**Life-cycle assessment of a Waste-to-Energy plant in central Norway: Current situation and effects of changes in waste fraction composition**

***Supplementary material***

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# Heimdal WtE plant data

## Plant design

The conversion of waste to energy in the present study is based on lines 1 and 2 at the Heimdal WtE plant in Norway, owned and operated by Statkraft Varme AS. The Heimdal plant exports hot water for district heating. Lines 1 and 2 at the Heimdal district heating plant started up operation in 1985. The process flow diagram for the overall energy conversion route is schematically shown in Figure 1. Municipal Solid Waste (MSW) and industrial waste are directly delivered by refuse collection trucks and dumped into bunkers. Mixing and feeding of the waste into the combustion unit is performed by overhead cranes. The combustion system is based on inclined reciprocating grates and two-stage combustion air injection. The primary air is preheated and distributed throughout the grate in four separately controlled zones. The bottom ash is discharged from the grate to a water-filled chain conveyor. Secondary combustion is controlled by the injection of air and clean, recirculated flue gas with non-catalytic NOx reduction, based on ammonia. Recovery of the combustion heat is achieved by water-tube membrane walls in the secondary chamber and a three-bundle water-tube boiler downstream from the post-combustion zone. Accumulated fly ash in the boiler is discharged by rotary valves and transported to a silo by a dry drag chain conveyor. The flue gas cleaning system in lines 1 and 2 is a standard design used during the 1980s and part of the 1990s. This design includes electrostatic precipitators for dust removal, followed by a wet scrubber or cleaning of gas-phase components including dioxins. The wastewater from the wet scrubber is cleaned in a water treatment unit before it is disposed of in the communal sewage network. The residues from the water treatment unit include the treated water and the filter cake. The filter cake, as well as the filter residue from the electrostatic precipitator, is classified as hazardous waste. This technological solution for the flue gas cleaning system (based on electrostatic precipitator and wet scrubber with water treatment) was replaced with semidry cleaning systems with bag filters at the end of the 1990s. The newer system feeds the water scrubber into the process before the bag filter, in order to control the flue gas temperature and increase the water content in the flue gas. This solution avoids the production of effluents into the sewage network, with the filter dust being the only residue from the flue gas cleaning.

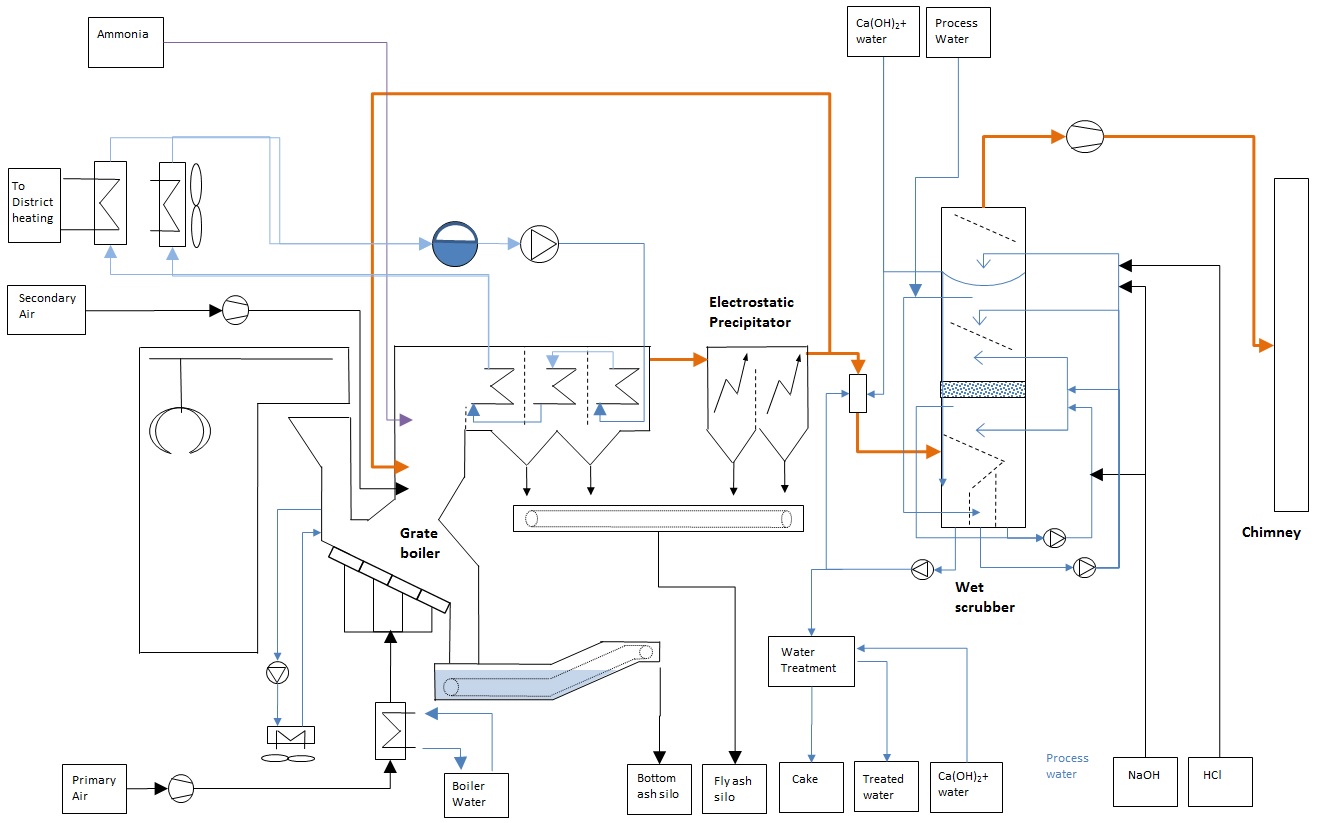


Figure 1: Schematic representation of the process design for lines 1 and 2 of the Statkraft Varme Heimdal WtE plant

## Operational data

Tables 1 and 2 show the main operational parameters and the overall mass and energy flows per unit tonne of waste, respectively, for both lines 1 and 2 of the Statkraft Varme Heimdal plant.

Table 1: General data Statkraft Varme Heimdal plant (lines 1 and 2)

|  |  |
| --- | --- |
| Output energy use | District heating |
| Thermal capacity | 33 MW |
| Waste throughput | 90 000tonnes |
| Waste fractions | 60% MSW + 40% Industrial waste |
| Average net calorific value of waste | 11.0 MJ/kg |
| Annual heat production | 240 GWh |
| Annual exported heat | 200 GWh |
| Gross thermal efficiency | 83 % |

Table 2: Overall mass and energy flows

|  |  |  |  |
| --- | --- | --- | --- |
| Output related to 1 tonne of input waste | | Input related to 1 tonne of input waste | |
| Heat (total) | 2232 kWh | Water (flue gas cleaning) | 0.2-0.25 m3 |
| Heat (to district heating network) | 1912 kWh | Quicklime | 8.8 – 10.5 kg |
| Flue gas to air | 5670 Nm3 (dry basis) | Sodium hydroxide, 30% | 2 kg |
| Bottom ash | 120-157 kg | Active carbon | 0.4-0.5 kg |
| Fly ash | 20-30 kg | Ammonia | 2.3 kg |
| Filter cake | 10 kg | Precipitating agents | 0.17 kg |
| Treated water (after flue gas cleaning) | 0.2 m3 | Diesel oil (aux. burners) | 1.2-2.4 liters |
| Electricity | 120 kWh |

## Emissions to air

Table 3 shows the average measured composition of the flue gas emitted to air from lines 1 and 2, based on the plant’s emissions report from 2010. Except for H2O and O2, all concentrations are normalized to 11 % vol. O2.

Table 3: Emissions to air, and calculated emission factors from equations (1)-(3)

|  |  |  |  |
| --- | --- | --- | --- |
|  | Emissions to air concentrations1,2 | Calculated emissions factors  (per kg of input waste) | Calculated emissions factors  (per MJ output energy) |
| Water (H2O) | 22.5 (% vol.) | - |  |
| Oxygen (O2) | 7 (% vol. dry) | - |  |
| Carbon dioxide (CO2) | 10.2 (% vol. dry) 1 | 1.14 kg | 0.124 kg |
| Carbon monoxide (CO) | 9.4 (mg/Nm3 dry) 2 | 55.69 mg | 6.100 mg |
| Nitrogen oxides (NOx) | 177 (mg/Nm3 dry) 2 | 1048.70 mg | 114.863 mg |
| Total dust | 4.2 (mg/Nm3 dry) 2 | 24.88 mg | 2.726 mg |
| Sulfur dioxide | 27.9 (mg/Nm3 dry) 2 | 165.30 mg | 18.105 mg |
| Hydrogen Chloride (HCl) | 0.93 (mg/Nm3 dry) 2 | 5.51 mg | 0.604 mg |
| Hydrogen Fluoride (HF) | 0.041 (mg/Nm3 dry) 2 | 0.24 mg | 0.027 mg |
| TOC (Total Organic Carbon) | 0.2 (mg/Nm3 dry) 2 | 1.18 mg | 0.130 mg |
| Total Dioxins | 0.039 (ng/Nm3 dry) 2 | 0.23 ng | 0.025 mg |
| Cd + Tl | 0.00175 (mg/Nm3 dry) 2 | 0.01 mg | 0.001 mg |
| As+Cr+Co+Cu+Mn+Ni+Pb+Sb+V | 0.05699 (mg/Nm3 dry) 2 | 0.34 mg | 0.037 mg |

Notes: year 2010; 1 average from continuous measurement; 2measured based on 11 %vol. dry O2

Based on the measured compositions in Table 3, emissions to air factors for each component in table 3, except for H2O, CO2 and O2 can be calculated from

(1)

where denotes the species in Table 3. Except for CO2, is the normal volume of flue gas to air per unit mass of input waste calculated from

(2)

with anddenoting the H/C and O/C atomic ratios for the combustible fraction of the waste transferred to the gas, and representing the molecular weight of the flue gas emitted to air estimated from . In this notation, , and denote transfer coefficient, mass fraction and atomic or molecular weight, the subscripts and denote atomic and molecular species, and the superscripts and denote flue gas emitted to air and input waste. The emissions factor for CO2 can be calculated from:

(3)

Using the measured composition in table 3 and assuming that all S, Cl and F in the flue gas are emitted to the air as SO2, HCl and HF, respectively, the elementary transfer coefficients for S, Cl and F, shown in table 7 can be calculated from:

(4)

## Emissions to water

Table 5 shows the measured composition of the aqueous effluent after treatment of the process water from the wet scrubber. Assuming that all S and Cl in the water are present as sulphate and chlorine ions, the transfer coefficients for S and Cl, shown in Table 7, can then be calculated from:

(7)

Table 4: Treated water measurements for the Statkraft Varme Heimdal plant (lines 1 and 2)

|  |  |
| --- | --- |
| pH | 9.5 |
| Chlorine (total), Cl2 | 18000 ppm |
| Sulphate (SO4) | 6500 ppm |

## Bottom ash and fly ash composition

Table 4 shows the measured composition of bottom ash and fly ash samples from the common silos for lines 1 and 2.

Table 5: Ash composition for the Statkraft Varme Heimdal plant (lines 1 and 2)

|  |  |  |  |
| --- | --- | --- | --- |
| Concentration | Units | Bottom ash | Fly ash |
|
| Carbon-C | % wt dry | 0.80 a | 0.00 a |
| Hydrogen-H | % wt dry | 0.00 b | 0.00 b |
| Oxygen-O | % wt dry | 17.25 b | 16.76 b |
| Nitrogen-N | % wt dry | 0.0405 b | 0.00 b |
| Sulfur-S | % wt dry | 0.61 a | 2.15 a |
| Chlorine-Cl | % wt dry | 0.31 a | 0.491 b |
| Fluorine-F | % wt dry | 0.0425 b | 0.0118 b |
| Cadmium-Cd | mg/kg dry | 1.30 a | 55.21 a |
| Thallium-Tl | mg/kg dry | 0.00 b | 0.00 b |
| Antimony-Sb | mg/kg dry | 76.00 a | 77.62 a |
| Arsenic-As | mg/kg dry | 20.00 a | 18.78 a |
| Lead-Pb | mg/kg dry | 1500.00 a | 677.60 a |
| Chromium-Cr | mg/kg dry | 290.00 a | 3.90 a |
| Cobalt-Co | mg/kg dry | 14.18 b | 0.36 b |
| Copper-Cu | mg/kg dry | 2300.00 a | 165.00 a |
| Manganese-Mn | mg/kg dry | 810.00 a | 0.00 a |
| Nickel-Ni | mg/kg dry | 190.00 a | 0.68 a |
| Vanadium-V | mg/kg dry | 0.00 a | 0.00 a |
| Mercury-Hg | mg/kg dry | 0.05 a | 34.43 a |
| Silicon-Si | mg/kg dry | 40100 b | 191200 b |
| Phosphorus-P | mg/kg dry | 6074 b | 4550 b |
| Aluminium-Al | mg/kg dry | 77340 b | 72780 b |
| Iron-Fe | mg/kg dry | 172400 b | 99330 b |
| Zinc-Zn | mg/kg dry | 3300.00 a | 5598.00 a |
| Sodium-Na | mg/kg dry | 22000 b | 74650 b |
| Potassium-K | mg/kg dry | 10200 b | 27750 b |
| Calcium-Ca | mg/kg dry | 10770 b | 94640 b |
| Magnesium-Mg | mg/kg dry | 19230 b | 94470 b |
| Barium-Ba | mg/kg dry | 1000.00 a | 7635.00 a |
| Boron-B | mg/kg dry | 31.04 b | 74.34 b |
| Beryllium-Be | mg/kg dry | 0.00 b | 0.00 b |
| Molybdenum-Mo | mg/kg dry | 21.00 a | 0.88 a |
| Tin-Sn | mg/kg dry | 1194 b | 6278 b |
| Strontium-Sr | mg/kg dry | 2.19 b | 0.00 b |
| Bromine-Br | mg/kg dry | 12.98 b | 5.80 b |
| Iodine-I | mg/kg dry | 0.0123 b | 0.01243 b |
| Silver-Ag | mg/kg dry | 18.99 b | 47.78 b |
| Selenium-Se | mg/kg dry | 0.00 b | 0.00 b |
| Scandium-Sc | mg/kg dry | 0.00 b | 0.00 b |
| Titanium-Ti | mg/kg dry | 0.00 b | 0.00 b |
| Tungsten-W | mg/kg dry | 0.00 b | 0.00 b |
| Lanthanum-La | mg/kg dry | 0.00 b | 0.00 b |

Notes: a Measured values;  b Calculated values from the Transfer Coefficients

The transfer coefficients for the elements measured in the bottom ash, fly ash and filter cake can then be calculated from

(5)

and

, (6)

where , and denotes the elementary mass fractions in the bottom ash, fly ash and waste, and are the total bottom ash and fly ash mass fractions and and are the moisture and ash content in the waste.

# Scenarios

## Scenario waste elements matrix *(E)*

The scenario waste elements matrix (*E*) is presented in Table 6 below. For each scenario (column), the sum of all the elements from oxygen to sodium is equal to 1.

Table 6: Scenario elements matrix E

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | Base Case | Car fluff - 10% | Clinical Waste - 5% | Waste wood - 10% | Waste wood - 50% |  |
| Lower heating value | LHV | MJ/kg | 11.5 | 12.7 | 11.7 | 11.8 | 12.7 | 1 |
| Water content | H2O | kg/kg | 2.90E-01 | 2.66E-01 | 2.82E-01 | 2.78E-01 | 2.32E-01 | 2 |
| Oxygen (without O from H2O) | O | kg/kg | 2.27E-01 | 2.16E-01 | 2.32E-01 | 2.40E-01 | 2.93E-01 | 3 |
| Hydrogen (without H from H2O) | H | kg/kg | 4.69E-02 | 4.90E-02 | 4.76E-02 | 4.72E-02 | 4.85E-02 | 4 |
| Carbon | C | kg/kg | 3.30E-01 | 3.46E-01 | 3.30E-01 | 3.37E-01 | 3.66E-01 | 5 |
| Sulfur | S | kg/kg | 3.19E-03 | 2.92E-03 | 3.16E-03 | 2.89E-03 | 1.72E-03 | 6 |
| Nitrogen | N | kg/kg | 4.20E-03 | 5.46E-03 | 4.25E-03 | 3.88E-03 | 2.59E-03 | 7 |
| Phosphorus | P | kg/kg | 6.95E-04 | 6.27E-04 | 7.48E-04 | 6.36E-04 | 4.02E-04 | 8 |
| Boron | B | kg/kg | 3.56E-06 | 3.21E-06 | 3.39E-06 | 3.21E-06 | 1.78E-06 | 9 |
| Chlorine | Cl | kg/kg | 6.81E-03 | 1.20E-02 | 7.66E-03 | 6.22E-03 | 3.82E-03 | 10 |
| Bromium | Br | kg/kg | 1.19E-05 | 1.45E-05 | 1.13E-05 | 1.07E-05 | 5.96E-06 | 11 |
| Fluorine | F | kg/kg | 7.10E-05 | 6.49E-05 | 6.74E-05 | 6.60E-05 | 4.60E-05 | 12 |
| Iodine | I | kg/kg | 1.68E-08 | 1.51E-08 | 1.59E-08 | 1.51E-08 | 8.38E-09 | 13 |
| Silver | Ag | kg/kg | 3.15E-06 | 3.26E-06 | 2.99E-06 | 2.84E-06 | 1.58E-06 | 14 |
| Arsenic | As | kg/kg | 7.37E-07 | 7.93E-07 | 7.00E-07 | 1.11E-06 | 2.61E-06 | 15 |
| Barium | Ba | kg/kg | 8.88E-05 | 9.37E-05 | 1.72E-04 | 9.15E-05 | 1.02E-04 | 16 |
| Cadmium | Cd | kg/kg | 8.16E-06 | 1.14E-05 | 2.97E-05 | 7.37E-06 | 4.19E-06 | 17 |
| Cobalt | Co | kg/kg | 1.61E-06 | 5.77E-06 | 1.53E-06 | 1.51E-06 | 1.08E-06 | 18 |
| Chromium | Cr | kg/kg | 1.67E-04 | 1.61E-04 | 2.24E-04 | 1.52E-04 | 9.09E-05 | 19 |
| Copper | Cu | kg/kg | 2.30E-03 | 2.92E-03 | 2.21E-03 | 2.07E-03 | 1.16E-03 | 20 |
| Mercury | Hg | kg/kg | 9.16E-07 | 8.70E-07 | 2.28E-05 | 8.33E-07 | 4.99E-07 | 21 |
| Manganese | Mn | kg/kg | 1.65E-04 | 1.60E-04 | 1.57E-04 | 1.59E-04 | 1.35E-04 | 22 |
| Molybdenum | Mo | kg/kg | 1.08E-06 | 1.16E-06 | 1.02E-06 | 9.85E-07 | 6.19E-07 | 23 |
| Nickel | Ni | kg/kg | 2.30E-04 | 2.13E-04 | 2.40E-04 | 2.07E-04 | 1.15E-04 | 24 |
| Lead | Pb | kg/kg | 6.65E-04 | 7.11E-04 | 7.19E-04 | 6.00E-04 | 3.44E-04 | 25 |
| Antimony | Sb | kg/kg | 1.55E-05 | 1.98E-05 | 1.47E-05 | 1.40E-05 | 7.75E-06 | 26 |
| Selenium | Se | kg/kg | 2.41E-07 | 3.61E-07 | 2.29E-07 | 2.17E-07 | 1.21E-07 | 27 |
| Tin | Sn | kg/kg | 2.45E-04 | 2.36E-04 | 2.55E-04 | 2.21E-04 | 1.23E-04 | 28 |
| Vanadium | V | kg/kg | 9.63E-06 | 6.22E-05 | 9.15E-06 | 8.73E-06 | 5.12E-06 | 29 |
| Zinc | Zn | kg/kg | 1.02E-03 | 1.08E-03 | 9.93E-04 | 9.56E-04 | 6.91E-04 | 30 |
| Beryllium | Be | kg/kg | 0.00E+00 | 3.43E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 31 |
| Scandium | Sc | kg/kg | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 32 |
| Strontium | Sr | kg/kg | 0.00E+00 | 6.07E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 33 |
| Titanium | Ti | kg/kg | 1.47E-05 | 8.18E-05 | 2.33E-04 | 9.51E-05 | 4.16E-04 | 34 |
| Thallium | Tl | kg/kg | 0.00E+00 | 2.74E-08 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 35 |
| Tungsten | W | kg/kg | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 36 |
| Silicon | Si | kg/kg | 3.84E-02 | 3.70E-02 | 3.77E-02 | 3.48E-02 | 2.06E-02 | 37 |
| Iron | Fe | kg/kg | 1.83E-02 | 1.84E-02 | 1.93E-02 | 1.68E-02 | 1.05E-02 | 38 |
| Calcium | Ca | kg/kg | 1.48E-02 | 1.38E-02 | 1.47E-02 | 1.36E-02 | 8.88E-03 | 39 |
| Aluminium | Al | kg/kg | 8.10E-03 | 1.97E-02 | 8.09E-03 | 7.40E-03 | 4.62E-03 | 40 |
| Potassium | K | kg/kg | 2.14E-03 | 1.92E-03 | 2.25E-03 | 1.99E-03 | 1.37E-03 | 41 |
| Magnesium | Mg | kg/kg | 1.62E-03 | 1.46E-03 | 1.67E-03 | 1.53E-03 | 1.14E-03 | 42 |
| Sodium | Na | kg/kg | 3.39E-03 | 3.43E-03 | 3.57E-03 | 3.13E-03 | 2.11E-03 | 43 |
| Total |  | kg/kg | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 | 1.00E+00 |  |

## Transfer coefficients matrix (*T)*

All the transfer coefficients are grouped in the transfer coefficients matrix (*T)* presented in Table 7 below.

Table 7: Transfer coefficient matrix T

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  |  | Bottom ash | Fly ash | Filter cake | Water emission | Air emissions |
|  |  | kg/kg | kg/kg | kg/kg | kg/kg | kg/kg |
| Oxygen | O | 6.98E-02 | 1.22E-02 | 9.60E-04 | 0.00E+00 | 9.17E-01 |
| Hydrogen | H | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 1.00E+00 |
| Carbon | C | 1.24E-02 | 3.44E-03 | 0.00E+00 | 0.00E+00 | 9.84E-01 |
| Sulfur | S | 2.60E-01 | 2.98E-01 | 3.68E-01 | 2.26E-02 | 5.08E-02 |
| Nitrogen | N | 1.00E-02 | 0.00E+00 | 8.67E-19 | 1.00E-03 | 9.89E-01 |
| Phosphorus | P | 8.80E-01 | 1.19E-01 | 8.67E-19 | 0.00E+00 | 1.00E-03 |
| Boron | B | 3.84E-01 | 1.66E-01 | 1.80E-01 | 1.50E-01 | 1.20E-01 |
| Chlorine | Cl | 6.19E-02 | 1.30E-02 | 1.59E-02 | 9.00E-01 | 9.51E-03 |
| Bromium | Br | 1.10E-01 | 8.87E-01 | 2.60E-18 | 0.00E+00 | 3.00E-03 |
| Fluorine | F | 6.15E-01 | 3.08E-01 | 2.10E-02 | 5.52E-02 | 8.19E-04 |
| Iodine | I | 7.13E-02 | 1.30E-02 | 6.48E-03 | 9.09E-01 | 1.08E-05 |
| Silver | Ag | 6.15E-01 | 2.79E-01 | 1.06E-01 | 7.29E-05 | 1.30E-05 |
| Arsenic | As | 4.47E-01 | 5.21E-01 | 3.19E-02 | 1.00E-04 | 4.93E-04 |
| Barium | Ba | 2.06E-01 | 5.01E-01 | 2.91E-01 | 0.00E+00 | 1.00E-03 |
| Cadmium | Cd | 2.17E-02 | 3.81E-01 | 5.97E-01 | 6.75E-04 | 1.28E-05 |
| Cobalt | Co | 8.50E-01 | 1.04E-01 | 4.59E-02 | 1.00E-05 | 3.00E-08 |
| Chromium | Cr | 2.37E-01 | 6.14E-03 | 7.54E-01 | 3.40E-03 | 1.22E-05 |
| Copper | Cu | 1.36E-01 | 3.45E-03 | 8.60E-01 | 0.00E+00 | 1.31E-06 |
| Mercury | Hg | 6.98E-03 | 3.13E-02 | 9.50E-01 | 1.12E-02 | 1.02E-03 |
| Manganese | Mn | 6.67E-01 | 1.30E-01 | 2.03E-01 | 1.00E-05 | 2.89E-05 |
| Molybdenum | Mo | 6.68E-01 | 1.10E-01 | 2.20E-01 | 0.00E+00 | 2.00E-03 |
| Nickel | Ni | 1.13E-01 | 1.43E-03 | 8.86E-01 | 0.00E+00 | 1.13E-06 |
| Lead | Pb | 3.07E-01 | 4.63E-02 | 6.46E-01 | 1.63E-04 | 4.85E-06 |
| Antimony | Sb | 1.61E-02 | 8.40E-01 | 1.44E-01 | 1.82E-04 | 0.00E+00 |
| Selenium | Se | 8.03E-02 | 8.49E-01 | 7.07E-02 | 0.00E+00 | 1.00E-08 |
| Tin | Sn | 4.96E-01 | 4.71E-01 | 3.18E-02 | 1.33E-05 | 1.33E-03 |
| Vanadium | V | 8.90E-01 | 1.00E-01 | 9.89E-03 | 1.00E-05 | 1.00E-04 |
| Zinc | Zn | 4.39E-01 | 1.78E-01 | 3.82E-01 | 1.63E-04 | 1.63E-05 |
| Beryllium | Be | 6.96E-01 | 2.94E-01 | 9.00E-03 | 0.00E+00 | 1.00E-03 |
| Scandium | Sc | 9.99E-01 | 0.00E+00 | 5.00E-04 | 0.00E+00 | 5.00E-04 |
| Strontium | Sr | 9.99E-01 | 0.00E+00 | 9.00E-04 | 0.00E+00 | 1.00E-04 |
| Titanium | Ti | 9.99E-01 | 0.00E+00 | 8.67E-19 | 0.00E+00 | 1.00E-03 |
| Thallium | Tl | 3.48E-01 | 6.50E-01 | 1.00E-03 | 0.00E+00 | 1.00E-03 |
| Tungsten | W | 7.51E-01 | 2.49E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Silicon | Si | 9.19E-01 | 7.91E-02 | 1.18E-03 | 0.00E+00 | 7.19E-04 |
| Iron | Fe | 8.99E-01 | 9.35E-02 | 6.68E-03 | 7.87E-04 | 3.34E-05 |
| Calcium | Ca | 8.62E-01 | 1.37E-01 | 0.00E+00 | 0.00E+00 | 1.30E-03 |
| Aluminium | Al | 8.53E-01 | 1.45E-01 | 1.85E-17 | 5.40E-04 | 1.56E-03 |
| Potassium | K | 6.68E-01 | 3.28E-01 | 0.00E+00 | 7.90E-04 | 3.01E-03 |
| Magnesium | Mg | 9.17E-01 | 8.13E-02 | 0.00E+00 | 3.20E-04 | 1.38E-03 |
| Sodium | Na | 6.14E-01 | 3.76E-01 | 1.99E-17 | 4.90E-04 | 9.41E-03 |

## Direct emissions at the WtE plant

Direct emissions vary linearly with waste composition if the emission in question is assumed to be waste-specific (computed with transfer coefficients), and are constant if process-specific.

Table 8: Direct emissions at WtE plant

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | Base Case | Car fluff - 10% | Clinical Waste - 5% | Waste wood - 10% | Waste wood - 50% |
| Carbon, biogenic share |  | [-] | 62.5 % | 53.6 % | 61.8 % | 67.0 % | 83.1 % |
| Carbon dioxide, total | CO2, total | kg/kg | 1.21E+00 | 1.27E+00 | 1.21E+00 | 1.23E+00 | 1.34E+00 |
| Carbon dioxide, fossil | CO2, fossil | kg/kg | 4.53E-01 | 5.87E-01 | 4.62E-01 | 4.08E-01 | 2.27E-01 |
| Carbon dioxide, biogenic | CO2, biogenic | kg/kg | 7.55E-01 | 6.80E-01 | 7.49E-01 | 8.27E-01 | 1.11E+00 |
| Carbon monoxide, total | CO, total | kg/kg | 5.11E-05 | 5.11E-05 | 5.11E-05 | 5.11E-05 | 5.11E-05 |
| Carbon monoxide, fossil | CO, fossil | kg/kg | 1.92E-05 | 2.37E-05 | 1.95E-05 | 1.69E-05 | 8.64E-06 |
| Carbon monoxide, biogenic | CO, biogenic | kg/kg | 3.19E-05 | 2.74E-05 | 3.16E-05 | 3.42E-05 | 4.25E-05 |
| Sulfur dioxide | SO2 | kg/kg | 3.24E-04 | 2.96E-04 | 3.18E-04 | 2.94E-04 | 3.21E-04 |
| Particulate matter | PM | kg/kg | 2.28E-05 | 2.28E-05 | 2.28E-05 | 2.28E-05 | 2.28E-05 |
| Hydrogen chloride | HCl | kg/kg | 6.67E-05 | 1.17E-04 | 7.49E-05 | 6.08E-05 | 3.74E-05 |
| Hydrogen fluoride | HF | kg/kg | 6.12E-08 | 5.60E-08 | 5.82E-08 | 5.69E-08 | 3.97E-08 |
| Nitrogen oxides | NOx | kg/kg | 9.63E-04 | 9.63E-04 | 9.63E-04 | 9.63E-04 | 9.63E-04 |
| Dioxin | 2,3,7,8-tcdd | kg/kg | 2.12E-13 | 2.12E-13 | 2.12E-13 | 2.12E-13 | 2.12E-13 |
| NH3 | NH3 | kg/kg | 7.60E-06 | 7.60E-06 | 7.60E-06 | 7.60E-06 | 7.60E-06 |
| NMVOC1 | NMVOC | kg/kg | 1.89E-06 | 1.89E-06 | 1.89E-06 | 1.89E-06 | 1.89E-06 |
| Methane, fossil1 | CH4, fossil | kg/kg | 5.44E-06 | 5.44E-06 | 5.44E-06 | 5.44E-06 | 5.44E-06 |
| Benzene1 | C6H6 | kg/kg | 3.63E-07 | 3.63E-07 | 3.63E-07 | 3.63E-07 | 3.63E-07 |
| Benzopyrene1 | C20H12 | kg/kg | 7.65E-12 | 7.65E-12 | 7.65E-12 | 7.65E-12 | 7.65E-12 |
| Hexachlorobenzene1 | C6Cl6 | kg/kg | 7.84E-11 | 7.84E-11 | 7.84E-11 | 7.84E-11 | 7.84E-11 |
| Pentachlorobenzene1 | C6HCl5 | kg/kg | 1.69E-10 | 1.69E-10 | 1.69E-10 | 1.69E-10 | 1.69E-10 |
| Pentachlorophenol1 | C6HCl5O | kg/kg | 5.84E-11 | 5.84E-11 | 5.84E-11 | 5.84E-11 | 5.84E-11 |
| Toluene1 | C7H8 | kg/kg | 7.26E-07 | 7.26E-07 | 7.26E-07 | 7.26E-07 | 7.26E-07 |

1 from ([Doka 2007](#_ENREF_1))

## Thermal energy efficiency ()

Variation in thermal energy efficiency for the different scenarios considered can be calculated using the input waste composition in Table 6 and the transfer coefficients in Table 7, using the formula

, (8)

where represents the lower heating value of the waste *k*, is the fraction of the output thermal power lost by dissipation and cooling, and and are the specific thermal enthalpy of the ash and the flue gas emitted to air calculated from

(9)

and

(10)

where and are the specific heat capacity of the bottom ash and fly ash, assumed to be 1.2 KJ/kg, and is the specific heat of the flue gas emitted to air estimated from . In Equations (9) and (10), and are the average temperature of the bottom ash leaving the grate and the average temperature of the fly ash from the boiler and electrostatic precipitator hoppers, assumed to be 500 deg. C and 300 deg. C respectively, and is the measured temperature of the flue gas emitted to air. The heat dissipation factor is calculated from the base case, assuming a thermal efficiency of 0.82, and kept constant for all scenarios.

## Consumables

The consumption of quicklime is linearly related to the sulfur and chlorine content of the waste and the consumption of sodium hydroxide is linearly related to the sulfur content of the waste.

(11)

(12)

, are the consumption rates and species concentration for the base case.

Table 9: Consumables consumption

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  | Base Case | Car fluff - 10% | Clinical Waste - 5% | Waste wood - 10% | Waste wood - 50% |
| Lime, 90% | CaO | g/kg | 9.65 | 14.38 | 11.23 | 8.79 | 5.34 |
| Sodium hydroxide, 30% | NaOH | g/kg | 2.00 | 1.83 | 1.97 | 1.82 | 1.08 |
| Active carbon |  | g/kg | 0.45 | 0.45 | 0.45 | 0.45 | 0.45 |
| Water (flue gas cleaning) |  | m3/tonne | 0.2-0.25 | 0.2-0.25 | 0.2-0.25 | 0.2-0.25 | 0.2-0.25 |
| Ammonia, 25% | NH3 | g/tonne | 2.3 | 2.3 | 2.3 | 2.3 | 2.3 |
| Hydrogen chloride | HCl | g/kg | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |
| Electricity | hydro | kWh/tonne | 120 | 120 | 120 | 120 | 120 |
| Diesel oil (aux. burners) |  | liter/tonne | 1.2-2.4 | 1.2-2.4 | 1.2-2.4 | 1.2-2.4 | 1.2-2.4 |

## Bottom ash and fly ash, total amounts

To compute the total amount of bottom ash and fly ash, the elements ending up in the bottom ash and fly ash compartment of the final compartment matrix (*F*) are further oxidized. The amount of bottom ash and fly ash are given in Table 10.

Table 10: Bottom ash, fly ash and filter cake - Total amounts

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Base Case |  | Car fluff - 10% | Clinical Waste - 5% | Waste wood - 10% | Waste wood - 50% |
| Bottom ash | kg/kg | 1.5E-01 |  | 1.6E-01 | 1.5E-01 | 1.3E-01 | 8.7E-02 |
| Fly ash and filter cake | kg/kg | 2.8E-02 |  | 3.2E-02 | 2.9E-02 | 2.6E-02 | 1.5E-02 |

# References

Doka, G. 2007. Life Cycle Inventories of Waste Treatment Services. Swiss Centre for Life Cycle Inventories, Dübendorf.