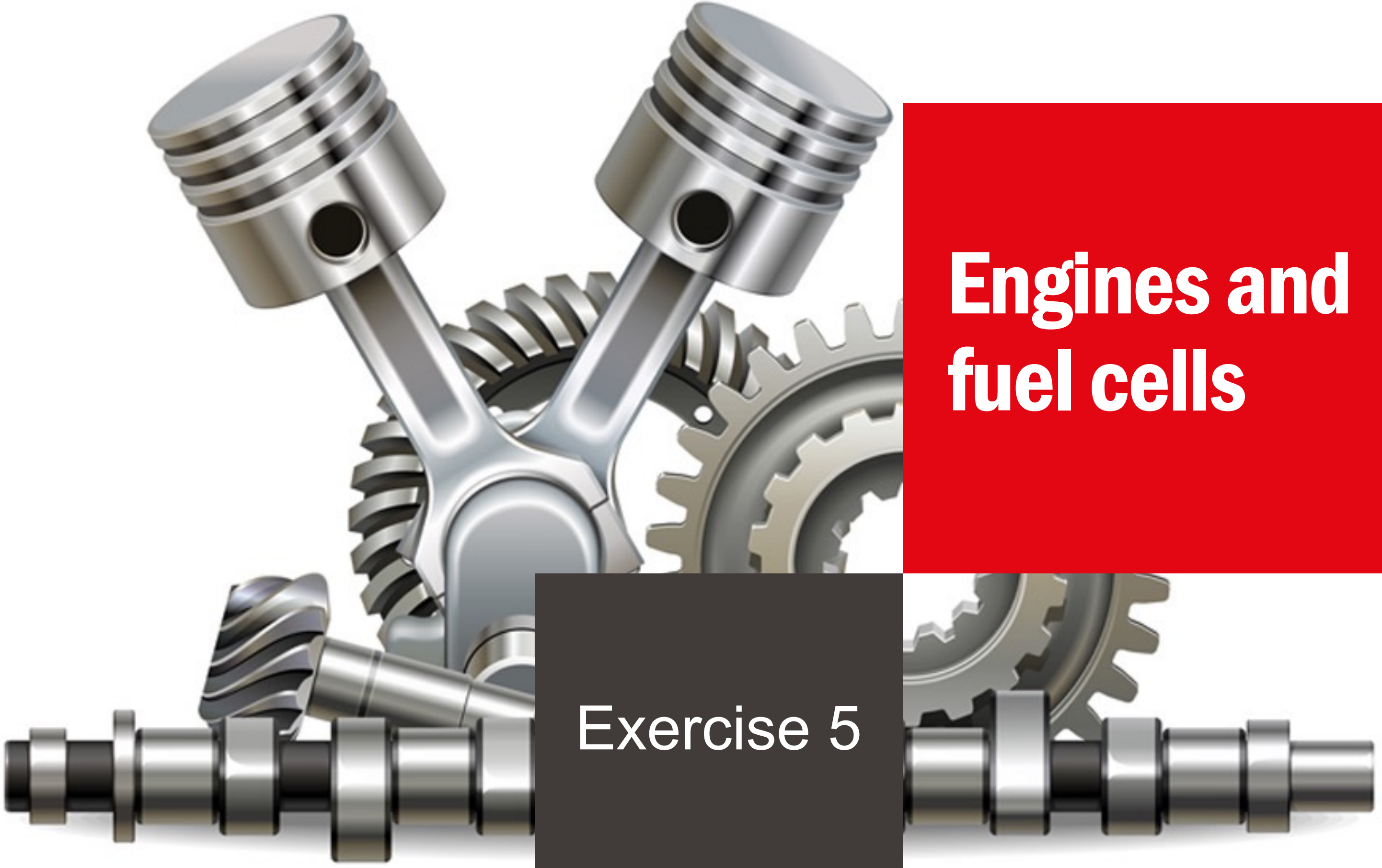

Engines and fuel cells

Exercise 5

Exercise 5

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
E2-D	4L	7 L	Diesel	1500	145.0	664.3	30.3	487	82	58	7.92
E3-NG	6L	12 L	Natural gas	1500	145.0	839	29.49	66	320	835	9.47
E4-BG	6L	12 L	BIOGAS 22% CO2	1500	145.0	810	28.52	71	410	651	9.38
E5-BG	6L	12 L	BIOGAS 35% CO2	1500	145.0	757	28.09	75	481	730	8.57

Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

1. Calculate for each engine the following specific emissions:

   a) NO_x, HC and CO ⇨ [g/kWh]
   b) NO_x and CO ⇨ [mg/Nm^3] at reference conditions = 5% O_2

   Remark: For the reference conditions, use the following relation:

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right)\cdot f_{O2} \quad with \quad f_{O2} = \frac{21-5}{21-\dot{c}_{O2}}$$

2. Explain / comment the results obtained in question (1)

3. Select an engine which satisfies the emission standards for three industrial plants

   a) Industrial plant is located in Switzerland
   b) Industrial plant is located in France
   c) Industrial plant is located in Italy

The emission standards for stationary engines are listed on page 3.

4. In which application field the manufacturer of the two Diesel engines is working?

Lower heating value of Diesel:	42'915 *kJ/kg*
Lower heating value of Natural gas:	47'120 *kJ/kg*
Air / Fuel ratio of Diesel:	14.5
Air / Fuel ratio of Natural gas:	16.2
Natural gas molar mass:	17.53 *kg/kmol*
Burned gas molar mass:	30.2 *kg/kmol*
CO_2 molar mass:	44.0 *kg/kmol*
CO molar mass:	28.0 *kg/kmol*
HC molar mass:	13.87 *kg/kmol*
NO_x molar mass:	46.0 *kg/kmol*
Universal gas constant:	8314 *J/kmolK*

Remarks:

⇨ We consider the Biogas Fuel as a mix of Natural gas and CO_2.
Therefore, the "fuel mass flow rate" value is related only to the Natural gas mass flow rate.

EPFL

Exercise 5

1. Calculate for each engine the following specific emissions:

   a) NO_x, HC and CO ⇨ [g/kWh]
   b) NO_x and CO ⇨ [mg/Nm³] at reference conditions = 5% O_2

   Remark: For the reference conditions, use the following relation:

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right)\cdot f_{O2} \quad with \quad f_{O2} = \frac{21-5}{21-\dot{c}_{O2}}$$

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
E2-D	4L	7 L	Diesel	1500	145.0	664.3	30.3	487	82	58	7.92
E3-NG	6L	12 L	Natural gas	1500	145.0	839	29.49	66	320	835	9.47
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E5-BG	6L	12 L	BIOGAS 35% CO2	1500	145.0	757	28.09	75	481	730	8.57

Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

Volume/mole %

Without CO_2

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

CO_2 mass flow rate calculation for biogas fuel inlet

$$\dot{M}_{CO2} = \boxed{\frac{\dot{M}_{Nat\ gas}}{\tilde{m}_{Nat\ gas}}}\cdot\left(\frac{\%_{CO2}}{\boxed{100-\%_{CO2}}}\right)\cdot\tilde{m}_{CO2} \quad , \dot{M} = \left[{kg}/{s}\right] \quad and \quad \tilde{m} = \left[{kg}/{kmol}\right]$$

Mole of nature gas

Fraction of nature gas

e.g. $\dot{M}_{CO2,E4-BG} = \frac{28.52\ kg/h}{17.53\ kg/kmol}\times\left(\frac{22\%}{1-22\%}\right)\times 44\ kg/kmol \approx 20.2\ kg/h$

Lower heating value of Diesel:	42'915 *kJ/kg*
Lower heating value of Natural gas:	47'120 *kJ/kg*
Air / Fuel ratio of Diesel:	14.5
Air / Fuel ratio of Natural gas:	16.2
Natural gas molar mass:	17.53 *kg/kmol*
Burned gas molar mass:	30.2 *kg/kmol*
CO_2 molar mass:	44.0 *kg/kmol*
CO molar mass:	28.0 *kg/kmol*
HC molar mass:	13.87 *kg/kmol*
NO_x molar mass:	46.0 *kg/kmol*
Universal gas constant:	8314 *J/kmolK*

Remarks:

⇨ We consider the Biogas Fuel as a mix of Natural gas and CO_2.
Therefore, the "fuel mass flow rate" value is related only to the Natural gas mass flow rate.

Exercise 5

1. Calculate for each engine the following specific emissions:

   a) NO_x, HC and CO ⇨ [g/kWh]
   b) NO_x and CO ⇨ [mg/Nm^3] at reference conditions = 5% O_2

   Remark: For the reference conditions, use the following relation:

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right) \cdot f_{O2} \quad with \quad f_{O2} = \frac{21-5}{21-\dot{c}_{O2}}$$

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
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Volume %

Without CO_2

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
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E4-BG	20.2	859.1	1.75	196.7	38.8
E5-BG	38.0	823.1	1.66	193.7	39.4

Total burned gas mass flow rate (Mass balance)

$$\dot{M}_{Exg} = \dot{M}_{air} + \dot{M}_{Fuel} = \dot{M}_{air} + \dot{M}_{Nat\ gas} + \dot{M}_{CO2}$$

e.g. $\dot{M}_{Exg,E4-BG} = 810\ kg/h + 28.52\ kg/h + 20.2\ kg/h \approx 859.1\ kg/h$

Remarks:

⇨ We consider the Biogas Fuel as a mix of Natural gas and CO_2.
Therefore, the "fuel mass flow rate" value is related only to the Natural gas mass flow rate.

Lower heating value of Diesel:	42'915 *kJ/kg*
Lower heating value of Natural gas:	47'120 *kJ/kg*
Air / Fuel ratio of Diesel:	14.5
Air / Fuel ratio of Natural gas:	16.2
Natural gas molar mass:	17.53 *kg/kmol*
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HC molar mass:	13.87 *kg/kmol*
NO_x molar mass:	46.0 *kg/kmol*
Universal gas constant:	8314 *J/kmolK*

EPFL

Exercise 5

1. Calculate for each engine the following specific emissions:

   a) NO_x, HC and CO ⇨ [g/kWh]
   b) NO_x and CO ⇨ [mg/Nm^3] at reference conditions = 5% O_2

   Remark: For the reference conditions, use the following relation:

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right)\cdot f_{O2} \quad with \quad f_{O2} = \frac{21-5}{21-\dot{c}_{O2}}$$

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
E2-D	4L	7 L	Diesel	1500	145.0	664.3	30.3	487	82	58	7.92
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E4-BG	6L	12 L	BIOGAS 22% CO2	1500	145.0	810	28.52	71	410	651	9.38
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Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

Volume %

Without CO_2

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
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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

Lambda ratio (excess air ratio)

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

$$\text{e.g. } \dot{\lambda}_{E4-BG} = \frac{810\ kg/h}{28.52\ kg/h}\times\frac{1}{16.2}\approx 1.75$$

Lower heating value of Diesel:	42'915 *kJ/kg*
Lower heating value of Natural gas:	47'120 *kJ/kg*
Air / Fuel ratio of Diesel:	14.5
Air / Fuel ratio of Natural gas:	16.2
Natural gas molar mass:	17.53 *kg/kmol*
Burned gas molar mass:	30.2 *kg/kmol*
CO_2 molar mass:	44.0 *kg/kmol*
CO molar mass:	28.0 *kg/kmol*
HC molar mass:	13.87 *kg/kmol*
NO_x molar mass:	46.0 *kg/kmol*
Universal gas constant:	8314 *J/kmolK*

Remarks:

⇨ We consider the Biogas Fuel as a mix of Natural gas and CO_2.
Therefore, the "fuel mass flow rate" value is related only to the Natural gas mass flow rate.

Exercise 5

1. Calculate for each engine the following specific emissions:

   a) NO_x, HC and CO ⇨ [g/kWh]
   b) NO_x and CO ⇨ [mg/Nm³] at reference conditions = 5% O_2

   Remark: For the reference conditions, use the following relation:

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right) \cdot f_{O2} \quad with \quad f_{O2} = \frac{21-5}{21-\dot{c}_{O2}}$$

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
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Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

Volume %

Without CO_2

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
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E4-BG	20.2	859.1	1.75	196.7	38.8
E5-BG	38.0	823.1	1.66	193.7	39.4

Specific fuel consumption

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

e.g. $BSFC_{E4-BG} = \dfrac{28.52\ kg/h \times 10^3 g/kg}{145\ kW} \approx 196.7\ g/kWh$

Lower heating value of Diesel:	42'915 *kJ/kg*
Lower heating value of Natural gas:	47'120 *kJ/kg*
Air / Fuel ratio of Diesel:	14.5
Air / Fuel ratio of Natural gas:	16.2
Natural gas molar mass:	17.53 *kg/kmol*
Burned gas molar mass:	30.2 *kg/kmol*
CO_2 molar mass:	44.0 *kg/kmol*
CO molar mass:	28.0 *kg/kmol*
HC molar mass:	13.87 *kg/kmol*
NO_x molar mass:	46.0 *kg/kmol*
Universal gas constant:	8314 *J/kmolK*

Remarks:

⇨ We consider the Biogas Fuel as a mix of Natural gas and CO_2.
Therefore, the "fuel mass flow rate" value is related only to the Natural gas mass flow rate.

Exercise 5

1. Calculate for each engine the following specific emissions:

   a) NO_x, HC and CO ⇨ [g/kWh]
   b) NO_x and CO ⇨ [mg/Nm^3] at reference conditions = 5% O_2

   Remark: For the reference conditions, use the following relation:

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right) \cdot f_{O2} \quad with \quad f_{O2} = \frac{21-5}{21-\dot{c}_{O2}}$$

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
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E3-NG	6L	12 L	Natural gas	1500	145.0	839	29.49	66	320	835	9.47
E4-BG	6L	12 L	$\boxed{\text{BIOGAS 22\% CO2}}$	1500	145.0	810	$\boxed{28.52}$	71	410	651	9.38
E5-BG	6L	12 L	$\boxed{\text{BIOGAS 35\% CO2}}$	1500	145.0	757	$\boxed{28.09}$	75	481	730	8.57

Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

Volume %

Without CO_2

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
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E4-BG	20.2	859.1	1.75	196.7	38.8
E5-BG	38.0	823.1	1.66	193.7	39.4

Global efficiency

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

Total energy from the fuel

e.g. $\eta_{e,E4-BG} = \dfrac{145\ kW}{47120\ kJ/kg \times 28.52 kg/h \times \frac{1}{3600} h/s} \approx 38.8\%$

Lower heating value of Diesel:	42'915 *kJ/kg*
Lower heating value of Natural gas:	47'120 *kJ/kg*
Air / Fuel ratio of Diesel:	14.5
Air / Fuel ratio of Natural gas:	16.2
Natural gas molar mass:	17.53 *kg/kmol*
Burned gas molar mass:	30.2 *kg/kmol*
CO_2 molar mass:	44.0 *kg/kmol*
CO molar mass:	28.0 *kg/kmol*
HC molar mass:	13.87 *kg/kmol*
NO_x molar mass:	46.0 *kg/kmol*
Universal gas constant:	8314 *J/kmolK*

Remarks:

⇨ We consider the Biogas Fuel as a mix of Natural gas and CO_2.
Therefore, the "fuel mass flow rate" value is related only to the Natural gas mass flow rate.

Exercise 5

1. Calculate for each engine the following specific emissions:

   a) NO_x, HC and CO ⇨ [g/kWh]
   b) NO_x and CO ⇨ [mg/Nm^3] at reference conditions = 5% O_2

   Remark: For the reference conditions, use the following relation:

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right)\cdot f_{O2} \quad with \quad f_{O2} = \frac{21-5}{21-\dot{c}_{O2}}$$

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
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Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

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**

Effective specific emission

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

$$\breve{c}_i\left(\frac{g_i}{kWh}\right) = \frac{\dot{M}_i(g/h)}{\dot{E}_e(kW)} = \frac{\dot{n}_i(mol/h)\times\tilde{m}_i\,(g/mol)}{\dot{E}_e(kW)} = \frac{\frac{\dot{c}_i(ppm)}{10^6\,ppm}\times\dot{n}_{Exg}(mol/h)\times\tilde{m}_i\,(g/mol)}{\dot{E}_e(kW)}$$

$$= \frac{\frac{\dot{c}_i(ppm)}{10^6\,ppm}\times\frac{\dot{M}_{Exg}(kg_{Exg}/h)}{\tilde{m}_{Exg}(kg/kmol)}\times\tilde{m}_i\left(\frac{kg_i}{kmol}\right)\times 10^3\,g/kg}{\dot{E}_e(kW)} = \dot{c}_i(ppm)\cdot\frac{\tilde{m}_i(kg_i/kmol)}{\tilde{m}_{Exg}(kg_{Exg}/kmol)}\cdot\frac{\dot{M}_{Exg}(kg_{Exg}/h)\cdot 10^{-3}}{\dot{E}_e(kW)}$$

e.g., $\breve{c}_{NO_x,E4-BG} = 71ppm\times\frac{46\,kg/kmol}{30.2\,kg/kmol}\times\frac{859.1kg/h\times 10^{-3}}{145\,kW}\approx 0.64\,g/kWh$

Lower heating value of Diesel:	42'915 *kJ/kg*
Lower heating value of Natural gas:	47'120 *kJ/kg*
Air / Fuel ratio of Diesel:	14.5
Air / Fuel ratio of Natural gas:	16.2
Natural gas molar mass:	17.53 *kg/kmol*
Burned gas molar mass:	30.2 *kg/kmol*
CO_2 molar mass:	44.0 *kg/kmol*
CO molar mass:	28.0 *kg/kmol*
HC molar mass:	13.87 *kg/kmol*
NO_x molar mass:	46.0 *kg/kmol*
Universal gas constant:	8314 *J/kmolK*

Remarks:

⇨ We consider the Biogas Fuel as a mix of Natural gas and CO_2.
Therefore, the "fuel mass flow rate" value is related only to the Natural gas mass flow rate.

Exercise 5

1. Calculate for each engine the following specific emissions:

   a) NO_x, HC and CO ⇨ [g/kWh]
   b) NO_x and CO ⇨ [mg/Nm³] at reference conditions = 5% O_2

   Remark: For the reference conditions, use the following relation:

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right)\cdot f_{O2} \quad with \quad f_{O2} = \frac{21-5}{21-\dot{c}_{O2}}$$

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/m³N	mg/m³N
E1-D	**7.36**	**0.23**	**0.21**		
E2-D	**3.55**	**0.37**	**0.13**		
E3-NG	**0.60**	**1.78**	**2.30**		
E4-BG	**0.64**	**2.25**	**1.77**		
E5-BG	**0.65**	**2.53**	**1.90**		

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
E2-D	4L	7 L	Diesel	1500	145.0	664.3	30.3	487	82	58	7.92
E3-NG	6L	12 L	Natural gas	1500	145.0	839	29.49	66	320	835	9.47
E4-BG	6L	12 L	BIOGAS 22% CO2	1500	145.0	810	28.52	71	410	651	9.38
E5-BG	6L	12 L	BIOGAS 35% CO2	1500	145.0	757	28.09	75	481	730	8.57

Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

Conversion between mole to volume in standard condition (1 bar, 273.15 K) with ideal gas

$$PV = nRT$$

Emission concentration based on the reference condition

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

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = 5\%\right) = \frac{\dot{M}_i(g/h)}{\dot{F}_{Exg}(m_N^3/h)} = \frac{\dot{n}_i(mol/h)\times\tilde{m}_i\,(g/mol)}{\dot{n}_{Exg}(kmol/h)\times V_N(m_N^3/kmol)} = \dot{c}_i(ppm)\times\frac{1}{V_N(m_N^3/kmol)}\times\tilde{m}_i\,(g/mol)$$

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

$$\breve{c}_i\left(\frac{mg_i}{m_N^3}, O_2 = \dot{c}_{O2}\right) = \dot{c}_i(ppm)\times f_{O2}\times\frac{1}{V_N(m_N^3/kmol)}\times\tilde{m}_i\,(g/mol)$$

$$= \dot{c}_i(ppm)\times\frac{21-5}{21-\dot{c}_{O2}}\times\frac{1}{V_N(m_N^3/kmol)}\times\tilde{m}_i\,(g/mol)$$

e.g., $\breve{c}_{NO_x,E4-BG} = 71ppm\times\frac{21-5}{21-9.38}\times\frac{1}{22.4(m_N^3/kmol)}\times 46kg/kmol \approx 200.76\ mg_{NOx}/m_N^3$

Lower heating value of Diesel:	42'915 *kJ/kg*
Lower heating value of Natural gas:	47'120 *kJ/kg*
Air / Fuel ratio of Diesel:	14.5
Air / Fuel ratio of Natural gas:	16.2
Natural gas molar mass:	17.53 *kg/kmol*
Burned gas molar mass:	30.2 *kg/kmol*
CO_2 molar mass:	44.0 *kg/kmol*
CO molar mass:	28.0 *kg/kmol*
HC molar mass:	13.87 *kg/kmol*
NO_x molar mass:	46.0 *kg/kmol*
Universal gas constant:	8314 *J/kmolK*

Remarks:

⇨ We consider the Biogas Fuel as a mix of Natural gas and CO_2.
Therefore, the "fuel mass flow rate" value is related only to the Natural gas mass flow rate.

Exercise 5

2. Explain / comment the results obtained in question (1)

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
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Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

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^3N	mg/m^3N
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**

a. 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%.

Exercise 5

2. Explain / comment the results obtained in question (1)

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
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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
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b. The very high CO and HC spec. emissions can be explained by the lower flammability range limit, which is close to λ = 1.80 for natural gas. A high amount of unburned hydrocarbons are generated when the combustion conditions are close to this limit.

Exercise 5

2. Explain / comment the results obtained in question (1)

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
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Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

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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**
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b. The very high CO and HC spec. emissions can be explained by the lower flammability range limit, which is close to λ = 1.80 for natural gas. A high amount of unburned hydrocarbons are generated when the combustion conditions are close to this limit.

c. 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).

Exercise 5

3. Select an engine which satisfies the emission standards for three industrial plants

   a) Industrial plant is located in Switzerland
   b) Industrial plant is located in France
   c) Industrial plant is located in Italy

Switzerland

Power range	Fuel	NO_x	CO
kW	-	mg/Nm^3 (@ 5% O_2)	mg/Nm^3 (@ 5% O_2)
> 100	Biogas WWTP gas (*)	400	650
> 100	other (**)	250	650

(*) WWTP = Waste water treatment plant
(**) Gaseous or liquid fuel

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^3N	mg/m^3N
E1-D	**7.36**	**0.23**	**0.21**	**2683**	**83**
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E5-BG	**0.65**	**2.53**	**1.90**	**199**	**774**

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
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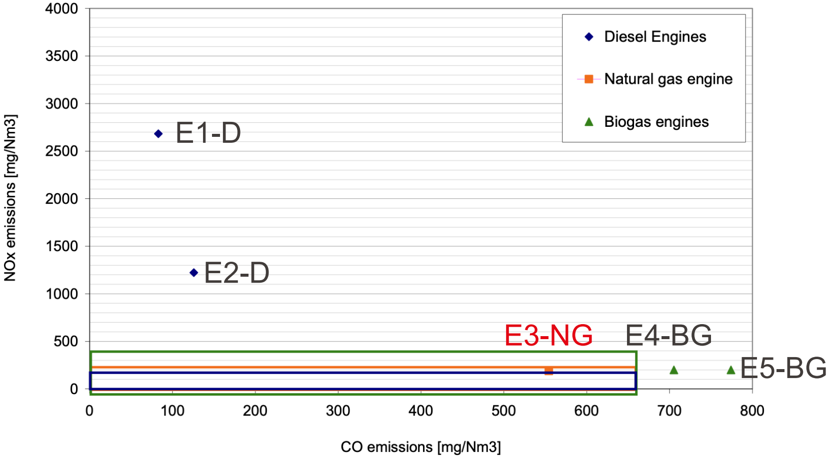
Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.



Exercise 5

3. Select an engine which satisfies the emission standards for three industrial plants

   a) Industrial plant is located in Switzerland
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France

Delivered Power	Fuel	NO_x	CO
MWh	-	mg/Nm^3 (@ 5% O_2)	mg/Nm^3 (@ 5% O_2)
20 - 100	Liquid	1000	650
	Gaseous	350	650
> 100	Liquid	600	650
	Gaseous	250	650

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^3N	mg/m^3N
E1-D	**7.36**	**0.23**	**0.21**	**2683**	**83**
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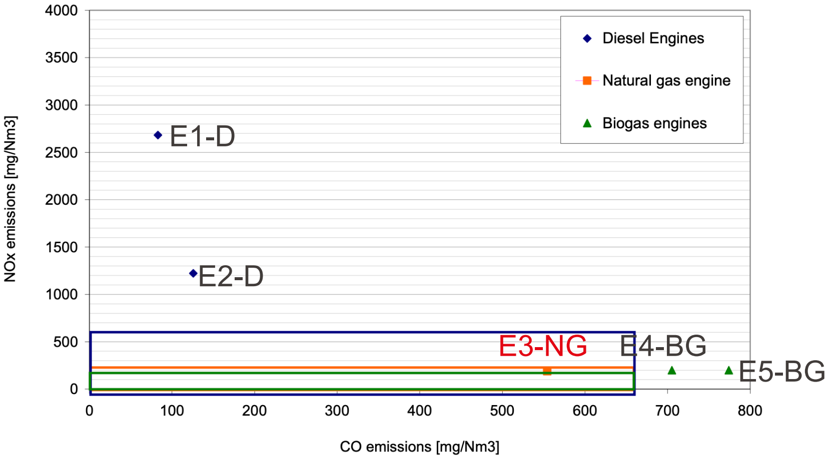

France doesn't gve advantage to Biofuel and NO_x emission will be close to the limit

Exercise 5

3. Select an engine which satisfies the emission standards for three industrial plants

   a) Industrial plant is located in Switzerland
   b) Industrial plant is located in France
   c) Industrial plant is located in Italy

Italy

Power range	Fuel	NO_x	CO
MW	-	mg/Nm^3 (@ 5% O_2)	mg/Nm^3 (@ 5% O_2)
< 3	Diesel engines	4000	650
> 3	Diesel engines	2000	650
all	Gas engines	500	650

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**
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Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
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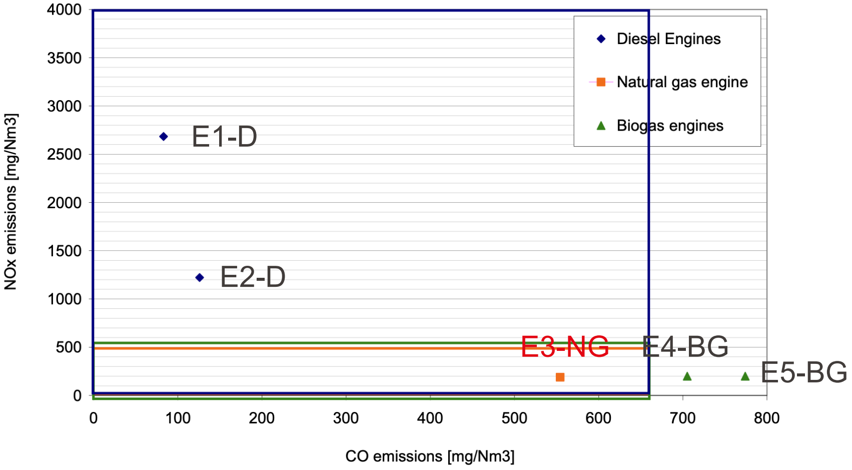

- Only the total cost (investment cost + operational cost) will influence the choice of the engine.
- High production volume of such engine types.

Exercise 5

3. Select an engine which satisfies the emission standards for three industrial plants

   a) Industrial plant is located in Switzerland
   b) Industrial plant is located in France
   c) Industrial plant is located in Italy

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
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Italy

Power range	Fuel	NO_x	CO
MW	-	mg/Nm^3 (@ 5% O_2)	mg/Nm^3 (@ 5% O_2)
< 3	Diesel engines	4000	650
> 3	Diesel engines	2000	650
all	Gas engines	500	650

Parameters	Values
Operating hours per year [h/year]	5000
Diesel cost [CHF/L]	1.5
ρ_{Diesel} [L/kg]	0.83

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

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

E1-D is more profitable

Exercise 5

Engine model	Cylinder geometry	Engine displacement	Type of fuel	Nominal speed	Effective power	Air mass flow rate	Fuel mass flow rate	NO_x emissions	CO emissions	HC emissions	O_2 concentration
				1/min	kW	kg/h	kg/h	ppm	ppm	ppm	%
E1-D	4L	6.6 L	Diesel	1500	145.0	698	28.17	965	49	92	9.20
E2-D	4L	7 L	Diesel	1500	145.0	664.3	30.3	487	82	58	7.92
E3-NG	6L	12 L	Natural gas	1500	145.0	839	29.49	66	320	835	9.47
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E5-BG	6L	12 L	BIOGAS 35% CO2	1500	145.0	757	28.09	75	481	730	8.57

Table 1: Technical data of 5 cogeneration engines of 145 kW effective power.

4. In which application field the manufacturer of the two Diesel engines is working?

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	kg/h	kg/h	-	g/KWh	%
E1-D	0.0	726.2	1.71	194.3	43.2
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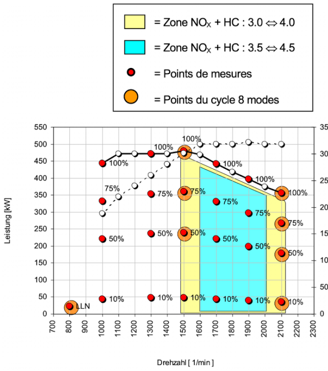
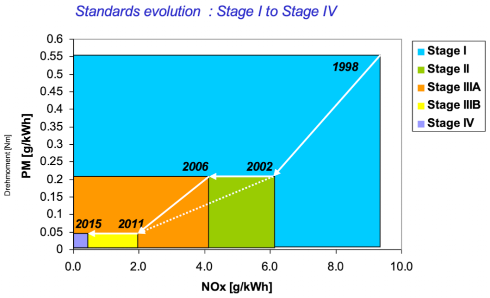
E4-BG	20.2	859.1	1.75	196.7	38.8
E5-BG	38.0	823.1	1.66	193.7	39.4

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^3N	mg/m^3N
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**

4. 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).





Exercise 5

Questions?