Report for

Implementation of a municipal solid waste incineration model in openLCA

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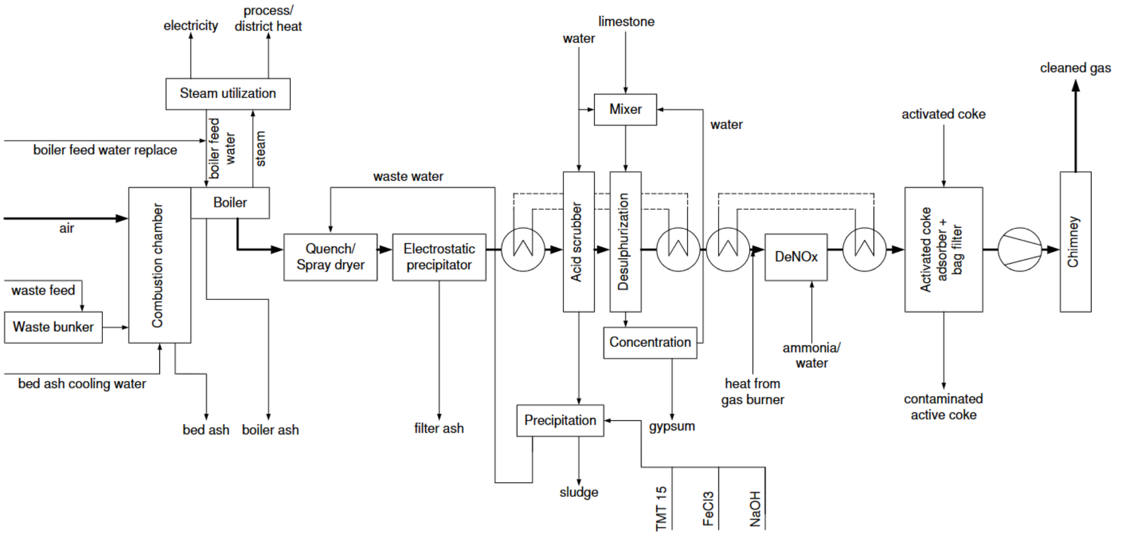
1 Introduction

Modelling the incineration process in the openLCA LCA software allows calculating the environmental impacts of the municipal waste incineration processes. Such an LCA model and product system was developed for openLCA, based on a modular model for calculating the input/output balance of a municipal solid waste incineration plant which was initially developed by Kremer M. et al. (Kremer et al., 1998). A first spreadsheet version of this model was developed by Ciroth (Ciroth, 1998), and later on updated and refined.

The process structure of the municipal waste incineration plant is shown in Figure 1. The processes and calculations are distributed in several files called "workbooks". Most cells in the workbooks are named and each name is unique in a workbook. This initial model assumes the technical state of the art for modern municipal waste incineration plants in Germany form the late 1990's (Kremer et al., 1998). As Figure 2 shows, the spreadsheet version by Ciroth are workbook files linked together by their input/output sheets (Ciroth, 1998). Each workbook contains the input and output results of each module. The system boundary of the unit process waste incineration with energy recovery comprises the combustion module, electrostatic precipitator module, gas scrubber module, DeNOx module, Flow absorber module and suction fan module. The calculation results (inputs and outputs) of the spreadsheet modules are united in Master balance module. The inputs and outputs are calculated. The waste composition is calculated in the file "Input.xls".



Based on [Kremer et al., 1998], modified

Figure 1: Process flow chart of the state-of-the-art plant modelled (Ciroth, 1998; Kremer et al., 1998)

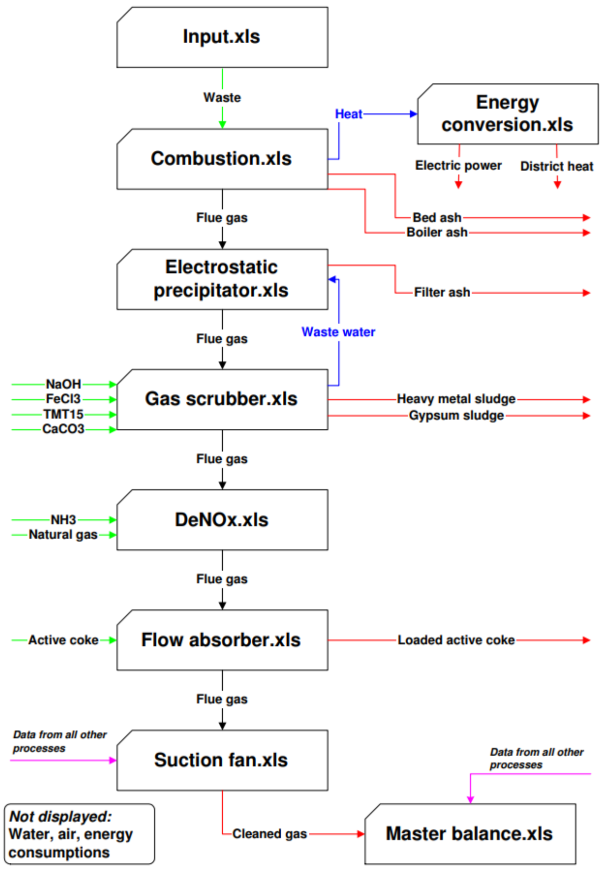


Figure 2: Workbook structure of the modular spreadsheet model by Ciroth (Ciroth, 1998), (Hagelüken et al., 2002)

2 *The MSWI model in openLCA*

The MSWI model was modeled as a process in openLCA to perform the calculation of impact results. The inputs and outputs from the MSWI were fed into the process of MSWI and were modeled as a waste flow. The waste is treated in the incineration plant with flue gas cleaning according to the MSWI model. Flue gas cleaning consists of electrostatic precipitator (ESP), gas scrubber, DeNOx (denitrification), flow absorber and suction fan (Hagelüken et al., 2002). Each of this modular was modeled as a separate process in openLCA 2.1.1, as shown in Figure 3.

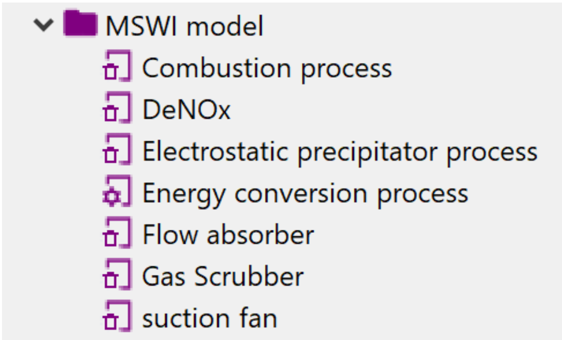


Figure 3: Processes of MSWI model in openLCA

Parameters were stored under some parameter folders, as shown in Figure 5. The folder "Inputs" is used to store parameters such as the mass fraction of the input waste or the heating value of the input waste. The folder "Constants" is used to store some constant parameters, e.g. "Molar mass of element “. These parameters should be constant. The mass fraction of the input waste should be the amount of the element in 1 kg of waste, e.g. 0.2 kg aluminium/kg of waste. The values of input waste composition are from Würzburg Waste and could be changed by assigning new values to the parameters. The flue gas was modeled as waste flow in openLCA 2.1.1, so that each of process could be connected with each other, see Figure 4. Electricity is provided for the combustion process and the bed ash and boiler ash are subsequently treated. The flue gas from the incineration is modeled as a waste flow and transported into the electrostatic precipitator, and the filter dust is emitted and modeled as residues. The flue gas is passed through a gas scrubber, a flow absorber and an extraction fan and then emitted into the air.

The model in openLCA is linked to an ecoinvent 3.10 cut-off database. An ecoinvent license is thus required for getting access to the model.

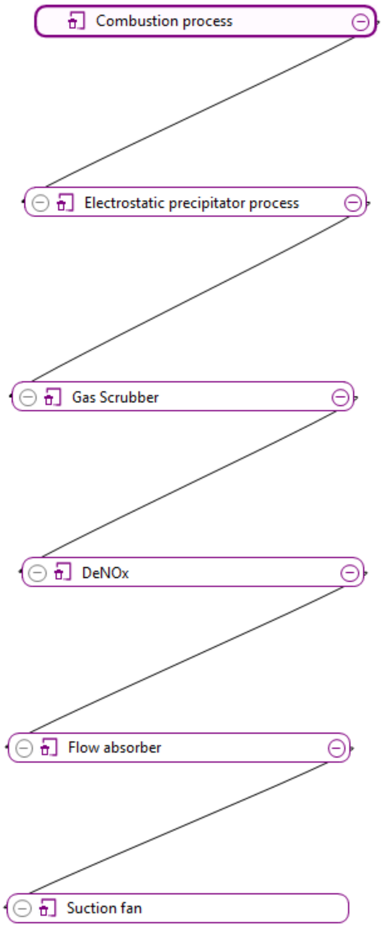


Figure 4: Model graph of this MSWI product system (showing only foreground processes)

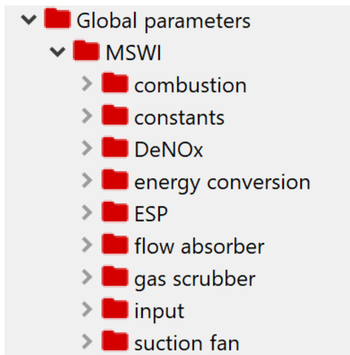


Figure 5: Parameter folders of MSWI model in openLCA

2.1 Combustion module

The input waste composition for testing is from Würzburg WASTE(Ciroth, 1998). The input waste was modeled as waste flow in open LCA. The amount of input waste consists of the sum of mass fraction of elements in the waste composition. By assigning the value to parameter of mass fraction of elements the flue gas, emission composition will be affected. For example, by changing the value of parameter "W1_m_As_waste"the mass fraction of Arsenic in input waste is also changed which will affect the end emission of arsenic in flue gas etw. The naming convention of parameter is <waste source>_m_<Element>_waste(Hagelüken et al., 2002). The distribution of metals, S, Cl and F[1] to the emission pathways are defined by empirical transfer coefficients. These transfer coefficients were examined at the Würzburg incinerator and naturally have only a limited validity (Hagelüken et al., 2002). The Air/oxygen requirements "m_Omin" for combustion should be calculated from oxidation of the input substance and could be changed by changing the input waste composition (Hagelüken et al., 2002). Fig. 6 shows the different ways of calculating the composition of the data stream. The incineration of MSW in the MSWI generates two types of residues: bed ash and boiler ash. The bed ash is modeled as a waste flow "bottom ash, MSWI, municipal solid waste" and the boiler ash is modeled as a waste flow "residues, MSWI, municipal solid waste". The model results include the impacts of bottom ash and municipal solid waste residuals processes provided by ecoinvent 3.10. Water use for bed ash cooling is modeled as an elementary flow "Water, river" as input.

[1] S: sulfur, Cl: chlorine, F: fluorine

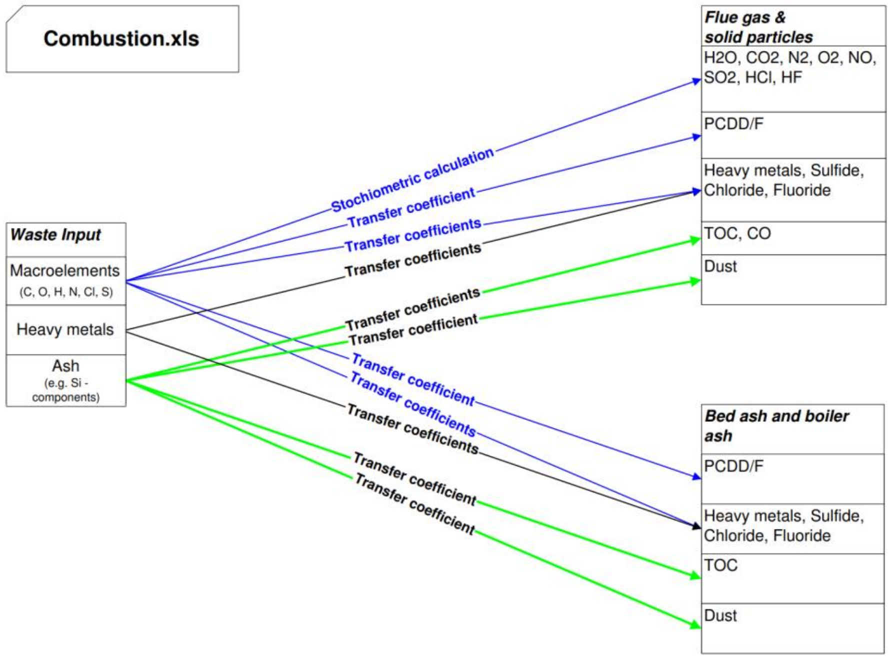


Figure 6: Overview of the combustion module (Hagelüken et al., 2002)

2.2 Energy conversion module

Energy conversion includes the use of heat from the combustion module to generate high pressure steam, pressure reduction in the turbine to generate electricity, use of low-pressure steam for process or district heating, and condensation of excess steam in the condenser, see Figure 7 (Hagelüken et al., 2002). The boiler feed water is modeled in this module as a product flow“water, decarbonised”.

Using the specified data for the different thermodynamic states of the working fluid in the energy conversion cycle, it is possible to calculate the amount of electrical energy and district heat. The following points should be taken into account in the calculation (Hagelüken et al., 2002):

- The energy transferred from flue gas (q_N_in_ec) corresponds to the energy output from flue gas (q_N).
- The total water consumption (m_Water_energyconversion) comprises the cooling water (m_KW) and circular flow water losses (m_SP_Verlust).

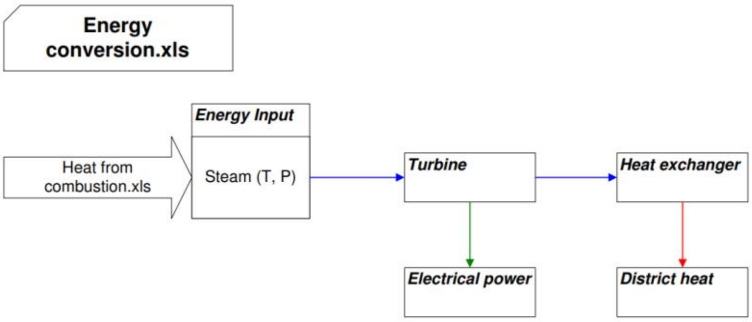


Figure 7: Overview of the energy conversion module (Hagelüken et al., 2002)

2.3 Electrostatic precipitator (ESP) module

In this module, metals, sulfur, chlorine, and all other substances adsorbed on solid particles in the flue gas are precipitated according to transfer coefficients, thus forming the filter ash (Hagelüken et al., 2002). The distribution of substances to the emission pathways (flue gas or filter ash) are defined by empirical transfer coefficients, as Figure 8 shows. The wastewater (m_AW_precip_aus) and the salts input (m_salts_precip_aus) with wastewater from gas scrubber module comes also into ESP module as waste flows. So, the flue gas output from ESP (v_FGaus_ESP) comprises the flue gas input (v_FG) and the wastewater(v_AW) (Hagelüken et al., 2002) (Hagelüken et al., 2002). At this stage, the wastewater and the salts in the wastewater come as waste flow from the gas scrubber as input.

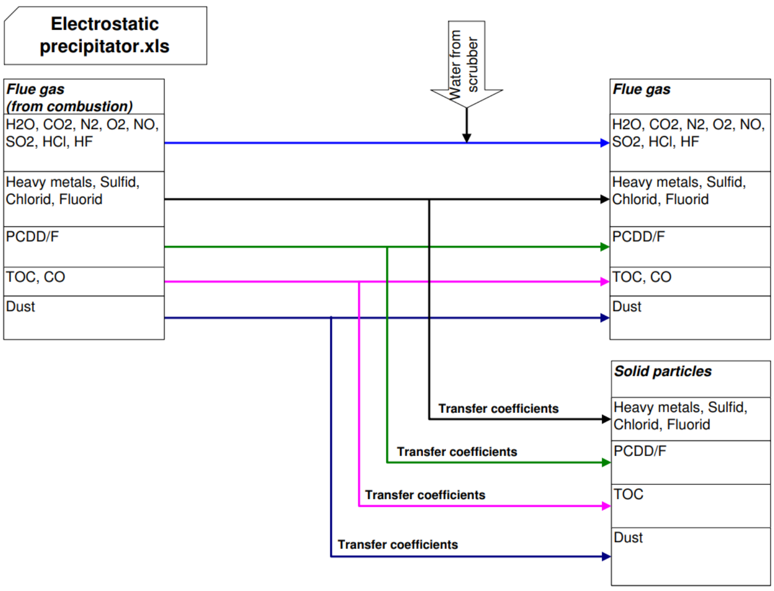


Figure 8: Overview of the electrostatic precipitator module (Hagelüken et al., 2002)

2.4 Gas scrubber module

In the module of gas scrubber, the flue gas will go through two stages (acid scrubber and desulphurization). The flue gas is neutralized with NaOH firstly in acid scrubber and heavy metals are flocculated and precipitated. The sludge is separated, and the remaining water (m_AW_precip_aus) is evaporated in the spray dryer and go to “electrostatic precipitator". During desulphurization the flue gas will result the wet gypsum which contains about 6% dry matter and modelled as waste flow “fly ash and scrubber ash”. (Hagelüken et al., 2002).

Based on the assumption that the separation of substances other than HCl and SO2 in the two stages of the gas scrubber depends on the transfer coefficient.

The calculation pathways are displayed in Figure 9. The naming convention of the transfer coefficients is <Red>_<Element>_<acid/lime>. The amount of NaOH (m_NaOH) needed is calculated from the difference between the input (c_HClein) and output (c_HClaus) HCl concentrations. The amount of TMT 15[2] and $FeCl_3$ needed depends on the amount of wastewater (m_AW_precip_aus), which depends on the difference between input and output HCl concentrations. CaCO3 (m_CaCO3_in_gs) required for desulphurization is calculated from the difference between the input(c_SO_2ein) and output(c_SO_2aus) SO2 concentrations (Hagelüken et al., 2002). At this stage, the wastewater and salts in the water are modeled as a waste stream and will be returned to the ESP.

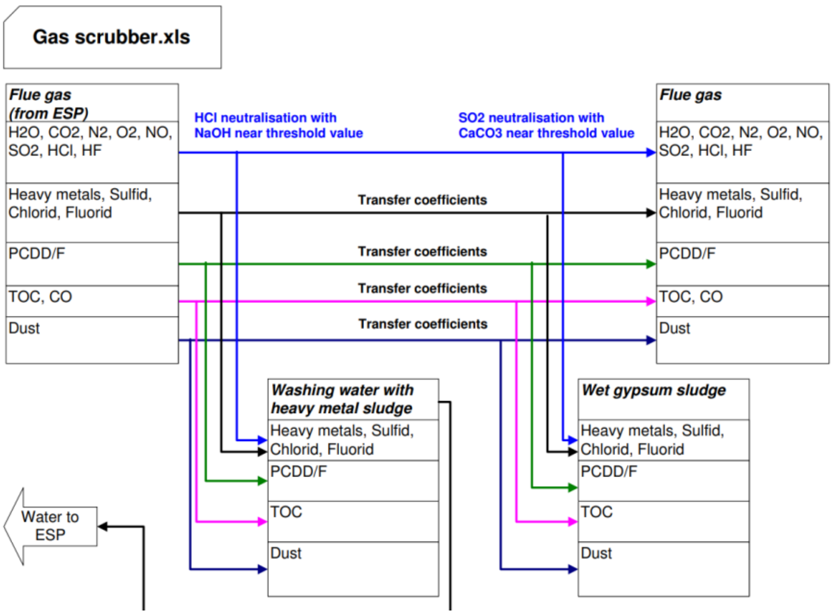


Figure 9: Overview of the gas scrubber module(Hagelüken et al., 2002)

[2] TMT 15® is a 15 % aqueous solution made up of trimercapto-s-triazine, trisodium salt, an organo-sulfide that reacts with heavy metals to form an extremely stable, virtually insoluble heavy metal-TMT solid compound that is easy to separate (Fogg et al., 1997).

2.5 DeNOx module

The DeNOx process is of the selective catalytic reduction type (SCR) using ammonia as reductive agent, as shown in Figure 10. For this reaction, a temperature of 320 ◦C (t_w_ein) has to be provided. This is achieved by a heat cycle including a natural gas auxiliary burner. The given exit concentration of NOx (c_NOx_{aus}) and the amount of excess ammonia ($c\_NH3_{Schlupf}$) determine the total consumption of ammonia(Hagelüken et al., 2002). The real mechanism consists of multiple reactions (Schnell, 1991), but only one of the major reactions is considered here (Hagelüken et al., 2002):

$$4\,NH_3 + 4\,NO + \ O_2 == 4\,N_2 + 6\,H_2O$$

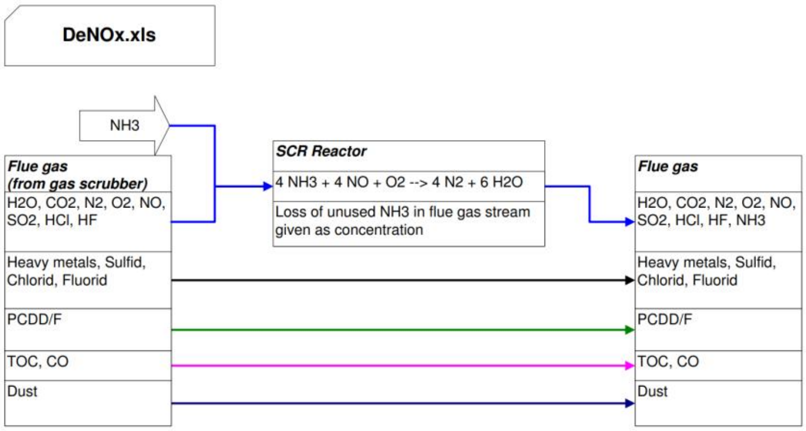


Figure 10: Overview of the DeNOx module(Hagelüken et al., 2002)

2.6 Flow absorber module

The flow absorber module uses activated coke to adsorb volatile heavy metals and organic compounds. The calculation of the precipitation is based on transfer coefficients, as shown in Figure 11. Maximum concentration of HCl, HF and SO2 in the activated carbon should be specified (x_HOK_HCl, x_HOK_HF, x_HOK_SO2). The substances are precipitated up to the maximum concentration. The consumption of fresh activated coke depends on the flue gas volume flow. The mass of loaded coke is the sum of input mass and the mass of precipitated substances(Hagelüken et al., 2002). The loaded activated carbon is modelled in this module as a waste flow.

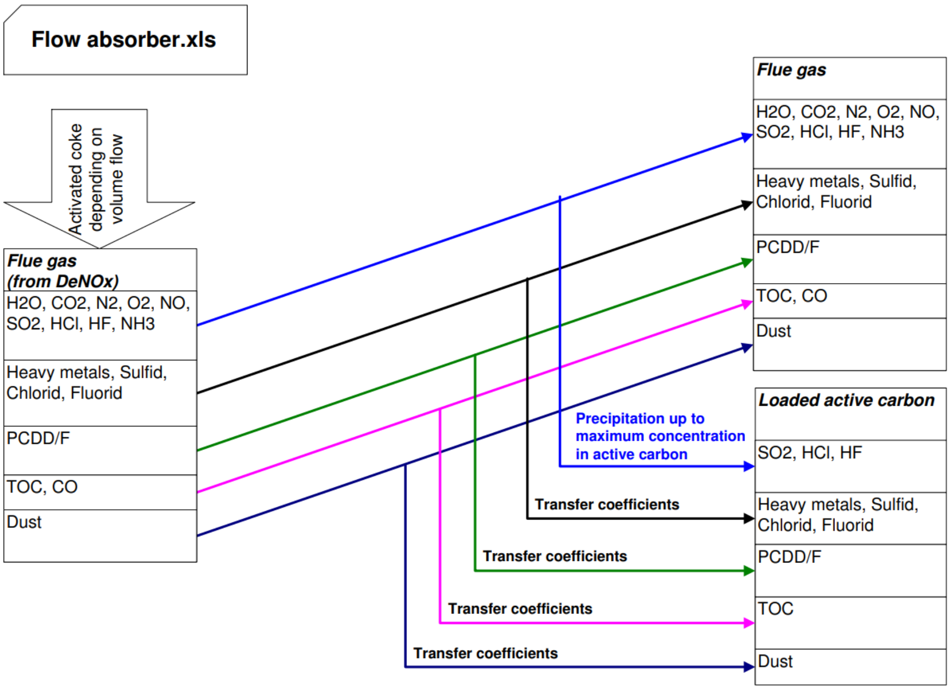


Figure 11: Overview of the flow absorber module (Hagelüken et al., 2002)

2.7 Suction fan module

This module uses data from all other modules to calculate the energy consumption of the suction fan that conveys the gases through the whole flue gas treatment. This model calculates the volume flow from the temperature and pressure in each process. In this module the elements from flue gas are modelled as elementary flow (emission to air). They are not real gases but only part of the flue gas. The amount of these flows are the mass fractions of these substances (Hagelüken et al., 2002).

3 Implementation of this model and impact results interpretation

In the following, a specific implementation is shown, based in the MSWI plant in Würzburg, Germany. These settings can be changed for a different case.

3.1 Functional Unit

The functional unit of this model is treatment of 1 kg waste for incineration. The lower heating value of the provided is 11.81 MJ.

3.2 System boundaries

This model includes combustion, electrostatic precipitator, energy conversion, flow absorber, gas scrubber and suction fan, as shown in Figure 1.

3.3 Software and databases

Calculations were conducted in the openLCA software, version 2.1.1, with the impact assessment method EF 3.1. The database ecoinvent version 3.10 cut off was used for this study. In the cases of multifunctionality within the processes, such as energy conversion process, physical allocation was applied to allocate the impacts.

3.4 Overall results

Table 1 displays the overall results for combustion of 1 kg of waste from Würzburg assessed with the LCIA EF 3.1 method. The results of the impact category include the upstream processes such as resource uptake, energy usage, transport and emissions related to the background processes. As shown in the Table 2, the highest contribution to these impact categories is mainly from the suction fan, due to the fact that in this module all parts of the flue gas are modeled as elementary flows (emitted into the air). In addition, electricity consumption contributes significantly to the impact categories.

The acidification potential of this model depends on the direct emission of nitrogen oxide, ammonia, and sulphur dioxide from suction fan. The climate change is contributed by carbon dioxide (direct emission) and methane from heat and electricity production. The treatment of the bottom ash and residues are the main contributors to ecotoxicity. Energy resources are affected by natural gas from petroleum and gas production. The cause of eutrophication is phosphates emitted from the lignite mining process, which prepares the ground for the electricity generation process. Human toxicity is mainly caused by coke production and treatment of residues and bottom ash. Particulate matter formation is mainly caused by direct emissions from suction fan. The main driver of land use is land transformation for electricity production. The treatment of the bottom ash is the next highest contributors to land use. Photochemical oxidant formation is contributed by the direct emission of nitrogen oxides and sulfur oxide. The processes contributing highest to the water use are system industrial water use and water use for the process ammonia production.

Table 1: Impact assessment results for the combustion of 1 kg waste from Würzburg

Name	Impact assessment result	Unit
Acidification	9.39E-04	mol H+-Eq
Climate change	9.90E-01	kg CO2-Eq
Climate change: biogenic	1.19E-04	kg CO2-Eq
Climate change: fossil	9.89E-01	kg CO2-Eq
Climate change: land use and land use change	5.87E-05	kg CO2-Eq
Ecotoxicity: freshwater	6.46E-01	CTUe
Ecotoxicity: freshwater, inorganics	5.96E-01	CTUe
Ecotoxicity: freshwater, organics	5.03E-02	CTUe
Energy resources: non-renewable	1.20E+00	MJ, net calorific value
Eutrophication: freshwater	6.33E-05	kg P-Eq

Name	Impact assessment result	Unit
Eutrophication: marine	2.86E-04	kg N-Eq
Eutrophication: terrestrial	2.89E-03	mol N-Eq
Human toxicity: carcinogenic	3.64E-10	CTUh
Human toxicity: carcinogenic, inorganics	1.34E-10	CTUh
Human toxicity: carcinogenic, organics	2.29E-10	CTUh
Human toxicity: non-carcinogenic	3.03E-09	CTUh
Human toxicity: non-carcinogenic, inorganics	2.99E-09	CTUh
Human toxicity: non-carcinogenic, organics	3.74E-11	CTUh
Ionising radiation: human health	7.09E-03	kBq U235-Eq
Land use	2.60E-01	dimensionless
Material resources: metals/minerals	5.83E-07	kg Sb-Eq
Ozone depletion	2.20E-09	kg CFC-11-Eq
Particulate matter formation	2.13E-09	disease incidence
Photochemical oxidant formation: human health	7.64E-04	kg NMVOC-Eq
Water use	7.43E-02	m3 world Eq deprived

Table 2: openLCA impact analysis showing breakdown of the contribution of processes

Name	Impact assessment result	Unit
Acidification	9.39E-04	mol H+-Eq
suction fan	7.61E-04	mol H+-Eq
Climate change	9.90E-01	kg CO2-Eq
suction fan	9.24E-01	kg CO2-Eq
Climate change: biogenic	1.19E-04	kg CO2-Eq
anaerobic digestion of manure | biogas | Cutoff, U - RoW	8.06E-05	kg CO2-Eq
heat and power co-generation, biogas, gas engine | electricity, high voltage | Cutoff, U - DE	1.54E-05	kg CO2-Eq
Climate change: fossil	9.89E-01	kg CO2-Eq
suction fan	9.24E-01	kg CO2-Eq
Climate change: land use and land use change	5.87E-05	kg CO2-Eq
electricity production, hydro, pumped storage | electricity, high voltage | Cutoff, U - DE	2.57E-05	kg CO2-Eq
electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | Cutoff, U - DE	1.15E-05	kg CO2-Eq
Ecotoxicity: freshwater	6.46E-01	CTUe
treatment of bottom ash, MSWI, municipal solid waste, slag compartment | bottom ash, MSWI, municipal solid waste | Cutoff, U - DE	2.03E-01	CTUe
treatment of residues, MSWI, municipal solid waste, residual material landfill | residues, MSWI, municipal solid waste | Cutoff, U - DE	1.78E-01	CTUe
chlor-alkali electrolysis, average production | sodium hydroxide, without water, in 50% solution state | Cutoff, U - RER	4.44E-02	CTUe
coke production | coke | Cutoff, U - RoW	4.02E-02	CTUe
lignite mine operation | lignite | Cutoff, U - RER	3.77E-02	CTUe
Ecotoxicity: freshwater, inorganics	5.96E-01	CTUe
treatment of bottom ash, MSWI, municipal solid waste, slag compartment | bottom ash, MSWI, municipal solid waste | Cutoff, U - DE	2.03E-01	CTUe
treatment of residues, MSWI, municipal solid waste, residual material landfill | residues, MSWI, municipal solid waste | Cutoff, U - DE	1.78E-01	CTUe

Name	Impact assessment result	Unit
chlor-alkali electrolysis, average production | sodium hydroxide, without water, in 50% solution state | Cutoff, U - RER	4.43E-02	CTUe
lignite mine operation | lignite | Cutoff, U - RER	3.77E-02	CTUe
Ecotoxicity: freshwater, organics	5.03E-02	CTUe
coke production | coke | Cutoff, U - RoW	3.58E-02	CTUe
wood preservation, pressure vessel, creosote, outdoor use, ground contact | wood preservation, pressure vessel, creosote, outdoor use, ground contact | Cutoff, U - RoW	5.60E-03	CTUe
Energy resources: non-renewable	1.20E+00	MJ, net calorific value
petroleum and gas production, onshore | natural gas, high pressure | Cutoff, U - RU	3.00E-01	MJ, net calorific value
petroleum and gas production, offshore | natural gas, high pressure | Cutoff, U - NO	1.07E-01	MJ, net calorific value
lignite mine operation | lignite | Cutoff, U - RER	1.05E-01	MJ, net calorific value
petroleum and gas production, offshore | natural gas, high pressure | Cutoff, U - RU	6.48E-02	MJ, net calorific value
Eutrophication: freshwater	6.33E-05	kg P-Eq
treatment of spoil from lignite mining, in surface landfill | spoil from lignite mining | Cutoff, U - GLO	2.66E-05	kg P-Eq
treatment of residues, MSWI, municipal solid waste, residual material landfill | residues, MSWI, municipal solid waste | Cutoff, U - DE	2.02E-05	kg P-Eq
treatment of bottom ash, MSWI, municipal solid waste, slag compartment | bottom ash, MSWI, municipal solid waste | Cutoff, U - DE	8.01E-06	kg P-Eq
treatment of spoil from hard coal mining, in surface landfill | spoil from hard coal mining | Cutoff, U - GLO	4.60E-06	kg P-Eq
Eutrophication: marine	2.86E-04	kg N-Eq
suction fan	2.17E-04	kg N-Eq
treatment of bottom ash, MSWI, municipal solid waste, slag compartment | bottom ash, MSWI, municipal solid waste | Cutoff, U - DE	2.44E-05	kg N-Eq
Eutrophication: terrestrial	2.89E-03	mol N-Eq
suction fan	2.47E-03	mol N-Eq
Human toxicity: carcinogenic	3.64E-10	CTUh
coke production | coke | Cutoff, U - RoW	1.58E-10	CTUh
treatment of residues, MSWI, municipal solid waste, residual material landfill | residues, MSWI, municipal solid waste | Cutoff, U - DE	1.16E-10	CTUh
chlor-alkali electrolysis, average production | sodium hydroxide, without water, in 50% solution state | Cutoff, U - RER	5.42E-11	CTUh
Human toxicity: carcinogenic, inorganics	1.34E-10	CTUh
treatment of residues, MSWI, municipal solid waste, residual material landfill | residues, MSWI, municipal solid waste | Cutoff, U - DE	1.16E-10	CTUh
suction fan	9.10E-12	CTUh
Human toxicity: carcinogenic, organics	2.29E-10	CTUh
coke production | coke | Cutoff, U - RoW	1.58E-10	CTUh
chlor-alkali electrolysis, average production | sodium hydroxide, without water, in 50% solution state | Cutoff, U - RER	5.42E-11	CTUh
Human toxicity: non-carcinogenic	3.03E-09	CTUh
suction fan	1.57E-09	CTUh
treatment of residues, MSWI, municipal solid waste, residual material landfill | residues, MSWI, municipal solid waste | Cutoff, U - DE	8.70E-10	CTUh
Human toxicity: non-carcinogenic, inorganics	2.99E-09	CTUh
suction fan	1.57E-09	CTUh

Name	Impact assessment result	Unit
treatment of residues, MSWI, municipal solid waste, residual material landfill | residues, MSWI, municipal solid waste | Cutoff, U - DE	8.70E-10	CTUh
Human toxicity: non-carcinogenic, organics	3.74E-11	CTUh
natural gas venting from petroleum/natural gas production | natural gas, vented | Cutoff, U - GLO	8.07E-12	CTUh
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	4.75E-12	CTUh
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	4.51E-12	CTUh
transport, pipeline, onshore, long distance, natural gas | transport, pipeline, onshore, long distance, natural gas | Cutoff, U - RU	2.08E-12	CTUh
Ionising radiation: human health	7.09E-03	kBq U235-Eq
treatment of tailing, from uranium milling | tailing, from uranium milling | Cutoff, U - GLO	5.18E-03	kBq U235-Eq
treatment of spent nuclear fuel, reprocessing | spent nuclear fuel | Cutoff, U - RoW	9.12E-04	kBq U235-Eq
treatment of low level radioactive waste, plasma torch incineration | low level radioactive waste | Cutoff, U - CH	4.31E-04	kBq U235-Eq
Land use	2.60E-01	dimensionless
road construction | road | Cutoff, U - RoW	3.34E-02	dimensionless
slag landfill construction | slag landfill | Cutoff, U - RoW	2.91E-02	dimensionless
photovoltaic mounting system production, for 570kWp open ground module | photovoltaic mounting system, for 570kWp open ground module | Cutoff, U - GLO	2.91E-02	dimensionless
process-specific burdens, slag landfill | process-specific burdens, slag landfill | Cutoff, U - Europe without Switzerland	2.79E-02	dimensionless
Material resources: metals/minerals	5.83E-07	kg Sb-Eq
sodium chloride production, powder | sodium chloride, powder | Cutoff, U - RoW	1.06E-07	kg Sb-Eq
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - RoW	9.42E-08	kg Sb-Eq
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CL	7.99E-08	kg Sb-Eq
copper mine operation and beneficiation, sulfide ore | copper concentrate, sulfide ore | Cutoff, U - CN	2.98E-08	kg Sb-Eq
Ozone depletion	2.20E-09	kg CFC-11-Eq
petroleum and gas production, offshore | natural gas, high pressure | Cutoff, U - NO	4.50E-10	kg CFC-11-Eq
transport, pipeline, onshore, long distance, natural gas | transport, pipeline, onshore, long distance, natural gas | Cutoff, U - RU	3.72E-10	kg CFC-11-Eq
chloroform production | chloroform | Cutoff, U - RER	2.82E-10	kg CFC-11-Eq
petroleum and gas production, offshore | natural gas, high pressure | Cutoff, U - RU	2.73E-10	kg CFC-11-Eq
petroleum and gas production, offshore | natural gas, high pressure | Cutoff, U - NL	1.18E-10	kg CFC-11-Eq
Particulate matter formation	2.13E-09	disease incidence
suction fan	5.20E-10	disease incidence
diesel, burned in building machine | diesel, burned in building machine | Cutoff, U - GLO	2.77E-10	disease incidence
electricity production, hard coal, at coal mine power plant | electricity, high voltage, for internal use in coal mining | Cutoff, U - CN	2.31E-10	disease incidence
Photochemical oxidant formation: human health	7.64E-04	kg NMVOC-Eq
suction fan	5.77E-04	kg NMVOC-Eq
natural gas venting from petroleum/natural gas production | natural gas, vented | Cutoff, U - GLO	7.13E-05	kg NMVOC-Eq

Name	Impact assessment result	Unit
Water use	7.43E-02	m3 world Eq deprived
suction fan	4.97E-02	m3 world Eq deprived
ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | Cutoff, U - RER w/o RU	7.53E-03	m3 world Eq deprived
ammonia production, steam reforming, liquid | ammonia, anhydrous, liquid | Cutoff, U - RU	6.56E-03	m3 world Eq deprived

3.5 Comparison of the model with other ecoinvent waste incineration model

In order to examine the applicability of this model, it was compared with models for MSWI used by ecoinvent. The ecoinvent model used for comparison is in ecoinvent 3.10 cutoff and the name of the ecoinvent process "treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, U - DE".

Table 3: Comparison of the model with other ecoinvent waste incineration model.

	Ecoinvent		MSWI model by (Ciroth, 1998)	
Product system	treatment of municipal solid waste, municipal incineration | municipal solid waste | Cutoff, U - DE		Combustion process	
Amount functional unit	1 kg municipal solid waste, for incineration		1 kg waste provided by WÜRZBURG AVG WASTE	
Waste composition kg/kg waste	H2O	2.29E-01	H2O	2.75E-01
	O	2.57E-01	O	1.43E-01
	H	4.83E-02	H	4.01E-02
	C	3.34E-01	C	2.92E-01
	S	1.12E-03	S	1.67E-03
	N	3.12E-03	N	1.17E-02
	P	8.94E-04	P	0.00E+00
	B	7.19E-06	B	0.00E+00
	Cl	6.87E-03	Cl	1.03E-02
	Br	1.36E-05	Br	0.00E+00
	F	5.64E-05	F	2.93E-04
	I	1.21E-08	I	0.00E+00
	Ag	7.14E-07	Ag	0.00E+00
	As	6.25E-07	As	5.15E-04
	Ba	1.49E-04	Ba	0.00E+00
	Cd	1.17E-05	Cd	6.36E-06
	Co	1.35E-06	Co	9.45E-06
	Cr	3.15E-04	Cr	2.43E-04
	Cu	1.21E-03	Cu	3.35E-04
	Hg	1.44E-06	Hg	2.26E-06
	Mn	2.59E-04	Mn	1.47E-04
	Mo	1.96E-06	Mo	0.00E+00
	Ni	1.07E-04	Ni	5.91E-05
	Pb	5.02E-04	Pb	3.56E-04

	Ecoinvent		MSWI model by (Ciroth, 1998)	
	Sb	2.26E-05	Sb	0.00E+00
	Se	3.20E-07	Se	0.00E+00
	Sn	7.34E-05	Sn	0.00E+00
	V	9.21E-06	V	1.63E-05
	Zn	1.31E-03	Zn	0.00E+00
	Si	4.85E-02	Si	0.00E+00
	Fe	3.00E-02	Fe	0.00E+00
	Ca	1.41E-02	Ca	0.00E+00
	Al	1.24E-02	Al	0.00E+00
	K	2.06E-03	K	0.00E+00
	Mg	3.38E-03	Mg	0.00E+00
	Na	5.14E-03	Na	0.00E+00
Lower heating value of waste	11.74 MJ		11.8 MJ	
Location	Germany		Germany	

As shown in Table 3, the waste compositions of the two models are different. The waste of the ecoinvent model has some elements that don't exist in the MSWI model like Zn, Fe, Ca, Al, K, Mg and Na, which could cause different impact assessment results. The lower heating value of waste from ecoinvent model and the MSWI model are similar. The incineration in ecoinvent model generates three types of residues: bottom ash, fly ash and scrubber sludge. In comparison to that, the combustion of waste in the MSWI process generates bed ash and boiler ash.
Table 4 shows the results of the ecoinvent waste incineration model.

Table 4: Impact results of impacts of ecoinvent waste incineration model

Name	Impact assessment result	Unit
Acidification	2.91E-04	mol H+-Eq
Climate change	5.19E-01	kg CO2-Eq
Climate change: biogenic	1.91E-05	kg CO2-Eq
Climate change: fossil	5.19E-01	kg CO2-Eq
Climate change: land use and land use change	8.88E-06	kg CO2-Eq
Ecotoxicity: freshwater	1.89E+00	CTUe
Ecotoxicity: freshwater, inorganics	1.82E+00	CTUe
Ecotoxicity: freshwater, organics	6.78E-02	CTUe
Energy resources: non-renewable	3.53E-01	MJ, net calorific value
Eutrophication: freshwater	4.45E-05	kg P-Eq
Eutrophication: marine	1.60E-04	kg N-Eq
Eutrophication: terrestrial	1.37E-03	mol N-Eq
Human toxicity: carcinogenic	5.02E-10	CTUh
Human toxicity: carcinogenic, inorganics	2.10E-10	CTUh
Human toxicity: carcinogenic, organics	2.92E-10	CTUh
Human toxicity: non-carcinogenic	5.77E-09	CTUh
Human toxicity: non-carcinogenic, inorganics	5.76E-09	CTUh
Human toxicity: non-carcinogenic, organics	1.35E-11	CTUh

Name	Impact assessment result	Unit
Ionising radiation: human health	8.19E-04	kBq U235-Eq
Land use	1.88E-01	dimensionless
Material resources: metals/minerals	1.03E-07	kg Sb-Eq
Ozone depletion	6.43E-10	kg CFC-11-Eq
Particulate matter formation	2.70E-09	disease incidence
Photochemical oxidant formation: human health	3.62E-04	kg NMVOC-Eq
Water use	6.83E-02	m3 world Eq deprived

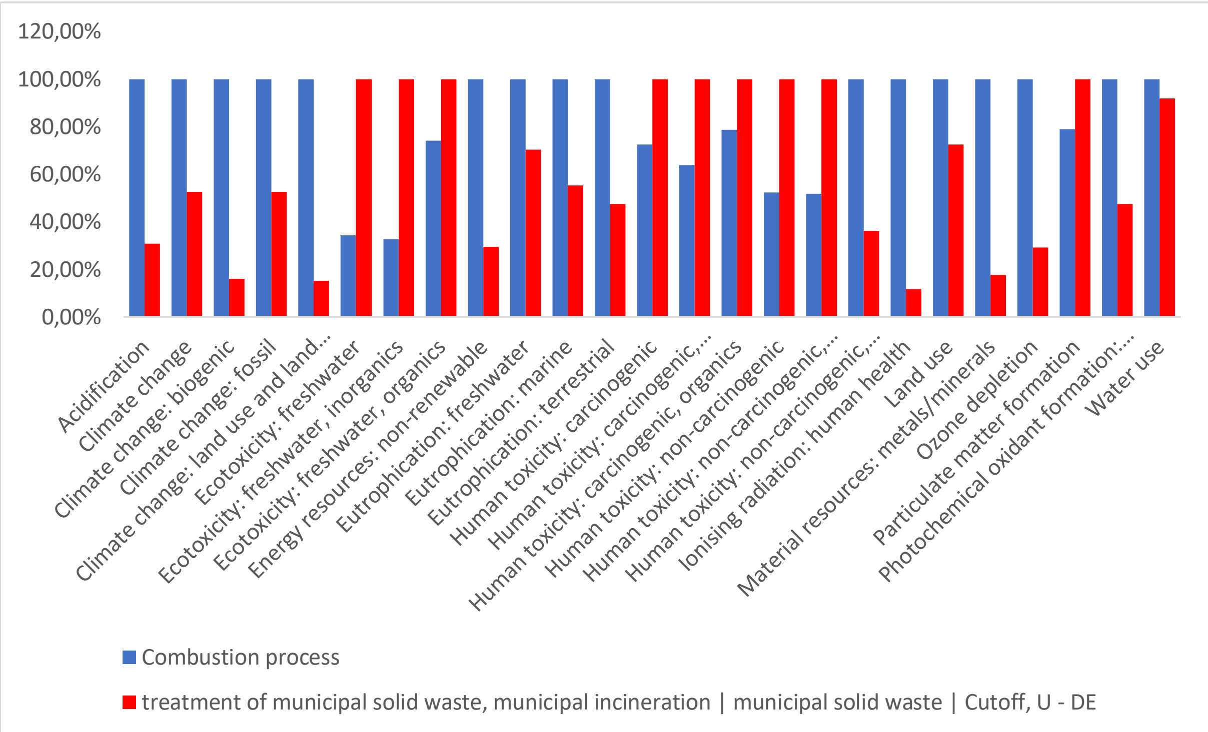


Figure 12: Graphical comparison of impact results of MSWI model and ecoinvent waste incineration model

Figure 12 shows the results of the impact assessment for the MSWI model and ecoinvent waste incineration model. Due to the different composition of the waste, the results of the impact assessment vary. Higher amount of bottom ash and residues are the main reason of ecotoxicity and particulate matter formation. Higher amounts of bottom ash and residues are the main contributors to eco-toxicity and particulate matter formation. The ecoinvent model includes municipal waste incineration facilities, which are not present in the MSWI model, which explains the higher human toxicity of the ecoinvent model. In the MSWI model, electricity production and oil/gas production are the largest contributors to the other impact categories, whereas in the ecoinvent model, residue treatment is always the largest contributor.

4 *Sensitivity analysis*

To represent how the model would react to a changing composition of waste, different scenarios with different parameters are compared in sensitivity analyses.

4.1 Sensitivity analysis: baseline scenario (Würzburg waste) vs. scenario with higher ash content in waste

The data of baseline scenario is from WÜRZBURG AVG WASTE. The ash fraction (0.23 kg/kg waste) in waste is replaced with new value (0.48 kg/kg waste), as shown in Table 5. The treatment processes are assumed to take place in Germany and therefore the distances between the different production stages are omitted. The background data required for electricity production, tap water production and emissions come from ecoinvent. The input and outputs (foreground data) are provided by (Ciroth, 1998) and were connected to the background data from the ecoinvent 3.10 database .

Table 5: Description of scenarios in sensitivity analysis

Parameter	Amount Base scenario	Amount Scenario 1	unit
m_Ash_waste	0.23	0.48	kg/kg waste

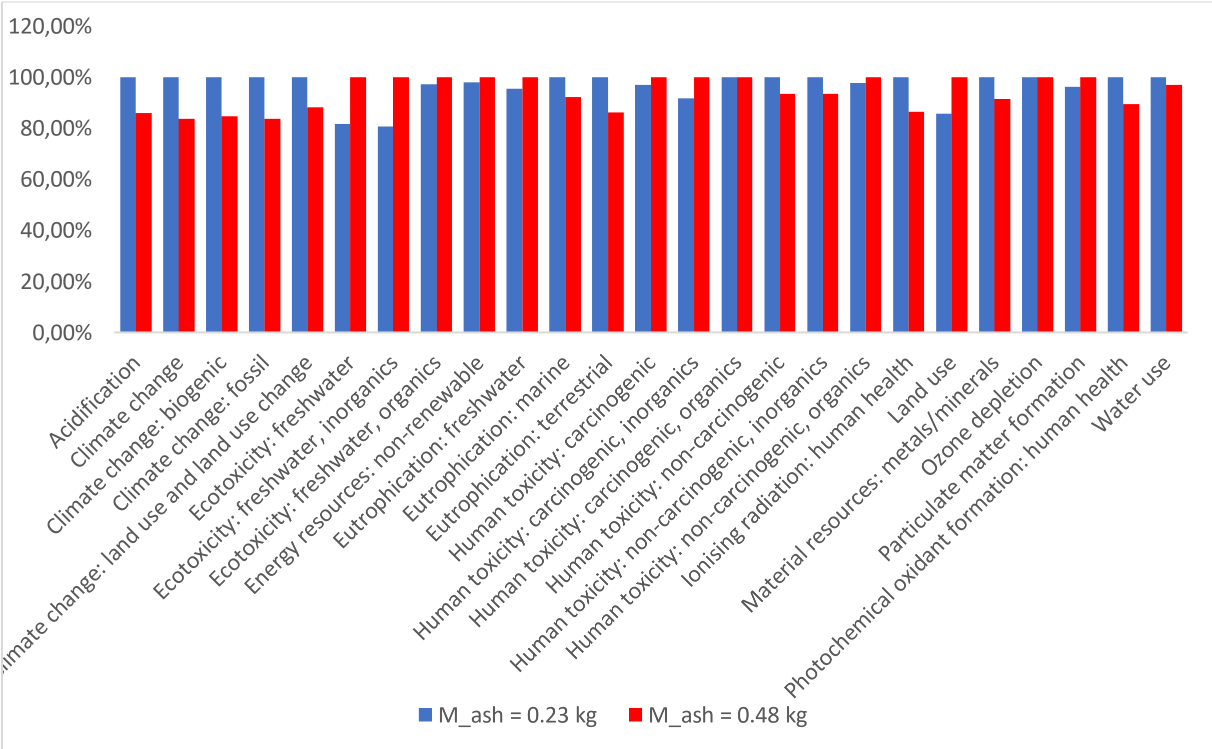


Figure 13: Graphical comparison of impacts of the scenarios in sensitivity analysis

Figure 13 shows the relative results of the scenarios in the sensitivity analysis. As the ash content increases, the amount of residue increases, so the bottom ash treatment contributes more to the impact category. However, if the mass fraction of ash in 1 kg of waste increases, the mass fraction of some of the other problematic elements decreases, which may reduce the emissions of these elements and thus the impact results.

Table 6: Overall results of scenario 1

Name	Impact assessment result	Unit
Acidification	2.98E-03	mol H+-Eq
Climate change	3.25E+00	kg CO2-Eq
Climate change: biogenic	3.73E-04	kg CO2-Eq
Climate change: fossil	3.25E+00	kg CO2-Eq
Climate change: land use and land use change	1.78E-04	kg CO2-Eq
Ecotoxicity: freshwater	7.58E-01	CTUe
Ecotoxicity: freshwater, inorganics	6.11E-01	CTUe
Ecotoxicity: freshwater, organics	1.47E-01	CTUe
Energy resources: non-renewable	3.41E+00	MJ, net calorific value
Eutrophication: freshwater	1.06E-04	kg P-Eq
Eutrophication: marine	8.28E-04	kg N-Eq
Eutrophication: terrestrial	9.16E-03	mol N-Eq
Human toxicity: carcinogenic	3.98E-07	CTUh
Human toxicity: carcinogenic, inorganics	4.99E-11	CTUh
Human toxicity: carcinogenic, organics	3.98E-07	CTUh
Human toxicity: non-carcinogenic	6.85E-09	CTUh
Human toxicity: non-carcinogenic, inorganics	6.75E-09	CTUh
Human toxicity: non-carcinogenic, organics	9.85E-11	CTUh
Ionising radiation: human health	2.20E-02	kBq U235-Eq
Land use	4.62E-01	dimensionless
Material resources: metals/minerals	1.80E-06	kg Sb-Eq
Ozone depletion	6.55E-09	kg CFC-11-Eq
Particulate matter formation	5.06E-09	disease incidence
Photochemical oxidant formation: human health	2.36E-03	kg NMVOC-Eq
Water use	2.42E-01	m3 world Eq deprived

5 Conclusion

This work presents the usage of the MSWI model. The model results were calculated with the method EF 3.1 and compared with the existing ecoinvent model for waste incineration to check the validity of the model. Comparison of the results shows that the two models are comparable, as their impact results do not differ by more than a factor of 10.

In addition, scenarios were investigated to compare the effects of changing certain parameters on the overall results. The usability of the parameters was also demonstrated after sensitivity analyses, as changing a parameter changes the results.

Overall, the model in openLCA offers the possibility to specifically reflect the waste composition of incinerated waste, and thus can be used also in cases where the ecoinvent waste compositions do not apply.

6 References

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