Appendix 3.3 Calculation of Emissions from CHP and Boiler

Emissions from CHP

Oa:	Oxygen concentration of flue gas, dry gas
Os:	Standard oxygen concentration, dry gas
Ca, dry, Oa:	Actual flue gas concentration, dry gas, Oa
Ca, dry, Os:	Actual flue gas concentration, dry gas, Os
Ca, wet, Oa:	Actual flue gas concentration, wet gas, Oa
Cs:	Flue gas concentration at standard conditions
Va, dry:	Volume of flue gas at emission point, dry gas
Va, wet:	Volume of flue gas at emission point, wet gas
Vs:	Volume of flue gas under standard condition, dry gas
M:	Mass of pollutant in flue gas
%H2O:	% of moisture in flue gas
Pa:	Pressure of flue gas at emission point
Ps:	Standard pressure
Ta:	Temperature of flue gas at emission point
Ts:	Standard temperature

In accordance with Annex VI of EU Directive 2010/75/EU,

Ca, dry, Oa	= Ca, dry, Os x (20.9 - Oa) / (20.9 - Os)	(eqn. 1)
Ca, dry, Oa	= M / Va, dry	(eqn. 2)
	= M / [Va, wet x (1 - %H2O)]	(eqn. 3)
Ca, wet, Oa	= M / Va, wet	
	= Ca, dry, Oa x (1 - %H2O)	(from eqn. 3)
	= Ca, dry, Os x (1 - %H2O) x (20.9 – Oa) / (20.9 – Os)	(from eqn. 1)
Ca, wet, Oa	= Ca, dry, Os x (1 - %H2O) x (20.9 – Oa) / (20.9 – Os)	(eqn. 4)
Cs	= M / Vs	(eqn. 5)

By ideal gas law, Pa x Va, dry / Ta = Ps x Vs / Ts
Since Pa = Ps, Therefore, Va, dry / Ta = Vs / Ts

From eqn. 2 and eqn. 5, (M / Ca, dry, Oa) / Ta = (M / Cs) / Ts
Therefore, Ca, dry, Oa = Cs x Ts / Ta

From eqn. 4, Ca, wet, Oa = Cs x (Ts / Ta) x (1 - %H2O) x (20.9 – Oa) / (20.9 – Os)

CHP1

Exhaust Flow rate (standard condition, wet)=	1,929	Nm3/hr at	273	K
Exhaust Flow rate (standard condition, dry)=	1,722	Nm3/hr at	273	K
Actual Flow rate (actual condition, wet)=	4,885	m3/hr at	699	K
Actual Flow rate (actual condition, dry)=	4,361	m3/hr at	699	K

Design duty CHP output with available biogas=	450	kWe at design operation capacity
Formaldehyde emission based on research paper=	14	g/GJ
Formaldehyde emission of the designed CHP=	0.0063	g/s
Formaldehyde emission limit=	14	mg/Nm^3

Parameter	Oa (%)	Os (%)	Hourly Average Emission Limit (mg/Nm^3)	Condition of Emission Limit (H_2O%=0%, T_s=273K, P_s=101325Pa)	Correction factor for Ca, wet, Oa (mg/m3) at standard temperature and pressure	Emission Rate (g/s)	*Remarks*
RSP	5	6	15	Os%=6%	*1.0671*	**0.0077**	*[1] [3]*
Carbon Monoxide	5	5	650	Os%=5%	*1.0000*	**0.3109**	*[2] [4]*
NO_x	5	5	250	Os%=5%	*1.0000*	**0.1196**	*[2] [4]*
SO_2	5	6	50	Os%=6%	*1.0671*	**0.0255**	*[1] [3]*
Methane	5	6	150	Os%=6%	*1.0671*	**0.0766**	*[1] [3]*
HCl	5	6	10	Os%=6%	*1.0671*	**0.0051**	*[1] [3]*
HF	5	6	1	Os%=6%	*1.0671*	**0.0005**	*[1] [3]*
Formaldehye (CH2O)	5	6	14	Os%=6%	*1.0671*	**0.0071**	*[3] [5]*

Remarks
- The hourly average emission limit pollutant concentrations are adopted based on standard air conditions.
*: Emission Rate is calculated by Peak Flow Rate*Hourly Average Emission Level/3600/1000
Unit CHP exhaust flow rate calculation based on supplier information:
CHP supplier exhaust flow rate (at 0% v/v water vapor) = 1722 Nm^3/hr (dry)
CHP supplier exhaust flow rate (at 11% v/v water vapor) = 1929 Nm^3/hr (wet)
CHP exhaust at actual condition (699K, ^101,325 Pa): 4885 m3/hr
CHP power output designed for EPP = 450 kWe
Actual Exhaust Flow rate conversion from standard condition
CHP exhaust at standard condition (273K , 101,325 Pa): 1929 Nm^3/hr (wet)
CHP exhaust at actual condition (699K, ^101,325 Pa): 4885 m^3/hr = 1.36 m^3/s
^Assume air pressure is same as standard condition.at altitude of exhaust discharge point.

Oxygen concentration correction factor (for emission rate estimation)
actual oxygen concentration in exhaust : 5% (same for CO and NOx at referenced/ standard condition)
standard oxygen concentration in exhaust : 6% (for RSP, SO2, Methane, HCl, HF and Formaldehyde)
oxygen correction factor : (20.9-5)/(20.9-6) = 1.0671 (for RSP, SO2, Methane, HCl and HF)

Example RSP pollution emission rate for CHP
1722Nm3/hr x 15mg/Nm^3 x 1.067 x 1hr/3600s x 1g/1000mg = 0.0077g/s

Formaldehyde emission estimate
Formaldehyde emission based on research paper (reference no. [5]) = 14 g/GJ
Formaldehyde emission of the designed CHP = 450kWe x (1GJ/s/10^{6}kWe) x 14g/GJ = 0.0063g/s
Formaldehyde emission concentration (dry exhaust) = 0.0063 g/s / (1722 Nm^3 / 3,600 s) = 0.01301 g/Nm^3 = 13.17 mg/Nm^3, dry
Formaldehyde emission limit = 14 mg/Nm^3 (round up from 13.17 mg/Nm^3)
Formaldehyde emission rate for modelling = 1722Nm3/hr x 14mg/Nm^3 x (1g/1000mg) x (1hr/3600s) = 0.0067g/s
with correction factor for O2 content in exhaust 0.0067g/s x (20.9-5) / (20.9-*6) = 0.0071g/s
* Assume oxygen concentration at 6% for referenced formaldehyde emission rate

References

[1] Agreement No. CE 7/2008 (EP) Organic Waste Treatment Facilities, Phase I - Feasibility Study Table 3.5
[2] CHP Supplier's information
[3] The emission level refers to an oxygen content of 6% and dry basis.
[4] The emission level refers to an oxygen content of 5% and dry basis.
[5] Valerio Paolini, Francesco Petracchini, Marco Segreto, Laura Tomassetti, Nour Naja & Angelo Cecinato (2018) Environmental Impact of Biogas: A short review of current knowledge, Journal of Environmental Science and Health, Part A, 53:10, 899-906, DOI: 10.1080/10934529.2018.1459076

Appendix 3.3 Calculation of Emissions from CHP and Boiler

Emissions from Boiler (BO)

Boiler Emission

Exhaust Flow rate (standard condition, dry)= 1,722 Nm3/hr at 273 K
Actual Flow rate (actual condition, wet)= 4,885 m3/hr at 699 K

Parameter	Emission Limit for Boiler Exhaust (mg/ Nm^3, dry)	Condition of Emission Limit (H_2O%=0%, T_s=273K, P_s=101325Pa)	Correction factor for Ca, wet, Oa (mg/m3) at standard temperature and pressure	Emission Rate (g/s)
RSP	15	Os%=6%	1.0671	**0.0077**
Carbon Monoxide	650	Os%=5%	1.0000	**0.3109**
NO_x	250	Os%=5%	1.0000	**0.1196**
SO_2	50	Os%=6%	1.0671	**0.0255**
Methane	150	Os%=6%	1.0671	**0.0766**
HCl	10	Os%=6%	1.0671	**0.0051**
HF	1	Os%=6%	1.0671	**0.0005**
Formaldehyde (CH2O)	14	Os%=6%	1.0671	**0.0071**

Remarks

[1] The hourly average emission limit pollutant concentrations are adopted based on standard air conditions.
[2] Given CHP and boiler emissions are both generated from combustion of the same biogas generated at the effluent polishing plant, the emission rates are considered comparable. Therefore, CHP emission limit of the respective pollutants are used to estimate those in the boiler emissions. In particular, the power of the boiler is the same as that of the CHP, so the same emission limit of formaldehyde for CHP is also applicable to boiler.
[3] CHP Exhaust gas flow rate to CH_4 consumption flow rate proportion based on CHP supplier information.
CHP exhaust flow rate per unit : 1722 Nm^3/hr (dry exhaust at 0% moisture concentration).
The boiler exhaust flow rate is the same as the CHP exhaust flow rate at 1722Nm^3/hr according to engineers.
[4] Example for RSP emission rate for boiler
RSP emission concentration as per CHP estimate : 15 mg/Nm^3
Boiler RSP emission rate = 1722Nm^3/hr x 15mg/Nm^3 x (20.9-5) / (20.9-6) x (1hr/3600s) x (1kg/1000g) = 0.0077 g/s

Appendix 3.3 Calculation of Emissions from CHP and Boiler

Emission Sources Listing in AERMOD

Description	Source ID	Type	X	Y	Base Elevation (m)	Flow Rate (m^3/s)	Height (mAG)	Exit Temp (K)	Exit Velocity (m/s)	Stack Diameter (m)	Working Hours	RSP Emission Rate (g/s)	FSP Emission Rate (g/s) [2]	NOx Emission Rate (g/s)	SO2 Emission Rate (g/s)	CO Emission Rate (g/s)
biogas engine	CHP1	POINTCAP	846570.81	814667.70	6.75	1.36	11.50	699.00	10.80	0.40	0000 - 2400	7.6565E-03	7.6565E-03	1.1958E-01	2.5522E-02	3.1092E-01
fire tube boiler	BO	POINTCAP	846570.81	814667.70	6.75	1.36	11.50	699.00	10.80	0.40	0000 - 2400	7.6565E-03	7.6565E-03	1.1958E-01	2.5522E-02	3.1092E-01

Description	Source ID	Type	X	Y	Base Elevation (m)	Flow Rate (m^3/s)	Height (mAG)	Exit Temp (K)	Exit Velocity (m/s)	Stack Diameter (m)	Working Hours	Methane Emission Rate (g/s)	HCL Emission Rate (g/s)	HF Emission Rate (g/s)	Formaldehyde Emission Rate (g/s)
biogas engine	CHP1	POINTCAP	846570.81	814667.70	6.75	1.36	11.50	699.00	10.80	0.40	0000 - 2400	7.6565E-02	5.1044E-03	5.1044E-04	7.1461E-03
fire tube boiler	BO	POINTCAP	846570.81	814667.70	6.75	1.36	11.50	699.00	10.80	0.40	0000 - 2400	7.6565E-02	5.1044E-03	5.1044E-04	7.1461E-03

Description	Source ID	Non-AQO Pollutant Emission Rate (g/s) [1]	Scaling Factor for Cumulative Concentration [1]			
			Mechane	HCL	HF	Formaldehyde (CH2O)
biogas engine	CHP1	1.000E+00	7.6565E-02	5.1044E-03	5.1044E-04	7.1461E-03
fire tube boiler	BO	1.000E+00	7.6565E-02	5.1044E-03	5.1044E-04	7.1461E-03

Remarks

1. A single non-AQO AERMOD model is employed for Methane, HCL, HF and Formaldehyde. Respective scaling factor is applied to the model output to obtain the emission rate shown in P.3.
   e.g. Methane emission rate of CHP1 = 1 x 7.6565E-02 = 7.6565E-02
   Methane emission rate of BO = 1 x 7.6565E-02 = 7.6565E-02.
2. RSP emission rate is adopted for FSP emission as a conservative approach.
3. No dry deposition applied for RSP and FSP.

Location of CHP and Boiler