

Exercise V: Selection of a cogeneration engine

Solutions:

1. Burned gas mass flow: $\dot{M}_{Exg} = \dot{M}_{air} + \dot{M}_{Fuel}$

For biogas engines, you have to consider the CO₂ gas flow coming from the biogas fuel:

$$\dot{M}_{CO_2} = \frac{\dot{M}_{Nat\ gas}}{\tilde{m}_{Nat\ gas}} \cdot \left(\frac{\%_{CO_2}}{100 - \%_{CO_2}} \right) \cdot \tilde{m}_{CO_2} \quad , \dot{M} = \left[\frac{kg}{s} \right] \quad and \quad \tilde{m} = \left[\frac{kg}{kmol} \right]$$

Then, the total burned gas mass flow is given by:

$$\dot{M}_{Exg} = \dot{M}_{air} + \dot{M}_{Fuel} = \dot{M}_{air} + \dot{M}_{Nat\ gas} + \dot{M}_{CO_2}$$

Lambda ratio:

$$\lambda = \frac{\dot{M}_{Air}}{\dot{M}_{Fuel}} \cdot \frac{1}{R_{A/F}}$$

Specific fuel consumption:

$$BSFC(kg / kWh) = CSE = \frac{\dot{M}_{Fuel}(kg / h) \cdot 1000}{\dot{E}_e(kW)}$$

Global efficiency:

$$\eta_e = \frac{\dot{E}_e}{\Delta h_i^0 \cdot \dot{M}_{Fuel}}$$

Effective specific emission:

$$\tilde{c}_i \left(\frac{g_i}{kWh} \right) = \dot{c}_i(ppm) \cdot \frac{\tilde{m}_i(kg_i / kmol)}{\tilde{m}_{Exg}(kg_{Exg} / kmol)} \cdot \frac{\dot{M}_{Exg}(kg_{Exg} / h) \cdot 10^{-3}}{\dot{E}_e(kW)}$$

Emission concentration at reference condition: $V_N = \frac{\Re \cdot T_N}{P_N} = \frac{8314 \cdot 273.15}{1.013 \cdot 10^5} = 22.4 \left(\frac{m_N^3}{kmol} \right)$

$$\tilde{c}_i \left(\frac{mg_i}{m_N^3} \right) = \dot{c}_i(ppm) \cdot \frac{P_N}{\Re \cdot T_N} \left(\frac{kmol}{m_N^3} \right) \cdot \tilde{m}_i \left(\frac{kg}{kmol} \right)$$

$$\tilde{c}_i \left(\frac{mg_i}{m_N^3} \right) = \dot{c}_i(ppm) \cdot \frac{1}{22.4} \cdot \tilde{m}_i \cdot f_{O_2} \quad with \quad f_{O_2} = \frac{21 - 5}{21 - \dot{c}_{O_2}}$$

With the relations above, we can calculate for each engine the following specific emissions in [g/kWh] and in [mg/Nm³]:

Engine model	CO ₂ gas mass flow rate (for Biogas)	Burned gas mass flow rate	Lambda ratio	Specific fuel consumption	Global efficiency
	kg/h	kg/h	-	g/KWh	%
E1-D	0.0	726.2	1.71	194.3	43.2
E2-D	0.0	694.7	1.51	209.1	40.1
E3-NG	0.0	868.2	1.76	203.4	37.6
E4-BG	20.2	859.1	1.75	196.7	38.8
E5-BG	38.0	823.1	1.66	193.7	39.4

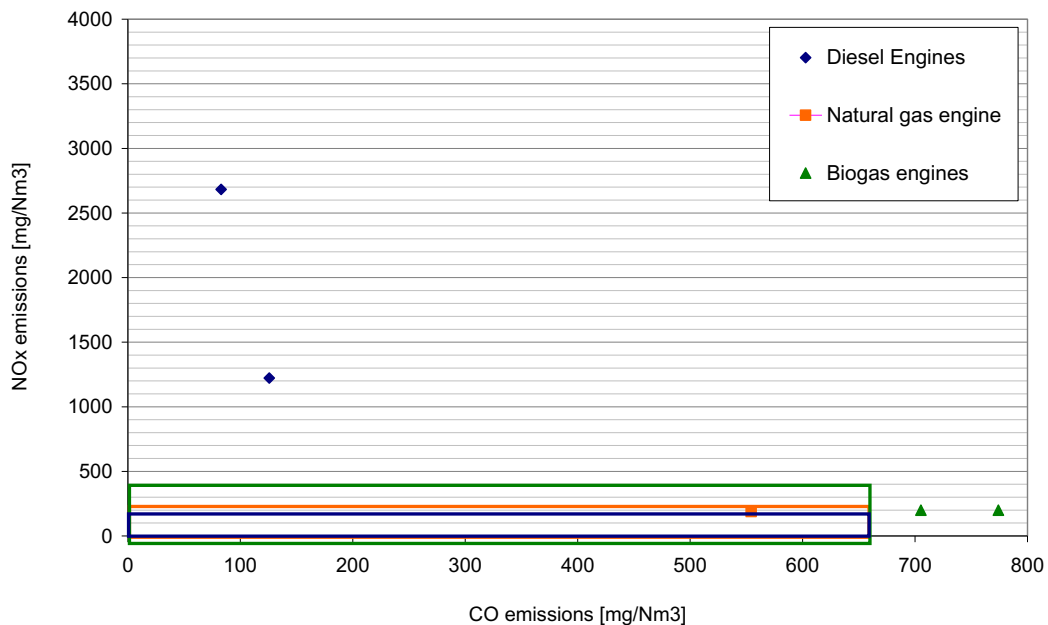
Engine model	spec. NO _x emissions	spec. CO emissions	spec. HC emissions	Normalized NO _x emissions at 5% O ₂	Normalized CO emissions at 5% O ₂
	g/kWh	g/kWh	g/kWh	mg/m ³ N	mg/m ³ N
E1-D	7.36	0.23	0.21	2683	83
E2-D	3.55	0.37	0.13	1222	126
E3-NG	0.60	1.78	2.30	188	554
E4-BG	0.64	2.25	1.77	200	705
E5-BG	0.65	2.53	1.90	199	774

Table 1A and 1B: Computed data of the 5 cogeneration engines of 145 kW effective power.

2. Observations:

- Diesel (or compressed ignition) engines produce much more NO_x emissions than the 3 spark ignition engines (Natural gas + BG). This is due to the fact that the combustion process in C.I engine is in a heterogeneous mixture whereas the combustion process takes place in a homogeneous mixture for S.I engines (E3, E4 and E5). The lambda ratio of the E2-D engine is lower than the E1-D engine and has probably an external gas recirculation system, consequently diminishing the specific NO_x emissions by ca. 50%.
- The very high CO and HC spec. emissions can be explained by the lower flammability range limit, which is close to $\lambda = 1.80$ for natural gas. A high amount of unburned hydrocarbons are generated when the combustion conditions are close to this limit.
- Although the specific fuel consumption of the 3 S.I engines is good, Diesel engines (E1 and E2) have a better global efficiency than S.I engines because of the higher compression ratio in this type of engine (18:1 instead of 13:1 in that case).

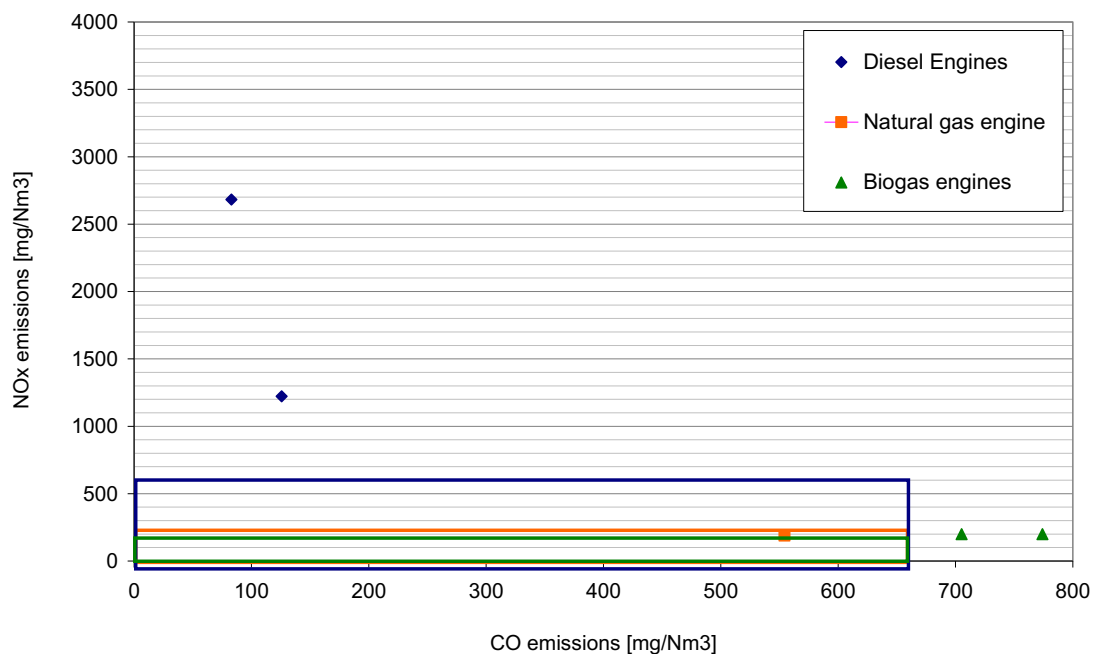
3. a) Stationary engines that satisfy the emission standards for an industrial plant located in Switzerland:



Only the engine model E3-NG fulfills the Swiss standards. A second solution will be to choose one of the 2 Biogas engines (E4-BG and E5-BG) and integrate an oxidation catalyst in order to reduce the CO emissions.

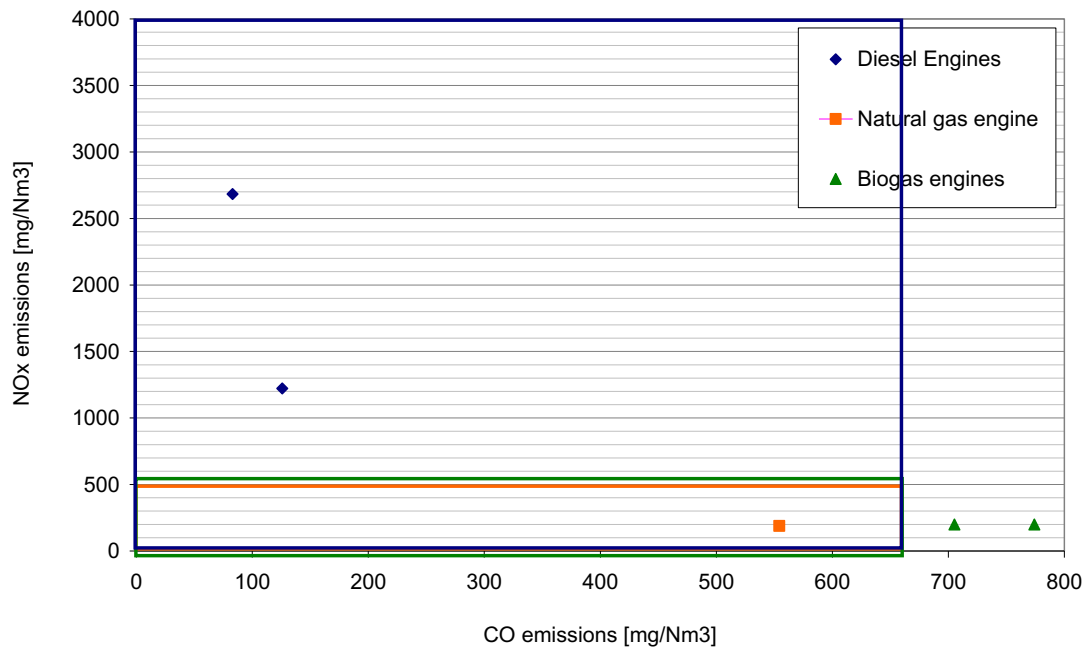
b) Stationary engines that satisfy the emission standards for an industrial plant located in France:

We can consider that the engine will run more than 700 hours per year (> 100 MWh). The standards are:



Here also, only the E3-NG fulfills the French standards. The same solution as in a) can be applied in order to reduce the CO emission on the 2 Biogas engines. But, we can point out that France doesn't give advantage to this Biofuel and NO_x emission will be close to the limit.

c) Stationary engines that satisfy the emission standards for an industrial plant located in Italy:



In Italy, the industrial company can either choose the two Diesel engines or the Natural gas engine. Here, only the total cost (investment cost + operational cost) will influence the choice of the engine. The two Diesel engines have a strong advantage due to the high production volume of such engine types. Certainly, the “worst” engine in term of emission (E1-D), will be chosen because of the lower operational cost. For instance, assuming 5'000 hours / year of operation and a Diesel cost of 1.50 CHF/L and $\rho_{\text{Diesel}} = 0.83$, the operational costs for the fuel are:

$$\text{E1-D: } \text{Cost}_{\text{year}}(\text{CHF}) = 5000 \cdot \frac{\text{CSE}}{1000} \cdot \dot{E}_e \cdot \rho_{\text{Diesel}}^{-1} \cdot 1.50(\text{CHF} / \text{L}) = 254'548 \quad (\text{CHF} / \text{year})$$

$$\text{E2-D: } \text{Cost}_{\text{year}}(\text{CHF}) = 5000 \cdot \frac{\text{CSE}}{1000} \cdot \dot{E}_e \cdot \rho_{\text{Diesel}}^{-1} \cdot 1.50(\text{CHF} / \text{L}) = 273'911 \quad (\text{CHF} / \text{year})$$

- The manufacturer of the two Diesel engines is probably an off-road engine company. We can assume that regarding the emission standards in g/kWh which are close to the “Stage II” and “Stage IIIA” standards (see Course chapter VI, slide 17).