand, the digestate is usually (and better) restituted to the soil as natural fertilizer, as it contains the inorganic nutrients N, K, P, and the carbon is then also recycled to the soil.

2) Gasoline / Diesel replacement by inland bioethanol / biodiesel production ?

Inland mobility fuel use in Switzerland is ~5.1 Mtoe gasoline and ~2 Mtoe diesel per year.

(1 Mtoe = 1 mega-tonne oil equivalent = 42 PJ)

Assume we want to replace part of it by inland biofuel production and that we could dedicate 1000 km^2 of the Swiss territory (total: 41'000 km^2) to sugar beet plantation and 1000 km^2 to rapeseed plantation (which are huge areas by the way).

Bioethanol (21.3 MJ / L) from sugar beet : yield 2500 L / ha (1 ha = 10'000 m^2 = 0.01 km^2)

Biodiesel (33 MJ / L) from rapeseed : yield 700 L / ha (one notices that the lower yield with biodiesel is in part compensated by the higher LHV, compared to bioethanol).

How much (%) of imported gasoline and diesel fuel consumption could be replaced this way ?

Ethanol : 2500 L/ha * 100 ha/km^2 * 1000 km^2 * 21.3 MJ/L = 5.325 PJ

Fossil gasoline = 5.1 Mtoe = 5.1 * 42 PJ = 214 PJ

→ 2.5% (5.325 PJ from 214 PJ) of gasoline could be replaced with bioethanol

Biodiesel : 700 L/ha * 100 ha/km^2 * 1000 km^2 * 33 MJ/L = 2.31 PJ

Fossil diesel = 2 Mtoe = 84 PJ

→ 2.75% (2.3 PJ from 84 PJ) of diesel could be replaced with biodiesel

If we were to dedicate instead 1000 km^2 of forest land (there is ~11'000 km^2 of forest in Switzerland) to bioethanol production (=>assume here renewable dry wood production of 20 ton / ha.yr, converting 3 kg wood to 1 kg ethanol), how much gasoline could we replace ? (ethanol density: 0.8 kg/L)

0.333 (weight yield 3 kg wood=>1 kg ethanol) * 20'000 kg/ha * 100 ha/km^2 * 1000 km^2 * 21.3 MJ/L / 0.8 kg/L = 17.75 PJ

→ 8.3% (17.75 PJ from 214 PJ) of gasoline could be replaced with bioethanol from wood

If we would instead convert this yearly available renewable wood quantity into methane (take wood-to-methane 70% energy efficiency yield) for mobility (gas vehicles) ? (Assume 16.7 MJ/kg dry wood)

0.7 (energy yield wood=>CH_4) * 20'000 kg/ha * 100 ha/km^2 * 1000 km^2 * 16.73 MJ/kg = **23.42 PJ**

Comment the results.

Wood energy is considerably <u>denser</u> than energy crops for liquid biofuels (considering the land use). Gasification to methane is still more energy efficient among the different considered cases. Bioethanol and biodiesel could be OK for exploiting ‘marginal’ land areas (land not particularly used otherwise), but can only deliver a limited contribution to fossil mobility fuel replacement at the current use rate.

With the efficiency of engines for transport of around ~20% (fuel-to-wheel), it is in theory smarter to convert the fuel to electricity with an efficient method (e.g. with fuel cells, to > 50%) and then use the electricity for EV driving. However, this then enters into other questions in terms of the electrical grid, vehicle range etc.