Updates to Life Cycle Inventories of Waste Treatment Services

Part II "Waste incineration"

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Significant digits

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Summary

This work updates the inventory model for municipal solid waste incinerators (MSWI). The previous model (Doka 2003-II) was based on the reference year 2000, the new model is based on most recent available data mostly from 2010-2012.

The MSWI inventories chiefly contain waste-specific emissions based on the **composition of the input waste material** and the use of so called **transfer coefficients** (TK) for chemical elements, like carbon, cadmium, nitrogen etc. The advantage of this approach is that specific characteristics of the incinerated waste material are heeded: if a waste material contains no cadmium, no direct cadmium emissions will be inventoried for this waste. A waste material with high heating value will generate more useful energy than a low-caloric waste. Instead of waste-unspecific disposal inventories for just the *average* kilogram of municipal solid waste mixture, very specific inventories tailored to the specific waste characteristics are generated.

The waste-specific inventories are however very much based on the average incinerator operation (the working point) and for this new data was collected. New, current information on stack emissions, auxiliaries consumption, energy production and internal consumption from Swiss waste incinerator plants was collected. Also new transfer coefficients were taken from literature and a new waste composition for the working point is applied. New information on organic carbon speciation in bottom ash is included. Also recoveries of scrap metals from bottom ash were extended to include aluminium and copper, in addition to iron scrap, which was already heeded before. While formerly energy products were not inventoried and a default share of 100% of the burden was allocated to the disposal function, the new inventories explicitly feature outputs of surplus electricity and heat (based on the waste's heating value). In ecoinvent v3, all by-product outputs of an activity – here useable energy and metal scrap – are listed in the process inventory as explicit exchanges. If and how those by-products are allocated, depends on the system model for the v3 database, which is at the unit process inventory stage undecided. The created unit process inventories presented here are therefore the basis for *several* different inventory results depending on the chosen system model. At the current time (Dec 2013) two system models are available: an attributional (named "default allocation") and a consequential ("consequential long-term").

Further efforts were made in this study to make waste incineration inventories more waste-specific: formerly constant contributions, which had simply been attributed to each kilogram of waste (the so called process-specific emissions) like emissions of carbon monoxide, dioxins, consumption of water and internal energy are now made dependent on waste characteristics, based again on observations of the average operation (working point).

Another aspect of the former inventories was maintained: the distinction of waste into burnable and inert materials. Inert materials are transferred completely into the bottom ash, while for burnable waste a distribution on several output streams (flue gas, wastewater, incineration residues) is calculated. In other words, the incineration inventories not only heed the specific waste composition, but also heed waste characteristics in the applied transfer coefficients (TK), instead of applying just the average incinerator transfer coefficients to all waste materials alike. The applied transfer coefficients are determined in a way so that for an average municipal solid waste mixture the average (working point) transfer coefficients result.

As previously, each inventory also includes the expenditures and waste-specific emissions from landfilling of incineration residues (bottom ash, boiler and fly ashes, scrubber sludge).

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1 Introduction

The goal of life cycle inventories for waste disposal within ecoinvent project is the provide information about the **end-of-life phase of materials**. Just like inventories for the *production* of for instance plastic materials are available in the database, the disposal datasets represent the burdens generated during the *disposal* of a certain material. The goal is to have good background data on disposal of single materials in order to complete life cycle data of those specific materials. The purpose is not to provide information to judge or optimise certain choices in the management of (average) municipal solid waste[1].

First models that calculated waste-specific inventories of disposal in the ETH ecoinvent database were generated by (Zimmermann et al. 1996). In 2003 those models were refined and extended for ecoinvent 2000 (Doka 2003-II). The work presented here is an update and further refinement of those previous models.

With the present model only MSWI activities mostly based on Swiss plants are inventoried. MSWI from other countries are not modelled, though the model probably well represents also modern MSWI plants in Europe, Japan and USA. Within ecoinvent v3 a global (worldwide) dataset of an activity is a prerequisite in order to inventory any country-specific activity (see chapter 4.2.1 'Geographical localisation' in Data Quality Guidelines DQG 2012). As no global detailed inventory model for MSWI is available, a global dataset would have to be approximated from the available Swiss data model. In order to have an explicit Swiss dataset, first a duplicate dataset would have to be created as the global one. In order to avoid unnecessary duplication of data, only a global dataset is created.

[1] This is very similar to the whole vein of the ecoinvent database: the dataset inventorying for instance converter steel production has the chief purpose of providing a good, generic estimate for the burdens associated with the production of 1kg converted steel, and not the intent of helping management choices in the converter steel business. However, outside LCA the *product-specificity* targeted here – the narrow focus on the fate of one single specific waste material within the incinerated waste mix – is a less common aspect in waste management than in industrial production.

2 Updated MSWI Inventory Features

Much of the MSWI inventory calculation structure has been maintained as described in (Doka 2010). A lot of base data was updated and partly calculation structure was altered. These changes are described in the following.

2.1 Incinerator Transfer Coefficients

New transfer coefficients for chemical elements from average MSWI operation are taken from a literature survey. Priority is given to the most recent data from (Taverna 2011) for the Spittelau MSWI. Data from Saner et al. (2010:Tab 11) for a generic wet scrubber incinerator is taken to fill remaining gaps. Some data is taken from Salzmann (2008:Tab 12+13), which features information for the element titanium, which is lacking in other sources. Löschau (2006) features transfer coefficients for boron, beryllium, and silver for the Spittelau MSWI. Data from Ciroth et al. (2002) is not used, as it does not offer any data missing in the other publications, transfer coefficients for effluents are missing in that study and the transfer coefficient data is based solely on a 1998 publication.

No distinction between boiler ash and filter ash output is made in the literature sources. To obtain a distinction, the split up observed in earlier data is used, with some proxy extensions, see Tab. 2.1 (right side) on page 11. The resulting values for average MSWI transfer coefficients ($TK_{average,\ k\ e}$) are shown in Tab. 6.1 on page 33 (where *k* is any of six possible outputs: bottom ash (a.k.a. slag[2]), boiler ash, ESP ash, scrubber sludge, water emissions, or air emissions).

But the *average* transfer coefficients should not be applied directly to calculate outputs from specific waste materials. In the incinerator model, a distinction between inert and burnable waste materials is made. For inert materials it is assumed that they completely go to bottom ash. For burnable materials a new set of transfer coefficients is needed. This new set depends on the on the new average transfer coefficients and also how the chemical elements are distributed between burnable and inert waste fractions in *average* waste. For each chemical element it is specified how much of it in average waste is present in burnable waste fractions. This is $fr_{burnable\ e}$ and is also calculated from data used earlier, provided from Hellweg (2000). See see Tab. 2.1 (left side) on page 11.

I.e. average waste composition (average input = $I_{average\ e}$) is being updated to current values (see 3.1 'Average Municipal Solid Waste' on page 26), but it is assumed that the typical distribution of chemical elements into burnable and inert fractions of the average waste is the same as previously. The index $_e$ in the following formulas is to signify that these calculations are performed for each single chemical element (and H_2O).

Eq. 2.1 $$I_{average\ e} = I_{burnable\ e} + I_{inert\ e} = I_{average\ e} * fr_{burnable\ e} + I_{average\ e} * (1 - fr_{burnable\ e})$$

where

$I_{average\ e}$ = the mass input of element e in average municipal waste, in kg

$I_{burnable\ e}$ = the mass input of element e in burnable waste materials, in kg

$I_{inert\ e}$ = the mass input of element e in inert (unburnable) waste materials, in kg

$fr_{burnable\ e}$ = fraction of element e in average municipal waste that stems from burnable waste, (kg/kg)

As in the previous MSWI model (see Doka 2010-II, chapter 3.2.1 'Differentiation of burnability of waste materials') knowledge of average transfer coefficients ($TK_{average,\ k\ e}$) and of the contributions of

[2] In Switzerland the common name for MSWI bottom ash is slag ("Kehrichtschlacke"), although it is not a high temperature, glassy residue like smelter slag. Landfilling of MSWI bottom ash occurs in a designated part of a sanitary landfill, the slag compartment ("Schlackenkompartiment").

burnable and inert waste parts to each chemical element in average waste ($fr_{burnable\ e}$) allows a calculation of transfer coefficients as applicable to burnable waste fractions ($TK_{burnable,\ k\ e}$).

For inert waste fractions, we simply assume transfer straight into bottom ash, i.e.

Eq. 2.2 $TK_{inert,bottom\ ash\ e} = 100\%$, and $TK_{inert,other\ outputs\ e} = 0\%$

where

$TK_{inert,\ xy\ e}$ = Transfer coefficient of element e in output stream x for inert waste materials, (kg/kg)

For burnable waste fractions, we can calculate transfer coefficients based on mass balances; for bottom ash:

Eq. 2.3 $TK_{burnable,\ bottom\ ash\ e} = 1 - (1 - TK_{average,\ bottom\ ash\ e}) / fr_{burnable\ e}$

and for all other outputs

Eq. 2.4 $TK_{burnable,\ other\ outputs\ e} = TK_{average,\ other\ outputs\ e} / fr_{burnable\ e}$

where

$TK_{burnable,\ [k]\ e}$ = Transfer coefficient of element e in output stream [k] for burnable waste materials, (kg/kg)

$fr_{burnable\ e}$ = fraction of element e in average municipal waste that stems from burnable waste, (kg/kg)

The transfer coefficients for *burnable* waste derived from this procedure are shown in the appendix in Tab. 6.2 on page 34. It turns out that the average waste composition ($I_{average\ e}$) is not really needed here, but that only $fr_{burnable\ e}$ is needed to calculate $TK_{burnable,\ k\ e}$. The average waste composition is however need to calculate the inventory for average waste incineration.

In this way the average transfer coefficients found in literature are converted into two sets of transfer coefficients for inert and burnable waste fractions. As a verification, for *average* waste, these transfer coefficients must give the same results as the average transfer coefficients. For average transfer coefficients, the generated outputs O are:

Eq. 2.5 $O_{k\ e} = I_{average\ e} * TK_{average,\ k\ e}$

where

$O_{k\ e}$ = the mass of element e in output k from average municipal waste, in kg

$I_{average\ e}$ = the mass input of element e in average municipal waste, in kg

$TK_{average,\ k\ e}$ = Transfer coefficient of element e in output stream k for average municipal waste, (kg/kg)

With the inert/burnable distinction, as performed in the model calculation, the results for bottom ash output are as follows:

$O_{bottom\ ash\ e} = O_{burnable,\ bottom\ ash\ e} + O_{inert,\ bottom\ ash\ e}$

$= I_{burnable\ e} * TK_{burnable,\ bottom\ ash\ e} + I_{inert\ e}$

$= I_{average\ e} * fr_{burnable\ e}\ [1 - (1 - TK_{average,\ bottom\ ash\ e}) / fr_{burnable\ e}] + I_{average\ e} * (1 - fr_{burnable\ e})$

$= I_{average\ e} * fr_{burnable\ e} - I_{average\ e} + I_{average\ e} * TK_{average,\ bottom\ ash\ e} + I_{average\ e} - I_{average\ e} * fr_{burnable\ e}$

$= I_{average\ e} * TK_{average,\ bottom\ ash\ e}$ (i.e. identical to Eq. 2.5)

and the results for the other outputs:

$O_{other\ outputs\ e} = O_{burnable,\ other\ outputs\ e} + O_{inert,\ other\ outputs\ e}$

$= I_{burnable\ e} * TK_{burnable,\ other\ outputs\ e} + 0$

$= I_{average\ e} * fr_{burnable\ e} * TK_{average,\ other\ outputs\ e} / fr_{burnable\ e}$

$= I_{average\ e} * TK_{average,\ other\ outputs\ e}$ (i.e. identical to Eq. 2.5)

The calculation model therefore allows the consideration of the burnability of a waste fraction, while at the same time being based on and reproducing the average behaviour of incinerators as shown in the literature data for average transfer coefficients and average waste.

Tab. 2.1 Share of chemical elements in burnable waste fractions of average waste $fr_{brunable\ e}$ (left); share of boiler ash in boiler + filter sah sum (right)

	$fr_{brunable\ e}$	comment	% boiler ash in (boiler + filter ash)	comment
H2O	100.00%	1	0.0%	
O	99.00%	2	16.7%	
H	100.00%	1	0.0%	
C	99.50%	2	0.0%	
S	93.57%		0.0%	
N	100.00%	1	0.0%	as C
P	99.00%	some P will be in bones	21.0%	
B	100.00%	1	25.4%	as Mg
Cl	90.00%	2	0.0%	
Br	100.00%	1	1.1%	
F	100.00%	1	0.0%	
I	100.00%	1	0.0%	
Ag	54.56%	same as Cu	0.0%	as Cu
As	71.85%	same as Se	7.3%	
Ba	24.18%		19.6%	
Cd	98.53%		0.0%	
Co	50.64%	same as Ni	7.7%	
Cr	17.61%		6.7%	
Cu	54.56%		0.0%	
Hg	99.00%	2	0.6%	
Mn	17.61%	same as Cr	7.7%	
Mo	50.64%	same as Ni	16.0%	
Ni	50.64%		35.9%	
Pb	60.38%		0.0%	
Sb	62.42%		2.2%	
Se	95.00%	2	15.3%	
Sn	76.55%		4.2%	
V	17.61%	same as Cr	10.0%	
Zn	74.93%		0.0%	
Be	74.06%	same as Mg	25.4%	as Mg
Sc	-	3	-	3
Sr	-	3	-	3
Ti	61.29%	same as Al	24.7%	as Al
Tl	-	3	-	3
W	-	3	-	3
Si	32.10%		32.4%	
Fe	27.94%		0.0%	
Ca	62.59%		26.8%	
Al	61.29%		24.7%	
K	99.71%		14.4%	
Mg	74.06%		25.42%	
Na	60.00%	2	25.00%	

1 All burnable is reasonable

2 Corrected to avoid negative $TK_{bottom\ ash\ burnable}$

3 The $TK_{average}$ for these elements are missing. Proxy estimates for $TK_{burnable}$ from coal power plant as in Doka 2010 apply.

Since transfer coefficients are ensured to sum up to 100%, all mass balances are adhered to. The ecoinvent database system nevertheless displays a validation warning of violated mass balance[3]. This is prompted by the fact that some waste mass ends up in landfills as ashes and residues. Some further emissions to groundwater occur from the landfills, but even after 60'000 years some mass is expected to remain within the landfill. Since for the purposes of these inventories the landfill is considered part of the technosphere, this material remaining in the landfill can neither be considered an exchange with the biosphere, nor is it transferred within the technosphere. There are no other features within the ecoinvent database system to account for material remaining in landfills.

2.2 Waste-specific combustion air and flue gas volume

The new MSWI model includes a calculation of the combustion air input and the resulting raw flue gas volume. Combustion air input is calculated from oxygen demand to incinerate a waste of a particular composition. For air demand, oxidation to gaseous species is considered[4] as well as oxidation of ash particles. Partial oxidation of bulk metallic iron and aluminium in bottom ash is heeded as well. From the minimal necessary, stoichiometric oxygen demand the real oxygen demand is calculated using an excess air number (lambda λ) of 2, which is typical for MSWI. Total combustion air volume is calculated heeding 21 V-% oxygen in input air and an ideal gas volume R of 22.413 m^3/kmol. The formula for waste-specific calculation of the oxygen demand are in the appendix.

For an average municipal solid waste mixture a combustion air input of 7.17 m^3 and a raw flue gas volume of 7.82 m^3 results. About 5% is due to oxidation of ashes. For other waste fractions, e.g. tin sheet packaging, the oxidation of ashes can become more relevant.

2.3 Nitrogen oxides

NO_x emission from combustion processes are essentially made up of two contributions:

- Thermal-NO_x are nitrogen oxides in flue gas which originate from the reaction of elemental nitrogen N_2 from combustion air during the combustion at elevated temperatures.
- Fuel-NO_x comes from the combusted nitrogen in the fuel.

A current value of 38 mg total NO_x per Nm^3 flue gas (cf. Tab. 6.4 on page 37) is the base figure for average operation conditions, from which either kind of NO_x emission is attributed to the properties of a specific waste material. As in the previous modelling, it is assumed that in an average MSWI operation, thermal-NO_x makes up 50% of flue gas emissions.

Both kinds of NO_x also require abatement measures in the DeNOx stage and related expenditures, like inputs of ammonia solution, natural gas, or catalyst materials – depending on applied technology.

2.3.1 Fuel NOx

As in the previous modelling, the fuel-NO_x part is attributed to the nitrogen contained in waste; or more precisely to the *nitrogen from fuel that arrives in the raw flue gas* (without the nitrogen removed previously to slag or ashes). From figures representing average operation of the MSWI with average waste, metrics are derived that relate the emissions and expenditures associated with fuel-NO_x to a unit

[3] The warning reads "Mass [...] deficit in activity dataset exceeds either 0.1% of input or output sum".

[4] For gaseous halogens not oxidation, but conversion to the *halogen acids* (HCl, HF etc.) is considered. This requires hydrogen from the waste matrix, which is subtracted from the hydrogen being oxidised to gaseous H_2O. So presence of halogens actually *reduces* oxygen demand, combustion air input, and flue gas output. For example 1 kg of polyethylene requires 20.9 m^3 of combustion air input, while 1 kg of polyvinylchloride (47.5w-% Cl) needs only 11.1 m^3 air.

of nitrogen in the raw flue gas. These figures can then be used to calculate the waste-specific emissions and expenditures associated with fuel-NO_x. Apart from the ultimate NO_x emission itself, they are emissions of ammonia, nitrous oxide (N_2O), Cyanide, and expenditures needed in DeNOx for abatement of fuel-NO_x.

2.3.2 Thermal NOx

Thermal-NO_x generation depends entirely on combustion air and elevated temperatures. In this study, the contribution of thermal NO_x and the expenditures for its removal in DeNOx processes[5] caused by the incineration of a particular waste fraction is assumed to be proportional to the *input of combustion air* necessitated by that waste fraction.

For average MSW, a value of 7.17 m^3 combustion air input per kg is calculated, including an air excess number λ lambda of 2. Waste materials with larger combustion air input will have proportionally larger burdens from thermal NO_x, while waste materials not requiring combustion air, like glass, will have no burdens from thermal NO_x. In the inventory, the emissions and expenditures from thermal NO_x are summed up with those for fuel-NO_x, and are not devised separately.

2.4 Dioxin Emissions

In the past, especially in the 1970s and 80s, Swiss MSWI have been the dominant source of dioxin emissions in Switzerland (BUWAL 1997). Swiss MSWIs have much improved in this respect. The low dioxin emissions of Swiss MSWI have been further reduced in the last decade. Dioxin emissions factors are mostly determined by combustion conditions. Elevated temperatures and homogenous combustion conditions reduce the probability of dioxin formation. Data from German MSWIs suggests however that there is considerable variation in dioxin emissions factors over three orders of magnitude reflecting a wide range of combustion conditions (Löschau 2009:Tab 3).

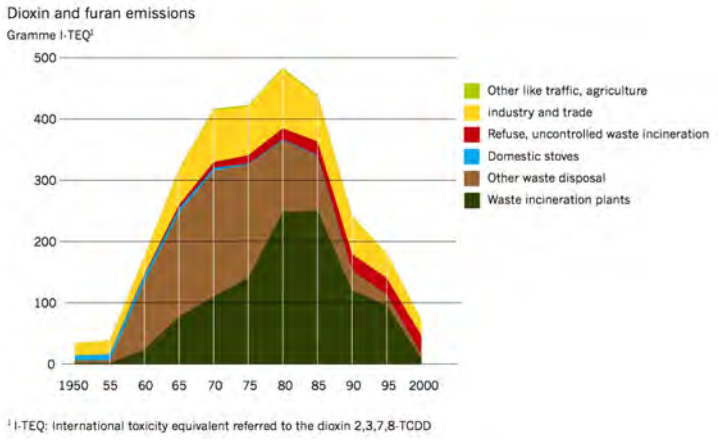

Fig. 2.1 Total Swiss dioxin and furan emissions 1950-2000 (adopted from BFS 2002:143)

In 2007 the Swiss Federal Air Pollution Control Regulation (LRV) introduced a new threshold limit value for dioxins for waste incineration of 0.1 ng I-TEQ/m3. Current major source of dioxin emissions are now households (illegal burning of waste, wood furnaces and fireplaces).

The past pollution profile has led to a persisting bad image of waste incinerator plants, especially in the environmental community of the USA. While it is probable that inferior MSWI performances

[5] Expenditures from DeNOx are inputs of ammonia, natural gas and DeNOx catalyst materials, as well as minor emissions of ammonia to air.

regarding dioxins still exist in the world, for the current study which focuses on Swiss MSWI, the observed low emission factors for Swiss plants are employed.

Literature values of recent air pollutant measurements in Swiss MSWIs are compiled in Tab. 6.4 on page 37. For average operation with average municipal waste a value of 0.01 ng/m3 is chosen for this study[6]. This value also matches the one given by Hans-Peter Fahrni, director at BAFU, the Swiss EPA, for waste and resources, for modern MSWIs (Fahrni 2006). With an average flue gas volume (dry, 11% O_2) of 6.849 m^3 per kg average municipal waste a base emission of 0.06849 ng per kg average waste results. This value is further processed depending on waste fraction characteristics as outlined in the chapter 2.5.2 'Attributing incomplete combustion products to waste material characteristics' on page 14.

2.5 Incomplete combustion products

2.5.1 Working point emissions of PM10, CO, VOC in average operation

Recent emission values in average MSWI operation (cf. Tab. 6.4 on page 37) indicate emissions of

- 0.6 mg particulates (PM_{10}) per Nm^3 flue gas
- 0.3326 mg VOCs per Nm^3 flue gas
- 8.5 mg carbon monoxide CO per Nm^3 flue gas

With a dry flue gas volume of 6.849 Nm^3 per kg average waste, these values can be converted to emissions per kg average waste.

As previously, the particulates are divided into 99.5% $PM_{2.5}$ and 0.5% $PM_{2.5\text{-}10}$. The VOC parameter is divided into individual components and a remainder NMVOC, using the old profile. The emissions derived this way are not modelled to be constant per kilogram of any waste (process-specific), but are made dependent on combustibility of the material. See next chapter.

2.5.2 Attributing incomplete combustion products to waste material characteristics

Emissions of carbon monoxide CO and organic compounds (NMVOCs, benzene, dioxins and others) originate from burnable materials, which are incompletely combusted due to heterogeneities in all or either of the following boundary conditions of operation: combustion temperatures, fuel/oxygen mixing ratios, fuel residence times (see e.g. Nussbaumer 2006:180ff.). These heterogeneities can result from combustion technology and process conditions alone, but incombustible waste material – like glass, metals, bones, ceramics – amplifies their occurrence. So the emission of incomplete combustion products in average incinerator operation can be seen as being caused by combustible waste on one hand, but to a certain extent simultaneously also on the presence of incombustible materials and also the applied technology. This study seeks to inventory emission attributable to the combustion of distinct waste fractions, like one kilogram of plastic or one kilogram of tin sheet. So how can the emissions of incomplete combustion products from average MSWI operation be attributed to a specific waste material?

For this study, a generic estimate was attempted, how low the emissions could be, if only well burnable waste were incinerated. A comparison with emissions from hard coal power plants was used,

[6] For plants without any DeNOx process a value of 6 ng/m^3 is retained. Although that option is not part of the current *Swiss* MSWI technology mix, it might be relevant in other regions.

based on mass of fuel input[7] (Dones et al. 2007, Tab 9.48, p.138). For relevant VOC species and CO it was found that the coal power plant has only 44% to 85% of the emission levels of a waste incinerator. A value of 62% for sum NMVOC is found, which is practically identical to the unweighted arithmetic mean for all species. This finding is taken to imply that if a waste incinerator would only incinerate burnable waste without any incombustible materials like glass or bulk metals, the emission levels of organic compounds and CO would be 62% compared to average waste. This seems like a fair estimate for the emissions attributable to a well combustible waste material. With higher burnable content of the waste lower VOC emissions are attributed; while higher incombustibility – low content of burnable material – bears higher VOC emissions. The characteristics of incombustibility vs. combustibility of a waste are taken to be represented by the amount of raw flue gas volume a particular waste fraction causes in the combustion process (with the unit m^3 gas/kg waste). The scheme below summarises the new modelling of incomplete combustion products.

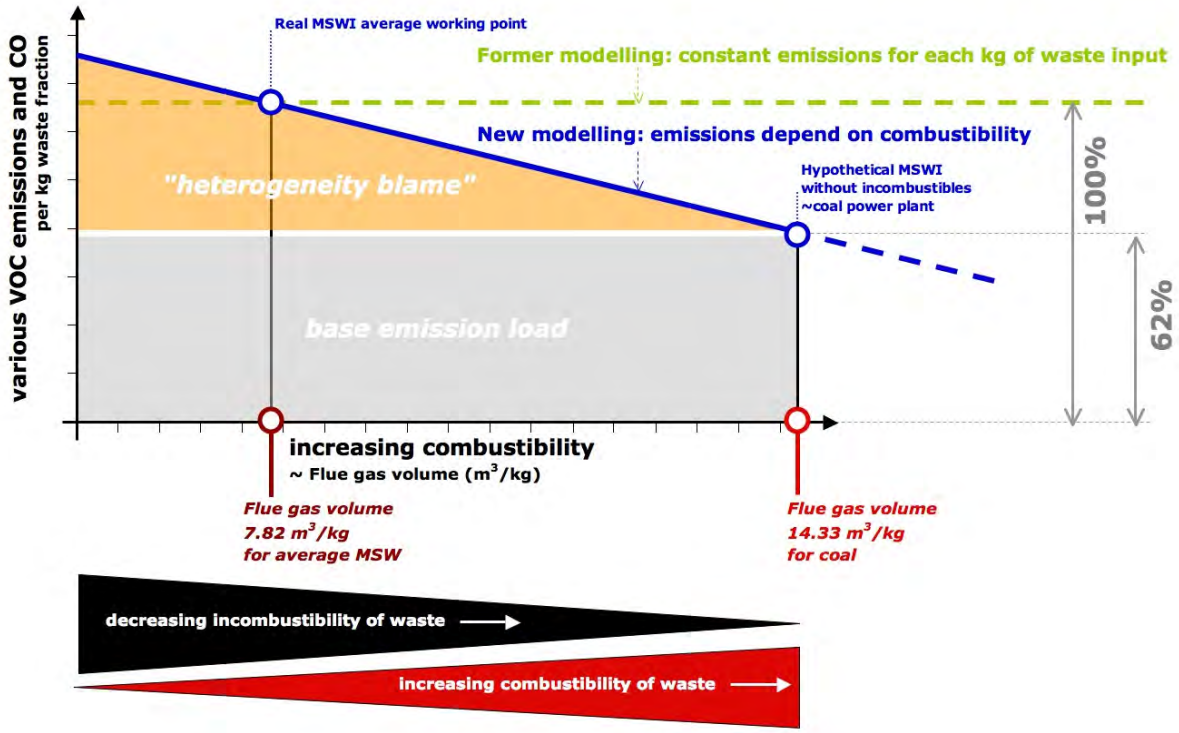

Fig. 2.2 Scheme of the new modelling of incomplete combustion products depending on combustibility of a waste materialThe new model is based on two points marked with blue circles: The emission level from average MSWI operation (left, 100% emission level) and the reduced emission level when only combustible material is incinerated (right, 62% emission level). The waste characteristic of "combustibility" is translated into the metric "specific flue gas volume" (x-axis): for the left point the raw (unnormalised, actual, wet) flue gas volume from average MSW is taken (7.82m^3/kg waste); for the right point raw flue gas volume from combustion of hard coal in MSWI is taken (14.33m^3/kg coal)[8,9]. A simple linear relationship through these two points assumed,

[7] Coal is chosen as proxy for a "well burnable fuel" since it is a solid fuel much like municipal solid waste. Even the best solid fuel introduces phase heterogeneities into the furnace, i.e. itself. Furthermore, coal power plants and waste incinerator technologies are rather similar. With the metric "kg emission per kg fuel" the air excess number has no influence, as opposed to using "kg emission per m^3 flue gas".

[8] These figures both include an air excess number (Λ lambda) of 2, appropriate for MSWIs.

[9] The issue of "combustibility" as used here shall not be confused with the discrete grouping of waste materials into inert (burnability=0) and burnable (burnability=1) materials during the definition of waste material compositions (see Doka 2010, →

representing the decrease of attributable emissions with increasing combustibility[10]. The inventoried emissions can be thought of being caused by a base emission (grey box "base emission load") and a variable component representing the combustibility of a waste fraction (orange triangle "heterogeneity blame"). The level of emissions attributable to an investigated water fraction within average MSWI operation is calculated with the following formula:

Eq. 2.1 $$emission\ level = 62\% + \frac{V_c - V_i}{V_c - V_m} \cdot (1 - 62\%)$$

where

V_c = specific flue gas volume for hard coal, 14.33 m^3/kg

V_i = specific flue gas volume for the investigated waste fraction, in m^3/kg

V_m = specific flue gas volume for average municipal solid waste, 7.82 m^3/kg

Hard coal has a fair amount of ash (5.25 w%)[11], so it still has some residual "incombustibility". Within the MSWI model, waste fractions with even larger flue gas volumes are possible. Polyethylene has the largest specific flue gas volume of the investigated fractions (21.6 m^3/kg, 1 w-% ash). It therefore receives only 18.7% of the average MSWI emission levels of VOC and CO species. The calculation of the emission level for polyethylene is exemplified below.

Eq. 2.2 $$62\% + \frac{14.33 - 21.6}{14.33 - 7.82} \cdot (1 - 62\%) \quad = 62\% + (-1.14) \cdot 38\% \quad = 18.7\%$$

Some CO is also assigned to wastes without any carbon in them. In ecoinvent CO emissions must be distinguished according to fossil and non-fossil carbon. Usually this is based on the carbon present in the waste. For wastes without carbon the question arises, what fractionation for CO should be employed. In order to adhere to the 100% rule, the distinction is based on average municipal waste, i.e. 60.4% non-fossil carbon.

2.6 DeNOx stage

2.6.1 DeNOx technology mix

The MSWI model distinguishes four different kinds of DeNOx-Technologies. For the present inventory a Swiss average technology mix is assumed. The technology mix was updated to figures

chapter 3.2.1 'Differentiation of burnability of waste materials'). For burnability only two values are possible: zero and one. But here "combustibility" is taken to be represented by a *continuous* variable, as expressed with the generated flue gas volume of a waste fraction. So there is a continuum of possible values for combustibility, which however cluster around two values of 0 m^3 for materials put into the inert class, and of 4 - 22 m^3 for materials put into the burnable class.

[10] At the other end of the spectrum, a completely incombustible waste fraction, like glass, receives an elevated level of emissions of about 145% of the average MSWI operation level. Keep in mind that the inventory represents the emissions attributable to a specific waste fraction, when burned in an average MSWI *together with average municipal solid waste*. So a specific flue gas volume of zero does not mean that *all* the input to the incinerator is inert. Burnable materials are co-incinerated with the investigated inert waste fraction. The latter causes more heterogeneities and is attributed an elevated level of those emissions.

[11] This ash figure is only indicative and must be understood as a coarse characterisation of the waste composition. It is the simple sum of elements in waste which are not atmophile during combustion (atmophile elements are C, H, O, N, S, halogens and any water). This ash figure excludes any weight increases from air oxygen uptake during combustion and therefore cannot be larger than 100%. In reality also some atmophile elements can end up in residual ashes, like carbon in slag.

derived from 2007 data given in (BAFU 2008:102ff.). A mix weighted with waste treatment capacity was calculated. The figure for SCR (75.5%) was divided according to the former split into low-dust SCR and high-dust SCR.

Tab. 2.2 Former and new DeNOX technology mix in the MSWI model.

	ecoinvent v1.0-2.2 representing the year 2000	**This study** most recent data (2007)
Without Denox	13.8%	**0.0%**
SNCR	29.4%	**24.5%**
SCR-high dust	32.2%	**42.8%**
SCR-low dust	24.6%	**32.7%**

The different DeNOX technologies influence the final air emissions of NO_x, ammonia NH_3, nitrous oxide N_2O, as well as the auxiliary inputs of natural gas, ammonia, and catalyst materials (TiO_2 + V_2O_5). Waste-specific emissions depend on the amount of nitrogen entering the flue gas, while emissions connected to thermal NO_x depend on the waste-specific combustion air input (see previous chapter).

2.6.2 Inputs to DeNOx

A current mean amount of 2.796 g ammonia solution (25 %) per kg average waste (cf. literature compilation in Tab. 6.5 on page 38) is used as a base figure, which equals 0.699 g of 100% ammonia. According to the specific inputs used earlier, this is split up to represent 0.9339 g NH_3 for SNCR and 0.6226 g NH_3 for SCR technology.

The base figures for natural gas input and catalyst materials are not changed.

According to the technology mix, the fuel nitrogen in raw flue gas (for fuel-NO_x) and the required combustion air (for thermal-NO_x) these inputs are attributed to a specific waste (cf. chapter 2.8.3 'Internal energy redistribution' on page 21)

2.7 Waste-specific ancillary materials

Base data for inputs of ancillary materials and distribution onto material flows in the flue gas scrubber is updated to recent values, based on a survey of available plant reports.

Tab. 2.3 Input of ancillary materials during average MSWI operation

Solution	**Concentration**	**Input of diluted solution g/kg waste**	**as 100% solution**
NaOH	30%	3.74	1.122
CaO	95%	3.45	3.2775
HCl	30%	0.191	0.0573
FeCl3	40%	0.149	0.0596
TMT 15	15%	0.0856	0.0128
Polyelectrolyte	[1]	0.218	0.218
Ammonia for DeNOx	25%	[2]	
water	100%	1390	1390

1 Dilution in use unknown

2 cf. chapter 2.6.2 'Inputs to DeNOx' on page 17

Firstly, a stoichiometric amount of NaOH is allocated to sulfur in the scrubber, i.e. 2.5g (pure) NaOH per kg S in scrubber. In average operation, an amount of 0.496 g NaOH per kg waste is therefore soley allocated to S in scrubber. The remainder of NaOH (1.122 – 0.496 = 0.626) is allocated to the acid formation potential of certain elements in the scrubber (N, P, Cl, Br, F, I) and individual specific consumption figures for these elements are calculated (Tab. 2.4, 5th column). Since the total NaOH input during average operation and the average waste composition has changed in the update, new specific consumption figures result.

The allocation of the other inputs is rather straightforward: consumption of a material during average operation is attributed to one or several allocands in the scrubber stage, as specified in columns 2 and three in Tab. 2.4 below. For instance hydrogen chloride (HCl) is used in small amounts to regulate the pH of the wastewater from the scrubber stage. The HCl consumption during average operation is 0.0573 g pure HCl per kg waste (Tab. 2.3, 4th column). This is set in relation to the total mass of all elements in the scrubber during average operation. The latter is calculated using an average waste input and transfer coefficients and comes to 4.921 g/kg waste (Tab. 2.4, 4th column). From this a specific consumption factor of 0.01164 kg HCl per kg mass in the scrubber stage is calculated (Tab. 2.4, 5th column; 0.01164 = 0.0573 / 4.921). This consumption factor is then applied to a specific waste composition using the mass arriving at the scrubber as calculated from the wastes composition and transfer coefficients. For other auxiliaries not mass, but other metrics like acid formation or mols can be employed too, as indicated in Tab. 2.4, 3rd column.

Tab. 2.4 Synopsis of the allocation of auxiliary material consumption to various allocation recipients.

Allocated material	**Allocation recipient (in scrubber)**	**Allocation key**	**Mass of allocation recipient in scrubber during average operation** Grams / kg waste	**Specific consumption factors of auxiliary materials** kg per kg allocation recipient in scrubber
NaOH	S	mol	0.1982	2.5
	N	acid production	0.003167	0.3863
	P	acid production	0.00439	0.3489
	Cl	acid production	4.001	0.1526
	Br	acid production	0.0414	0.06769
	F	acid production	0.03671	0.2847
	I	acid production	0.000008278	0.04262
CaO	N	acid production	0.003167	2.021
	P	acid production	0.00439	1.825
	Cl	acid production	4.001	0.7982
	Br	acid production	0.0414	0.3541
	F	acid production	0.03671	1.489
	I	acid production	0.000008278	0.223
HCl	all elements [1]	mass	4.921	0.01164
$FeCl_3$	all toxic (semi)metals [2]	mass	0.027	2.207
TMT 15	Hg	mol	0.0003757	28.65
	Cd	mol	0.00004061	51.13
Polyelectrolyte	all elements [1]	mass	4.921	0.0443
Water	all elements [1]	mass	4.921	282.47

1 Mass of all elements removed in scrubber, but excluding H_2O, H, O

2 Ag, As, Ba, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, V, Zn, Be, Sc, Sr, Ti, Tl, W

2.8 Energy production and internal consumption

2.8.1 Gross efficiency of energy production

Waste incinerators can produce usable heat and electricity from the incinerated waste. Boilers produce steam, which can be fed into district heating systems. Steam can also be converted into electricity with steam turbine generators and fed into the electricity grid.

On average operation, Swiss MSWI convert 15.84% of the lower heating value of the input waste into electricity and 28.51% into usable heat (data for 2011 from Binggeli & Hügi 2012). The remainder of 55.7% is waste heat.

These are the values for an average Swiss MSWI plant in 2011. An individual plant can have quite different efficiencies with more electric production in exchange for less heat production, or vice versa. The range of encountered values is shown in Fig. 2.3.

The development 2000 to 2011 lead to all plants producing electricity *and* heat simultaneously, while in 2000 there where plants who would only produce either. A shift to higher efficiencies (red line) is evident. In that time, gross heat efficiency has increased by 4.11% (from 24.4% to 28.51%) and gross electric efficiency has increased by 2.84% (from 13% to 15.84%).

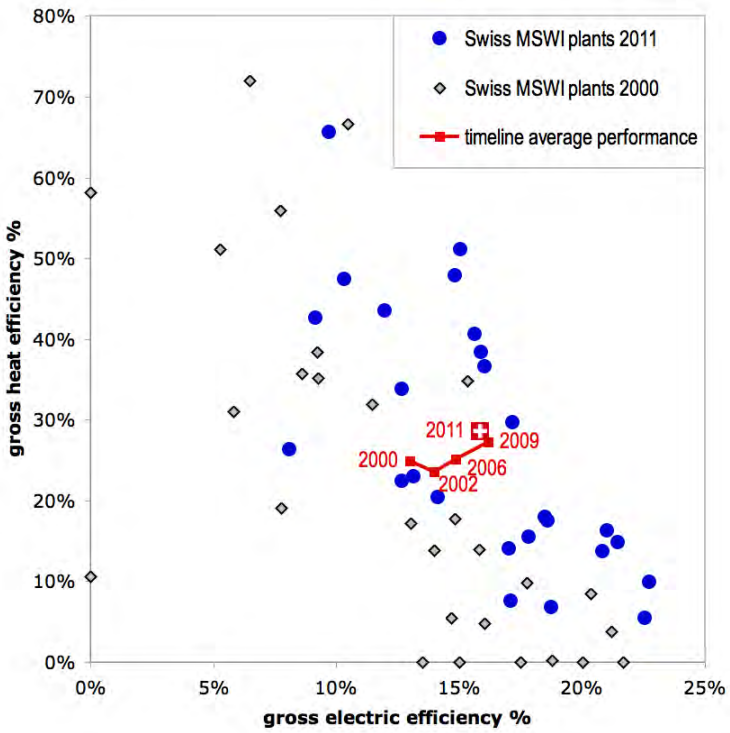

Fig. 2.3 Gross energy production efficiencies of Swiss MSWI plants in 2011 (●) and in 2000 for comparison (◇). The development of the average performance is shown as red line with years indicated (–■–)

2.8.2 Internal energy consumption

Some of the produced gross energy is needed to run the incinerator operation. This internal energy consumption of heat and electricity is deducted from the gross energy production of a waste and results in the net energy production.

In the former inventories, the internal energy consumption was simply a constant amount per kilogram of waste. This is changed here to a variable amount depending on the waste characteristics and causalities for internal energy consumption.

For instance, a large part of internal electricity consumption is caused by suction fans of the flue gas purification stage. Accordingly, a waste which does produce no or little raw flue gas requires less internal electricity than an average waste. Similarly, internal heat is needed to heat up combustion air. For instance glass waste will need no combustion air and therefore no internal heat, as opposed to a burnable waste. Table Tab. 2.5 shows the distribution of internal energy demand to causes.

Tab. 2.5 Contribution to internal energy demand in MSWI, based on MSWI Niederurnen, Linthgebiet (Egli 2005)

Internal electricity demand [1]		**Waste-related cause**
Flue gas treatment	46.4%	Raw flue gas volume [2]
Steam generator	20.6%	Lower heating value
Combustion chamber	11.3%	Combustion air input [3]
Waste handling and shredding	7.2%	Waste mass input
Auxiliary facilities	7.2%	Waste mass input
Building services	5.2%	Waste mass input
Wastewater treatment	2.1%	Mass arriving in wastewater treatment
Internal heat demand [4]		**Waste-related cause**
Air pre-heating	100%	Combustion air input

1 Data from (Egli 2005, p.10). 3% for sludge incineration was distributed pro rata.

2 Largest originators are flue gas suction fans, electro-static precipitation filters (EPS) and pumps for wet flue gas treatment (Egli 2005, p.15/16).

3 Largest originator is the combustion air processing (Egli 2005, p.14).

4 Any internal heat demand is attributed here to combustion air pre-heating (without natural gas input for DeNOx)

Tab. 2.6 Attribution of internal energy demand in MSWI model

	Allocation	Internal energy demand per kg average waste	Allocands in average waste		Specific internal energy demands
Total average internal electricity demand [1]		**0.1273 kWh/kg**	**unit /kg waste**	**unit**	**kWh/unit**
Flue gas treatment	46.4%	0.05905	7.78	m3 raw gas volume	0.007586843
Steam generator	20.6%	0.02622	11.7	MJ LHV	0.00224072
Combustion chamber	11.3%	0.01438	7.13	m3 combust air input	0.002015765
Waste handling and shredding	7.2%	0.00916	1	kg waste input	0.009163024
Auxiliary facilities	7.2%	0.00916	1	kg waste input	0.009163024
Building services	5.2%	0.00662	1	kg waste input	0.006617739
Wastewater treatment	2.1%	0.00267	0.0057	kg in wastewater treatment	0.472728746
Metals recovery	–	–	–	recovered metals from bottom ash [2]	0.04167
Total average internal heat demand [1]		**0.4853 MJ/kg**			**MJ/unit**
Air pre-heating	100%	0.4853	7.13	m^3 combust air input	0.068018848

1 Data for 2011 from Binggeli & Hügi 2012

2 0.04167 kWh per kg recovered metals corresponds approximately to 0.0004638 kWh/kg average waste, i.e. negligible contribution in *average* operation, but relevant contribution for metallic waste materials like tin sheet.

2.8.3 Internal energy redistribution activity

Swiss waste incinerators are energetically autonomous, meaning that in average operation with *average* waste, they do not require any electricity or heat inputs from commercial grids, but are net producers (an exception is the input of natural gas for low-dust SCR, which is heeded separately from the waste-to-energy balance).

This study primarily inventories several non-average, *individual* waste materials. Some of those waste materials might require a net energy *input*, if they do not have a heating value large enough to produce the energy needed for their treatment, e.g. glass, metals, very wet wastes, or other low-calorific waste materials. Within the framework of this model, this means that the energy needed for such waste fractions is supplied by *other* waste fractions with positive net energy production, it is not supplied by consumption of grid energy, since in reality there is no input from commercial grids to the incinerator plant. This represents a sort of "cross-subsidy" of low-calorific wastes by high-calorific wastes. This can also be seen as an example of a form of closed-loop recycling, where a recycled good – the useful energy – is used internally by the same activity. But since what in reality are only virtual sub-parts of the whole incineration activity are made into individual process inventories for the various waste materials in this study, the sources and sinks of the recycled good have to be made explicit also in the inventory.

In order to inventory this situation appropriately, two exchanges for the internal MSWI energy products (electricity, heat) are used, which allow the correct, process-internal sourcing for the energy supply required for low-calorific wastes. The exchanges

- "electricity, municipal waste incineration" and
- "heat, municipal waste incineration"

are used for the energy by-products (outputs) of the incineration of sufficiently high-calorific wastes. These same exchanges will be used as inputs for any necessitated internal energy inputs for the disposal of individual low-calorific wastes. In order to connect any remaining energy to the *external* energy market, two additional activities

- "electricity from incineration to generic market for electricity, medium voltage" and
- "heat from incineration to generic market for heat, district or industrial, other than natural gas"

are created, which merely change the name of the energy products to their generic-market counterparts. These "name changer" datasets can be though of being located at the boundary of the MSWI operation (cf. Fig. 2.4 on the right). For electricity the generic-market exchange counterpart is "electricity, medium voltage"[12]; for heat it is "heat, district or industrial, other than natural gas".

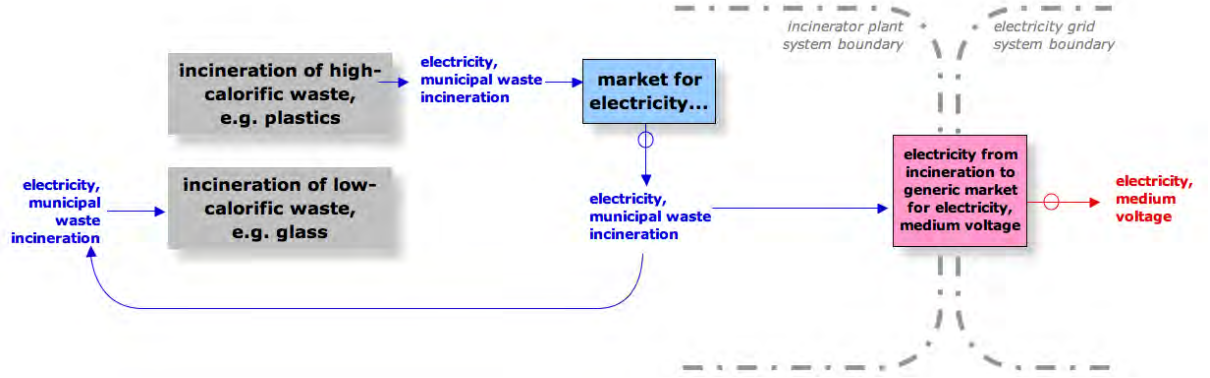

Fig. 2.4 **Scheme of internal electricity redistribution between incineration datasets for high- and low-calorific wastes (left) and the "name changer" dataset for release to external grid market (right). "electricity, municipal waste incineration" (blue exchange) is the exchange for the internal electricity product ; "electricity, medium voltage" (red exchange) is for the produced net energy product. Analogous redistribution for internal heat product.**

The previous text describes the physical reality of the process: low-calorific wastes reduce the net energy production of the incinerator and net energy production is fed into the generic-market grids. This also reflects the modelling used for an *attributional* System Model.

For the use in a *consequential* System Model additional features must be introduced. In a consequential approach the internal redistribution of energy within the MSWI can be modelled like a constrained market. This means that the market dataset in Fig. 2.4 (blue dataset box) must be constructed as a constrained market. A conditional exchange is introduced in the market dataset, which will only be active, if the System Model is consequential, and not in other System Models. This conditional exchange is an negative output (output with negative amount) and also an activity link to the "name changer" dataset ("electricity from incineration to generic market for electricity, medium voltage").

[12] Acording to (Dettli 2004:58) the new Swiss MSWI plant in Posieux, built in 2002, produces medium voltage electricity (60kV), not high voltage. It is assumed that this applies also to other MSWIs.

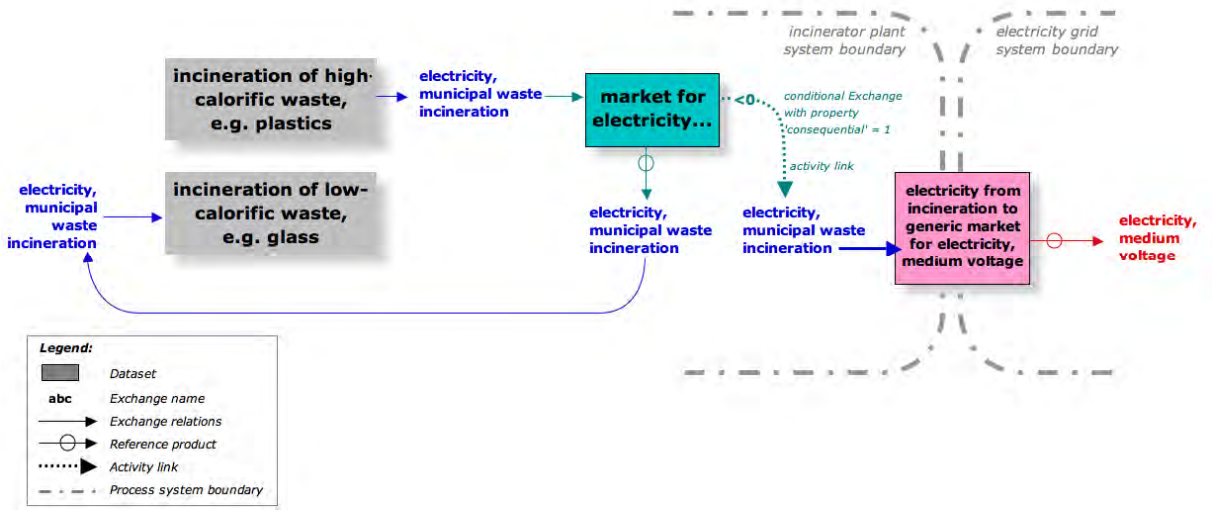

Fig. 2.5 **Extended scheme of internal electricity redistribution for a consequential System Model. The (constrained) market (blue-green box in centre) contains a conditional activity link to the "name changer" dataset for release to external grid market (right).**

The global production volumes for the net energy from MSWI fed into the generic markets are estimated. A worldwide mass of 200 million tonnes of municipal solid waste incinerated in waste-to-energy plants for 2010 is given in (Pike 2010). Using the modelled Swiss MSWI net efficiencies for consistency, this results in 77.5 TWh electricity and 570 petajoules heat as annual production volumes.

2.9 Metal scrap removal from bottom ash

The BAFU (2008:96) reports that in 25 of the 29 MSWI of 2006 some sort of descrapping of bottom ash is done either at the plant site and/or at the bottom ash landfill site. Not only magnetic iron is removed, but also non-ferrous metals. In 2006 the Swiss MSWI recovered approximately 58% of metallic iron from bottom ash, and 31% of the non-ferrous metals (BAFU 2008:45).

These figures are used here to calculate removal of iron, aluminium and copper from bottom ash of waste fractions. With the indication of how much of the contained iron, aluminium and copper is in a well recyclable (bulky and metallic) form, together with the elemental masses of the given waste fraction composition data ending up in raw, untreated bottom ash, and the above removal efficiencies the masses of removed iron scrap, aluminium scrap, and copper scrap can be calculated.

The descrapped bottom ash is sent on to landfill. The recovered scrap is inventoried as output (the exchanges "iron scrap, sorted, pressed", "aluminium scrap, post-consumer, prepared for melting", and "copper scrap, sorted, pressed" are used).

For instance, if a waste contains 80% copper which is indicated to be 100% recyclable, a mass of 248 grams copper scrap (=80%·31%) per kg waste can be recovered. The total mass and the copper content of landfilled bottom ash is accordingly reduced.

Ideally, heterogeneous waste materials should be divided up into an inert and a burnable part. Recyclable metal scrap is usually largely inert, so there should be no burnable waste materials with recyclable metals in them. Concerning the differentiation into inert and a burnable waste see also bullet 7 in chapter 6 'Calculation manual' (Doka 2010) and also chapter 3.2.1 'Differentiation of burnability of waste materials'.

2.10 Carbon in bottom ash

Bottom ash from municipal waste incinerators contains typically 9000 – 18'000 ppm carbon[13]. Approximately half of this amount is inorganic carbon mostly in the form of carbonates (CO_3^{2-}). Total Inorganic Carbon (TIC) represents the non-organic carbon present[14]. The remaining carbon is termed Total Organic Carbon (TOC). TOC is made up from carbon in chemical compounds with covalent C-C or C-H bonds, which includes Elemental Carbon (EC, graphite and soot)[15]. The total carbon content (TC) is made up from TOC + TIC.

In past versions of the ecoinvent waste incineration model, any carbon in bottom ash was assumed to be 100% *organic* carbon, neglecting the inorganic carbon part. In the landfill (slag compartment) the carbon was assumed to lead to TOC emissions. The model is now changed, so that only the organic part in total carbon leads to TOC emission in the slag compartment landfill model. The TIC part is assumed to be harmless and is not inventoried as emission. The slag compartment landfill model is modified to be based on a lower organic carbon content of landfilled materials.

2.11 Water outputs

In order to assess consumptive water use properly in LCIA, any water outputs from the process must be included in the inventory.

The two principal water outputs of an MSWI are the water vapour released in flue gas and the water effluent in wastewater releases. A smallish amount of water is removed in humidity in bottom ash. Calculations in Morf (2006:88) show that large contributions to the total water stream though the MSWI come from *incinerated hydrogen* in waste and *waste humidity* on one hand and the process water added to flue gas scrubbers on the other hand. He also shows that the water outputs via wastewater effluent is only about 31% – 38% of the process water input. I.e. on average, some 65.7% of process water are evaporated to flue gas.

For the MSWI process, water from the incinerated waste material itself is assumed to be released completely to air via flue gas. Some process water is removed in humidity in bottom ash (waste-specific mass; for average waste this is only 3.6 w% of process water input). Based on the above information, the 65.7% of the reminder of process water, is assumed to be released to air, and 34% to surface water (as purified effluent).

2.12 Representativeness

The MSWI model is based on base data (working point) from mainly Swiss plants, but also data from other plants in Austria and Germany is used. The model is well representative for similar modern plants in Europa, Japan or USA. The energy production is based on the average Swiss technology mix

[13] Based on a literature survey of recent publications (Alwast & Riemann 2010, BMG 2010, BMG 2011, BMG 2012, Bouvier et al. 2005, Chang et al. 2009, Chen et al. 2008, Hyks 2008, Morf & Kuhn 2009, Morf 2006, Morf 2010, Svensson 2006)

[14] Most frequently, non-organic carbon means carbon in carbonate anions (CO_3^{2-}). Also included are the related compounds bicarbonate anion (HCO_3^-), carbonic acid (H_2CO_3) and carbon dioxide (CO_2). Probably also any Cyanide (CN-) would fall under the definition of TIC, but this is of no quantitative importance.

[15] In ecoinvent, an overlaying distinction between *fossil* (non-renewable) and *biogenic* (renewable) carbon is made. Fossil carbon can be organic carbon (e.g. C in plastics) or inorganic carbon (e.g. C in limestone. For instance CO_2 released from lime calcination during cement production is categorised as a fossil C emission). Biogenic carbon is commonly from biogenic tissue and is usually organic (e.g. C in wood fibres or other plant matter), but also biogenic, *inorganic* carbon is imaginable, for instance carbonates in shells. Therefore, the distinctions of organic/inorganic and fossil/biogenic carbon are separate issues.

of MSWI plants. The range in this technology mix is rather wide (see Fig. 2.3 on page 19) and does obviously not represent any particular single plant, but only the national average. The Swiss MSWI model is used to create Global datasets in the database (GLO)[16]. Worldwide approximately 200 million metric tonnes of MSW were incinerated in 2010 with energy recovery, i.e. waste-to-energy, WTE, not counting landfill gas valorisation (Pike 2010). In Switzerland 3.55 million metric tonnes of MSW were incinerated in 2011 (Binggeli & Hügi 2012) and all Swiss MWSIs recover some energy. Thus the model coarsely represents 1.8% of the global activity, though for some exchanges representativeness might be smaller, but in general the model is suitable also for similar modern MSWI plants.

[16] Datasets with geographic localisation for Switzerland (CH) are *not* created for ecoinvent v3.1, in order to save database space, as this would merely duplicate the same information of the GLO MSWI datasets. Within this project, MSWI datasets are also created in Ecospold 1 format compatible with ecoinvent v2.2. There, the geographic localisation is CH, not GLO, but contains essentially the same information as the v3.1 datasets.

3 Waste compositions

3.1 Average Municipal Solid Waste

A new waste composition is taken from Morf (2006:Tab 1), which is for household waste incinerated 2003 in the MSWI Thurgau (Switzerland). This appears to be the most recent, extensive waste analysis for municipal solid waste in Switzerland. Missing composition data (N, B, I, Ag, Ba, Co, Mn, Mo, Se, V) is augmented with previous composition data for average municipal waste, based on Hellweg (2000). Values for beryllium and titanium are "back-engineered", from composition values in MSWI bottom ash of 2066 ppm and 11'066 ppm (from Eggenberger & Mäder 2010, Svensson 2006), their average transfer coefficients to bottom ash (cf. Tab. 6.1 on page 33) and 20% bottom ash mass per kg average waste. The total mass of all these added elements is 0.66%.

Another problem arises with the data from Morf: although all major and macro elements including water content is accounted in the analysis, and the analysis by Morf (2006:Tab 1) is explicitly for a *wet* mass composition, the mean total overall mass sums up to only 87.6w%; i.e. there is 12.4 w% of average waste composition unaccounted for. Although the material is inherently variable, this seems like a large gap, and even all the upper confidence values given by Morf sum up to only about 94 w%. A comparison with the previous waste composition used by Hellweg (2000) reveals that the imbalance appears to be caused mainly by two elements, while all other elements contribute only small differences: Morf gives a value of 19 w% *oxygen* in waste and 2.08 w% *silicon*, which were previously at 25.7 w% and 4.85 w% respectively. The difference of these two elements alone make up 9.5 w%. To obtain a 100%-composition the following procedure is applied:

- The old, higher value of 4.85 w% silicon from Hellweg (2000) replaces the value by Morf
- The whole composition, including the lower heating value is then raised by a factor of 1.0263. This brings the lower heating value from 11.4 as given by Morf to 11.7 MJ/kg, which is the current average value for Swiss MSWI in 2011 (Liechti 2012:18).
- The remaining mass gap is filled by augmenting the oxygen mass to a value of 26.1 w%.

The so obtained average waste composition is shown in Tab. 6.3 on page 36. Compared to the previous average waste composition in Hellweg (2000), there are clearly less heavy metals like mercury, chromium, nickel and – to a lesser degree – cadmium, copper, lead and zinc. Also observable is an *increase* of toxic halogens (bromine, fluorine) and toxic semimetals (arsenic, antimony).

The incineration model requires the split of heterogeneous wastes into a burnable and inert part. For average municipal solid this is performed by applying the parameter defining the share of an element in a burnable fraction $fr_{burnable\ e}$ as elaborated earlier; see see Tab. 2.1 (left side) on page 11.

The model requires information on the share of recyclable metals. Recyclable metals are attributed to the inert part only[17]. With a share of 100% recyclable metals in the inert part and heeding the efficiency of scrap removal in the technology mix (see chapter 2.1 on page 8) amounts of 9.8 g iron scrap and 1.34 g non-ferrous scrap (Al+Cu) recovered per kg average municipal waste result. Within the inherent variability of the subject matter, this appears to be in rather good accordance with values of 12.6 g iron scrap and 1.34 g non-ferrous scrap recently measured in the field in 2006 (BAFU 2008:45)[18]. So setting the share of recyclable metals in the inert part to 100% yields reasonable results.

[17] Recyclable metals of a useful size can hardly be labelled "burnable".

[18] An annual iron scrap production of 46'000 tons and non-ferrous scrap of 4900 tons from 3.65 million tons of incinerated waste in 2006 results in 12.6 g iron scrap and 1.34 g non-ferrous scrap per kg average municipal waste.

3.2 Waste from electronics dismantling

Various waste fractions are derived from the dismantling or/and shredding of electronic devices in the LCIs of electronics (Hischier et al. 2007-V). Most metal parts are recycled and plastics incinerated. Here some special wastes are defined which are not covered elsewhere.

3.2.1 Shredder residues from electronics dismantling

Eight different shredder residues are defined in (Hischier et al. 2007-V) which stem from mechanical dismantling of 7 different types of devices and one generic shredder residue from manual dismantling. These shredder residues are assumed to be incinerated in MSWIs.

Tab. 3.1 Material fractions in shredder residues of electronic devices

Device type	Hischier et al. 2007-V	Aluminium	Copper	Ferro	Glass	Plastics	Silver	Gold	Lead	others
Desktop PC	p.34	7.21%	2.97%	12.4%	2.98%	66.9%	0.0345%	0.00346%	0.218%	7.27%
Laptop PC	p.40	3.61%	1.71%	1.99%	0.335%	50%	0.0176%	0.00116%	0.0372%	42.3%
CRT Screen	p.46	2.19%	1.86%	2.32%	1.39%	84.3%	0.0144%	0.000445%	0.0715%	7.88%
LCD Screen	p.52	2.22%	0.358%	0.0121%	0.0336%	96.4%	0.00285%	0.000175%	0.00595%	1%
Laser Printer	p.58	0.151%	2.25%	1.42%	0%	89.4%	0%	0%	0%	6.74%
Industrial Device	p.64	0.0742%	0.596%	22.4%	0.0767%	74.6%	0.00653%	0.0004%	0.0136%	2.27%
IT accessories /peripherals	p.68	0.353%	1.99%	1.57%	1.03%	92.4%	0.0108%	0.000334%	0.0536%	2.55%
shredder residue after manual dismantling	p.71	5.92%	3.54%	2.96%	7.02%	74%	0.0392%	0.000121%	0.34%	6.17%

These material fractions are translated by (Hischier et al. 2007-V) into following materials available in the MSWI model:

- Aluminium is assessed as Aluminium in MSW (contains some Cu, Zn, Cd traces)
- Copper is assessed as Wire Copper (100% pure Cu)
- Ferro is assessed as MSWI iron scrap (contains traces of Cu, Si, Al, Mn, Cr, Ni etc.)
- Glass is assessed as Glass in MSW (mostly glass packaging)
- Silver and Gold are assessed together as 100% Silver as Gold is not in the MSWI model.
- Lead is assessed as Lead in Automotive shredder residue (ASR)
- Plastics and others are assessed together as 2% rubber, 49% Plastics from electronic consumer goods. 49% Plastics from electronic industrial goods

3.2.2 LCD module

The TFT-LCD module is the screen of an LCD monitor itself plus some associated electronics. During dismantling the LCD module is separated and subsequently incinerated. The module is composed of following materials:

Tab. 3.2 Material fractions in separated used LCD modules

Material	Weight fraction
ITO coating	0.12%
Liquid crystals	0.83%
Plastics	1.74%
Copper	0.87%
Electronics	14.47%
Glass	81.97%

Following assumptions for these materials were made by (Hischier et al. 2007-V):

- ITO coating layer it is assumed to be an 90:10 In_2O_3/SnO_2 mix (by weight). Indium is not assessed in the MSWI model, so a minor mass gap results here.
- Liquid crystals are assumed to be burnable and composed of 40% fossil carbon, 40% oxygen, 10% nitrogen, 10% hydrogen.
- Plastics is assessed 50% Plastics from electronic consumer goods† and 50% Plastics from electronic industrial goods†
- Copper is assessed as Wire Copper† (100% pure Cu)
- Electronics is assessed as electronic goods†
- Glass is assessed as Glass in MSW† (mostly glass packaging)

† = fractions that are available in the MSWI model from other sources

3.2.3 Coatings/lumiphore of CRT screens

In order to recycle the glass of CRT screens, the inner coating must be removed. The inner coating – or lumiphore – is the luminous layer of a CRT screen. This isolated coating is incinerated in an MSWI. As composition, (Hischier et al. 2007-V:115) assumes 10% water, 30.23% ZnS:Ag,Al (98% ZnS, 1% Ag, 1% Al), 25.67% ZnS:Cu,Al (98% ZnS, 1% Cu, 1% Al), and 34.10% Y_2O_2S:Eu (99% Y_2O_2S, 1% Eu).

This results in 10% H_2O, Zn 36.8%, Y 24.8%, S 22.5%, Al 0.559%, Eu 0.31%, Ag 0.302%, Cu 0.257%. Since Y and Eu are not available in the MSWI model, (Hischier et al. 2007-V) inventoried Y as Sr and Eu as Ba.

3.2.4 Capacitors

Capacitors from used electronic devices might not be recycled and need to be disposed in hazardous waste incinerators. (Hischier et al. 2007-V:113) defines a generic mixture of waste capacitors consisting of 75% electrolyte capacitors (> 2 cm height), 20% electrolyte capacitors (< 2 cm height), 5% through-hole-mounted film capacitors and calculates following generic composition:

Tab. 3.3 Composition of waste capacitors (Hischier et al. 2007-V:113)

Material	Weight fraction
Aluminium	47.78%
Copper	2.106%
Iron	3.063%
Lead	0.0212%
Nickel	0.0450%
Phosphorus	0.0525%
Silver	0.4847%
Tin	0.1937%
Zinc	0.4196%
Plastics	13.17%
Rubber	2.52%
Paper	7.74%
ethylene glycol electrolyte, $C_2H_6O_2$	22.42%

Following assumptions for these materials were made by (Hischier et al. 2007-V):

- Plastics is assessed 50% Plastics from electronic consumer goods† and 50% Plastics from electronic industrial goods†
- Rubber is assessed as Rubber†
- Paper is assessed as average paper†
- Ethylene glycol is assessed as pure $C_2H_6O_2$ and summed up together with all metals and phosphorus as a burnable remainder fraction (765.7g per kg capacitors).

† = fractions that are available in the MSWI model from other sources.

3.3 Used rail track support material

Inert fines in this waste, i.e. non-pollutants, are assumed to be SiO_2 (formerly pure silicon, which lead to a large oxygen insufficiency in bottom ash).

3.4 Average wastewater treatment sludge

In (Jungbluth et al. 2007) the incineration of sludges from municipal wastewater treatment was inventoried. Two different types of WWTP sludge are inventoried: raw sludge and digester sludge. Raw sludge has not undergone digestion or fermentation, while digester sludge has been through digester and produced some digester gas (biogas). Digester sludge has therefore lower carbon content. The source considers a generic reduction of TOC during digestion of 45% (Jungbluth et al. 2007:643). This is assumed to reduce the C,O,H content in sludge accordingly. Both sludges are dewatered from 95% water content to 73% water content prior to incineration. The removed water contains some dissolved carbon, nitrogen and phosphorus. Their removal is also reflected in the remaining dewatered composition. Upper and lower heating values are calculated from composition using (Michel 1938).

Both sludges have 27% dry matter content, but the digester sludge has lower carbon content and conversely higher inorganics content.

These datasets shall not be used for the disposal of sludges from the treatment of *specific* wastewaters, e.g. wastewater from paper production, as they pertain only to average sludge from average WWTP operation and therefore treatment of *average* wastewater.

3.5 Waste material name changes in ecoinvent

All water contents are removed from the names for Intermediate Exchanges for waste materials. A term designating materials as used or spent is usually applied, like "waste plastic", "scrap copper", "spent cation exchange resin".

The ecoinvent Centre has chosen to change following waste materials base names from the original designation in (Doka 2010):

Waste paperboard (was packaging cardboard)

The term cardboard is in common usage in the English language, but not anymore in the paper industry . Cardboard could refer to various types of paper and board like card stock, paperboard, or corrugated fibreboard. Commonly, paperboard is a paper with a basis weight above 224 g/m^2. The German term "Karton" remains in common usage also in the industry.

In (Doka 2010) a composition of waste cardboard was inventoried. This waste has been renamed by the ecoinvent Centre to "waste paperboard". The ecoinvent Centre effected only a name change. The waste composition for the new Intermediate Exchanges "waste paperboard" is referenced in (Doka 2010, part I) under "packaging cardboard".

Graphical paper (was average paper)

In (Doka 2010) a composition of average waste paper was inventoried to be a mixture of 10% newspaper and 90% packaging paper. This waste has been renamed by the ecoinvent Centre to "waste graphical paper". The composition remains that of the mixture specified in (Doka 2010).

4 Information for particular waste disposal datasets

4.1 No biowaste incineration in future plant

In (Jungbluth et al. 2007:638f) disposal of biowaste and digester sludge in a so called "future MSWI plant" was inventoried. Project management however mandated to adopt planning data from one single plant – the modernisation of MSWI Hagenholz-Zurich – as the future MSWI data. Planning data provided by the Hagenholz operators was a gross thermal efficiency of 56.3% and a gross electric efficiency of 16.7%.

Although this data proved more or less accurate for the Hagenholz plant itself[19], there is little point in providing a "future MSWI" dataset based on the specifics of a single plant. The Hagenholz obviously has a large share of heat utilisation, due to mandates of the Zurich municipality to utilise district heat for residential heating and warm water. This situation does not apply to other MSWI plants and is hardly a good proxy for the average Swiss situation – present or future. The average gross thermal efficiency of the Swiss MSWI plants in 2011 was 28.51% – and increased a mere 4% in the last 11 years (cf. Fig. 2.3 on page 19). It seems rather unlikely that an average gross thermal efficiency of 56.3% (as derived from Hagenholz planning data) is a good representation for an average Swiss MSWI of any possible future.

Also there appears no use for the resulting datasets in the database v2.2. No activity actually requires these disposals in a future MSWI. Any "future MSWI" datasets should be consistently created for all waste materials, and not just for a rather arbitrary selection.

For biowaste and digester sludge the incineration datasets are created based on the incineration in *present* Swiss MSWI plants. Datasets for disposal in a "future MSWI" are not created.

[19] In 2011, the Hagenholz MSWI plant had gross efficiencies of 51.14% for heat and 15.06% for electricity (Binggeli & Hügi 2012).

5 Ecospold1 variant LCIs

The LCI data of this study is part of ecoinvent v3.1. The data format of ecoinvent v3 is Ecospold2. Some Swiss LCA practitioners prefer, for various reasons, to use the format ov previous ecoinvent versions: Ecospold1. As an auxiliary result, the new LCI data established in this study is also provided as Ecospold1 format and compatible with the old ecoinvent v2.2 methodology.

Some changes have been effected to produce the Ecospold1/eiv2.2 data:

- Any by-product outputs of the incineration process (net energy, metal scrap) are not listed in the ecospold1 inventory. This means that 100% of the process burden is allocated on the disposal function of the MSWI and 0% onto the by-products like electricity, useful heat, iron, copper, aluminium scrap.
- In ecoinvent v3 all transports of material inputs are inventoried in separate market datasets and must not be included in the inventory of the receiving process. For the Ecospold1/eiv2.2 data all transport expenditures of auxiliary material inputs like cement, NaOH, CaO etc are added heeded default transport distances of the ecoinvent 2000 project (eiv1-2.2).
- Exchanges of eiv3 such as input of oxygen and output of water as vapour or effluent are not included.

Due to the inventory changes, but also due to the different allocation rules of ecoinvent v3.01, the inventory results of v2.2 and v3.01 should not be expected to be identical. LCA practitioners shall use the inventories compatible with the other inventories used in a study.

6 Appendix

6.1 Average transfer coefficients

Tab. 6.1 Average transfer coefficients in municipal waste incinerators (working point data for operation with average municipal solid waste). From literature compilation, rounded to 5 digits.

g/kg	Bottom ash	Boiler ash	ESP ash	Scrubber sludge	Water emissions	Air emissions	source
H_2O	0	0	0	0	0	1000	1
O	34.3	2.2767	11.383	1.04	0	951	2
H	0	0	0	0	0	1000	1
C	8.991	0	0.999	0.4995	0.4995	989.01	2
S	577.11	0	288.56	54.726	74.627	4.9751	2
N	9.9518	0	0.060352	0	0.98783	989	1
P	855.14	29.003	109.05	5.6865 (3)	0.10936 (3)	1.0061 (3)	1
B	878.71	30.734	90.154	0.39996	0	0	4
Cl	109.89	0	289.71	0.4995	599.4	0.4995	2
Br	189.81	5.5187	483.99	0.4995	319.68	0.4995	2
F	413	0	480.39	54.8	45.4	6.4093	1
I	-	-	-	-	-	-	
Ag	801.7	0	195.5	0.8	2	0	4
As	497	36.277	460.6	0.49547	2.5305E-08	5.628	1
Ba	879	21.81	89.224	9.0048	0.012373	0.9491	1
Cd	80.358	0	914.07	5.0223	0.050223	0.50223	2
Co	887	7.1211	85.453	19.5	0.0050305	0.92105	1
Cr	918	5.4492	76.288	0.095155	0.013674	0.15378	1
Cu	939.44	0	59.964	0.4997	0.04997	0.04997	2
Hg	29.073	2.1075	368.82	571.43	0.50125	28.07	2
Mn	931.98	5.117	61.404	1.4445	0.020944 (3)	0.033632	1
Mo	878.39	19.089	99.992	1.835	0.026655 (3)	0.66636 (3)	1
Ni	969	10.869	19.409	0.063785	0.022545	0.6362	1
Pb	686.5	0	308.43	4.9746	0.049746	0.049746	2
Sb	390	13.235	596.76	0.0005	0.0005	0.0005	2
Se	80	127.99	709.67	71	0.0015151	11.333	1
Sn	520	20.282	459.72	0.0005	0.0005	0.0005	2
V	899	8.7403	78.663	9.8528	0.0091661	3.735	1
Zn	472.1	0	522.32	5.0223	0.050223	0.50223	2
Be	900.71	24.887	73.003	1.3999	0	0	4
Sc	-	-	-	-	-	-	
Sr	-	-	-	-	-	-	
Ti	868.23	30.981	94.291	5.8295	0.16124	0.50853	3
Tl	-	-	-	-	-	-	
W	-	-	-	-	-	-	
Si	970	9.7059	20.294	0.0005	0.0005	0.0005	2
Fe	991.48	0	8.012	0.50075	0.0050075	0.00050075	2
Ca	827.59	42.292	115.34	4.9261	4.9261	4.9261	2
Al	889.55	27.191	82.754	0.49975	0.0049975	0.00049975	2
K	413.79	82.132	489.3	4.9261	4.9261	4.9261	2
Mg	907.4	22.978	67.401	0.46116	0.97652 (3)	0.78122 (3)	1
Na	650.25	83.744	251.23	4.9261	4.9261	4.9261	2

1 Saner et al. 2010:Tab. 11 2 Taverna 2011:Fig 4-5 3 Salzmann 2008:Tab 12+13 4 Löschau 2006:Tab C-1

6.2 Transfer coefficients for burnable waste

Tab. 6.2 Derived transfer coefficients for *burnable* waste in municipal waste incinerators.

g/kg	Bottom ash	Boiler ash	ESP ash	Scrubber sludge	Water emissions	Air emissions
H_2O	0	0	0	0	0	1000
O	24.5	2.3	11.5	1.05	0	961
H	0	0	0	0	0	1000
C	4.01	0	1	0.502	0.502	994
S	548	0	308	58.5	79.8	5.32
N	9.95	0	0.0604	0	0.988	989
P	854	29.3	110	5.74	0.11	1.02
B	384	0	166	180	151	120
Cl	11	0	322	0.555	666	0.555
Br	190	5.52	484	0.5	320	0.5
F	413	0	480	54.8	45.4	6.41
I	11	0	322	0.555	666	0.555
Ag	721	3.21	273	2.07	0.0765	0.393
As	300	50.5	641	0.69	3.52E-08	7.83
Ba	500	90.2	369	37.2	0.0512	3.93
Cd	66.7	0	928	5.1	0.051	0.51
Co	777	14.1	169	38.5	0.00993	1.82
Cr	534	30.9	433	0.54	0.0776	0.873
Cu	889	0	110	0.916	0.0916	0.0916
Hg	19.3	2.13	373	577	0.506	28.4
Mn	614	29.1	349	8.2	0.119	0.191
Mo	760	37.7	197	3.62	0.0526	1.32
Ni	939	21.5	38.3	0.126	0.0445	1.26
Pb	481	0	511	8.24	0.0824	0.0824
Sb	22.7	21.2	956	0.000801	0.000801	0.000801
Se	31.6	135	747	74.7	0.00159	11.9
Sn	373	26.5	601	0.000653	0.000653	0.000653
V	426	49.6	447	55.9	0.052	21.2
Zn	295	0	697	6.7	0.067	0.67
Be	696	0	294	9	0	1
Sc	999	0	0	0.5	0	0.5
Sr	999	0	0	0.9	0	0.1
Ti	785	50.5	154	9.51	0.263	0.83
Tl	348	0	650	1	0	1
W	751	0	249	0	0	0
Si	907	30.2	63.2	0.00156	0.00156	0.00156
Fe	970	0	28.7	1.79	0.0179	0.00179
Ca	725	67.6	184	7.87	7.87	7.87
Al	820	44.4	135	0.815	0.00815	0.000815
K	412	82.4	491	4.94	4.94	4.94
Mg	875	31	91	0.623	1.32	1.05
Na	417	140	419	8.21	8.21	8.21

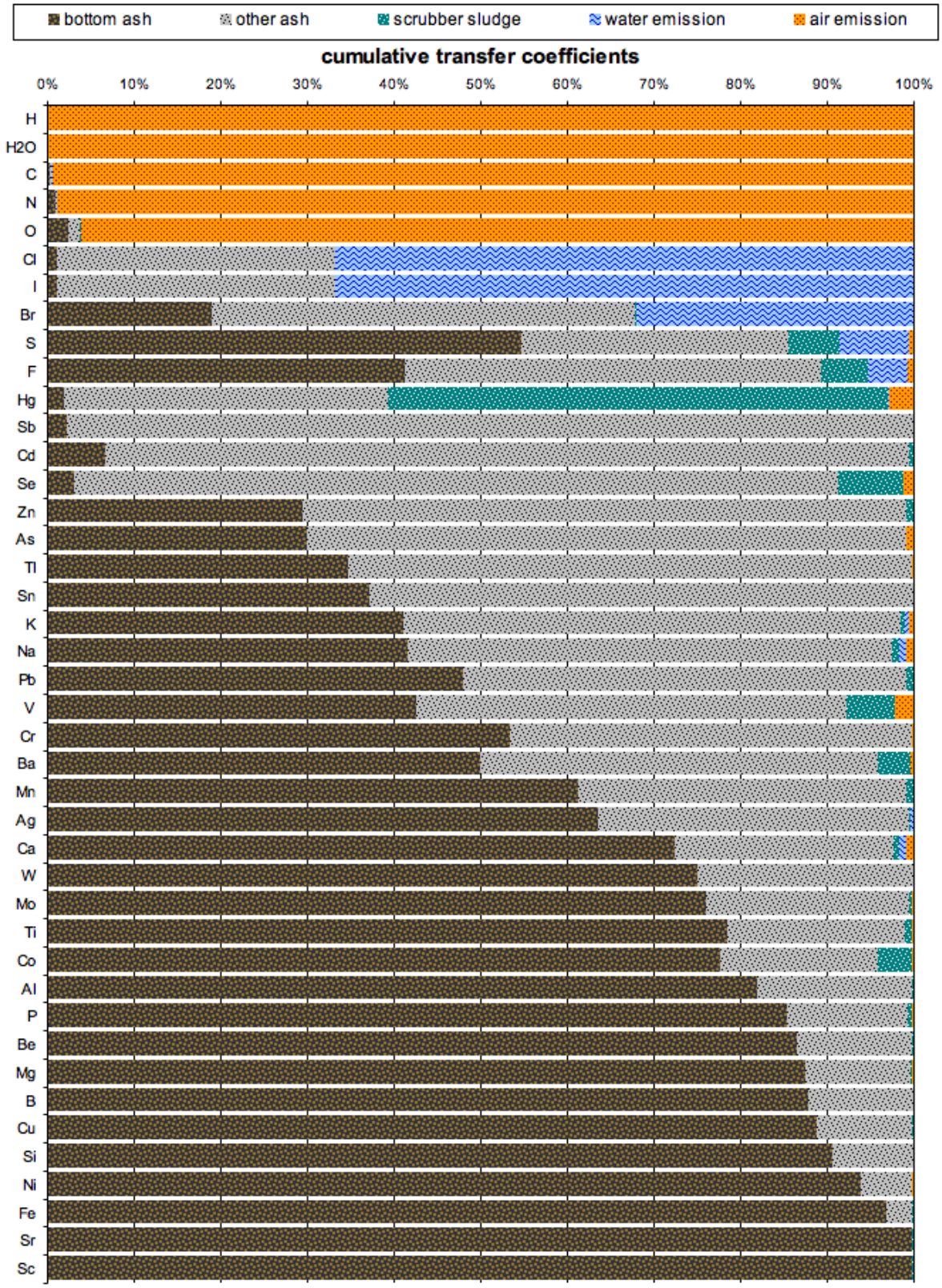

Fig. 6.1 Transfer coefficients for *burnable* waste in municipal waste incinerators

6.3 Average municipal waste composition

Tab. 6.3 Average municipal waste composition. Details see chapter 3.1 'Average Municipal Solid Waste' on page 26.

	Average municipal waste	Burnable fraction	Unburnable fraction
UHV (MJ/kg)	13.049	14.066	0
LHV (MJ/kg)	11.7	12.612	0
H_2O	225'260	242'820	0
O	261'060	278'580	36'115
H	43'105	46'464	0
C	338'960	363'540	23'446
S	1532.3	1545.4	1363.9
N	3206.1	3455.9	0
P	757.42	808.27	104.78
B	7.3826	7.9578	0
Cl	6670	6470.8	9227.4
Br	129.32	139.39	0
F	366.39	394.94	0
I	0.012418	0.013386	0
Ag	0.73279	0.43095	4.6067
As	1.4061	1.0889	5.4761
Ba	152.96	39.868	1604.4
Cd	8.0053	8.5025	1.6238
Co	1.3807	0.7537	9.4273
Cr	139.58	26.496	1590.9
Cu	930.87	547.44	5851.9
Hg	0.65684	0.70094	0.090869
Mn	266.19	50.529	3034
Mo	2.0065	1.0953	13.7
Ni	52.342	28.573	357.39
Pb	413.61	269.2	2266.9
Sb	53.368	35.907	277.48
Se	0.3281	0.33598	0.22695
Sn	99.553	82.141	323.02
V	9.4572	1.7952	107.79
Zn	1127.9	911.01	3911.8
Be	470.85	375.91	1689.4
Sc	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.
Ti	2616.4	1728.7	14'010
Tl	n.a.	n.a.	n.a.
W	n.a.	n.a.	n.a.
Si	49'786	17'228	467'650
Fe	23'628	7'116	235'540
Ca	18'346	12'379	94'938
Al	11'395	7'529	61'016
K	2132.7	2292.2	85.947
Mg	2568.9	2050.9	9216.9
Na	4741.6	3066.6	26'238
Mass sum	1'000'000	1'000'000	1'000'000

6.4 Air emissions at the working point

Tab. 6.4 Various emissions to air from recent measurement reports in Swiss MSWIs (in mg/Nm^3 flue gas, dioxins in ng/Nm^3)

plant	date	source	PM10	HCl	HF	SO2	NO2	NH3	Hg	Cd	Pb + Zn	CO	Dioxin	VOC
per Nm^3			mg	mg	mg	mg	mg	mg	mg	mg	mg	mg	**ng**	mg
GL Niederurnen	Aug 2007	1	<1	<6.7	<0.4	<2	29	<1	<0.005	<0.001	<0.09	<5	0.005	<2
GL Niederurnen	Nov 2008	1	<0.3	1	<0.1	2.1	30.5	<0.5	0.006	<0.001	0.03	6.3	0.018	<2
LU Luzern	2009	2	0.1	<0.21	<0.1	1.01	57	<0.72	<0.001	<0.003	0.066		0.00025	
SO Zuchwil	2009	3	0.85	0.18	0.025	10	54	1.13	0.003	0.001	0.051	13	0.03	0.45
TI Giubiasco 1	Jan 2010	4	0.8	<0.04	<0.02	<0.1	28	0.04	0.0006	<0.0006	0.038	10	0.011	<0.3
TI Giubiasco 2	Jan 2010	4	2	<0.04	<0.02	0.14	29	0.05	<0.0004	<0.0007	0.093	8	0.005	<0.3
AG Turgi	May 2010	5	1.31	0.41	0.041	4.92	26.9	1.39	0.0156	0.00205	0.172	12.9	0.0221	0.246
VD Tridel 1	July 2008	6	0.6	0.9	0.21	3.3	39	0.062	0.014	0.003	0.056	6	<0.01	
VD Tridel 2	July 2008	6	0.5	2.5	0.3	1.2	43	0.027	0.007	<0.001	0.031	11	<0.04	
VD Tridel 1	30 June 2009	6	0.5	1.7	0.04	3.7	53	0.17	0.009	<0.0006	0.064	6	0.094	
VD Tridel 2	30 June 2009	6	0.6	1.3	0.02	1.7	37	0.1	0.013	<0.0007	0.104	10	0.023	
VD Tridel 1	June 2010	6	0.6	1.7	0.04	4.3	43	0.1	0.008	<0.0005	0.043	7	0.008	
VD Tridel 2	June 2010	6	0.4	0.9	<0.02	1.3	40	0.07	0.009	<0.0005	0.046	7	0.013	
Geomean			**0.603**	**0.938**	**0.0575**	**2**	**37.9**	**0.12**	**0.00652**	**0.00183**	**0.0578**	**8.49**	**0.01**	**0.333**

1 http://www.kva-linthgebiet.ch/Messwerte.htm

2 http://www.kva-luzern.ch/index.php?id=20

3 http://www.kebag.ch/cms/front_content.php?idcat=46

4 http://www3.ti.ch//DT/cartellastampa/pdf-cartella-stampa-43376492648.pdf

5 http://www.kvaturgi.ch/fileadmin/pdf/Emissionen_2010.pdf

6 http://www.tridel.ch/userfiles/pdf/TRIDEL_2008-09-10_Comparatif_emissions.pdf

6.5 Auxiliary material inputs at the working point

Tab. 6.5 Various auxiliary material inputs to from recent measurement reports in MSWIs (in grams per kg waste incinerated)

plant	year	source	NaOH (30%)	CaO (95%)	HCl (30%)	FeCl3 (40%)	TMT 15 (15%)	Polyelectrolyte (100%)	Ammonia for DeNOx (25%)	Water (100%)
			g/kg waste	g/kg waste	g/kg waste	g/kg waste	g/kg waste	g/kg waste	g/kg waste	g/kg waste
KVA Buchs CH	2011	1	5.79	4.19	0.164	0.0405	0.0466	0.354	3.82	-
KVA Buchs CH	2010	1	5.77	4.11	0.207	0.0543	0.0508	0.413	3.82	-
KVA Buchs CH	2009	2	6.47	4.13	0.195	0.0593	0.05	0.67	3.75	-
KVA Buchs CH	2008	2	7.21	3.96	0.207	0.0516	0.0473	0.714	3.79	-
KVA Basel CH	2007	3	0.162	4.14	0.211	-	0.035	-	2.77	1740
KVA Basel CH	2008	3	-	4.16	0.166	-	0.061	-	3.04	1660
KVA Basel CH	2009	3	0.094	4.21	0.255	-	0.063	-	3.06	1570
KVA Basel CH	2010	3	2.75	3.69	0.17	-	0.054	-	2.82	1590
KVA Basel CH	2011	3	4.42	3.03	0.329	-	0.052	-	3.01	1950
KVA Basel CH	2004	4	-	3.1	-	-	0.04	-	4.1	1600
MVA Flötzersteig AT	2004	5	3.83	2.26	0.0811	0.089	0.0997	0.0041	1.77	939
MVA Flötzersteig AT	2005	5	3.9	2.55	0.125	0.224	0.174	0.00785	1.88	1160
MVA Flötzersteig AT	2006	5	3.85	2.23	0.0905	0.17	0.121	0.00655	1.76	1080
MVA Flötzersteig AT	2007	5	3.93	2.7	0.081	0.136	0.197	0.00415	1.71	837
MVA Flötzersteig AT	2008	5	3.86	2.31	0.0884	0.128	0.173	0.00201	1.94	793
MVA Spittelau AT	2006	6	2.4	2.6	-	0.1	0.1	-	3	746
MVA Wels AT	2000	7	3	6.4	0.5	0.65	-	0.006	1.4	850
MVA Spittelau AT	2002	8	2.4	2.4	-	0.09	0.09	-	2.9	3000
geomean			**3.74**	**3.45**	**0.191**	**0.149**	**0.0856**	**0.218**	**2.8**	**1390**

1 http://www.kva-buchs.ch/downloads/GB2011.pdf

2 http://www.kva-buchs.ch/downloads/GB09_Internetversion.pdf

3 http://www.iwb.ch/media/KVA/Dokumente/umweltbericht_2011_kva_basel.pdf

4 http://www.iwb.ch/de/unternehmen/kehricht-verwertung/umwelt/spezifische_mengenfluesse/

5 http://www.wienenergie.at/media/files/2010/brosch%C3%BCre%20fl%C3%B6tzersteig_16603.pdf

6 http://www.wienenergie.at/media/files/2010/brosch%C3%BCre%20spittelau%20englisch_16602.pdf

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6.6 Waste specific calculation of the oxygen demand in incineration

Following equations apply:

(technical oxygen demand; kg O/ kg waste) = (stoichiometric demand; kg O/ kg waste) * (lambda; -)

(stoichiometric demand; kg O/ kg waste) = (gross oxygen demand; kg O/ kg waste) – (oxygen present in waste; kg O/ kg waste) = (net oxygen demand; kg O/ kg waste)

The oxygen present in waste is given through the definition of waste composition, which includes oxygen.

Gross oxygen demand is the sum of oxygen demand for airborne species and for solid residues

(gross oxygen demand; kg O/ kg waste) = (oxygen demand for airborne species; kg O/ kg waste) + (oxygen demand for solid residues; kg O/ kg waste)

Oxygen demand for airborne species is calculated as a sum across all chemical elements for the fraction of waste converted to airborne species (defined by transfer coefficients to air for each element) and the specific oxygen demand to oxidise an element, i.e. nitrogen N to nitrogen dioxide NO2.

(oxygen demand for airborne species; kg O/ kg waste) = ∑ [(element e in waste composition; kg e / kg waste) * (Transfer coefficient for element e to air) * (oxygen demand for oxidising element e as air emission; kg O/kg e)]

Oxygen demand for solid residues is calculated in a similar fashion as for airborne species, but since the combustion products are different, different weight increases apply. For instance nitrogen N in a solid residue will be nitrate NO_3^-, not nitrogen dioxide NO_2 or nitrite NO_2^-, and therefore require more oxygen a gaseous emission of nitrogen.

(oxygen demand for solid residues; kg O/ kg waste) = ∑ [(element e in waste composition (kg e / kg waste) * (Transfer coefficient sum for element e to solid residues) * (oxygen demand for oxidising element e as solid residue; kg O/kg e)]

Tab. 6.6 Oxygen demand for chemical elements as air emissions

Element e	Oxidised species in air emission	Oxygen demand for oxidising element e as an air emission, kg O/kg e	Molecular weight airborne combustion product mol/kg
H2O	H2O	0%	55.55555556
O	var.	0%	
H	H2O	800.0%	500
C	CO2	266.7%	83.33333333
S	SO2	100.0%	31.25
N	NO2	228.6%	71.42857143
P	PO3	155.0%	
B	B2O3	888.9%	
Cl	HCl *	-22.6%	28.20635771
Br	HBr *	-10.0%	12.51407834
F	HF *	-42.1%	52.63157895
I	HI *	-6.3%	7.880220646
Ag	Ag2O	7.4%	
As	As2O3	32.0%	
Ba	BaO	11.6%	
Cd	CdO	14.2%	8.896797153
Co	CoO	27.2%	
Cr	Cr2O3	46.2%	
Cu	CuO	25.2%	
Hg	HgO	8.0%	4.985293385
Mn	MnO	29.1%	
Mo	MoO3	50.0%	
Ni	NiO	27.3%	
Pb	PbO	7.7%	
Sb	Sb2O3	19.7%	
Se	SeO	20.3%	
Sn	SnO2	27.0%	
V	V2O5	78.5%	
Zn	ZnO	24.5%	15.2975371
Be	BeO	177.8%	
Sc	Sc2O3	53.3%	
Sr	SrO	18.3%	
Ti	TiO2	66.8%	
Tl	Tl2O	3.9%	
W	WO3	26.1%	
Si	SiO2	113.9%	
Fe	Fe2O3	43.0%	
Ca	CaO	39.9%	
Al	Al2O3	88.9%	
K	K2O	20.5%	
Mg	MgO	65.8%	
Na	Na2O	34.8%	

* Oxygen demand for the halogens negative here: it is assumed that halogens (X = Cl, Br, F, I) are converted to hydrogen halides (a.k.a hydrohalic acids) HX. This conversion does not require oxygen, but hydrogen, assumed to be supplied by the waste matrix. Hydrogen ending up in hydrogen halides has not been converted to its more common incineration product H_2O (water vapour). Therefore presence of halides in air emissions has reduced the oxygen demand for oxidising hydrogen in the waste. This is heeded by using negative values for oxygen demand of halogens. For average waste this correction is negligible and represents 0.0005% of the gross oxygen demand for hydrogen. For wastes rich in halogens like PVF, this correction can be more relevant (0.16%), but is still hardly perceptible. So the assumption whether or not hydrogen halides consume hydrogen from waste is of little relevance for the calculation of oxygen demand. The effect is still kept in the calculation for completeness.

Element e	Oxidised species in air emission	Oxygen demand for oxidising element e as an solid residue, kgO/kg e
C	TOC/CO3 *	200.0%
S	SO3	150.0%
N	NO3	342.9%
P	P2O5	129.2%
B	B2O3	222.2%
Cl	ClO	45.1%
Br	BrO	20.0%
F	FO	84.2%
I	IO	12.6%
Ag	Ag2O	7.4%
As	As2O3	32.0%
Ba	BaO	11.6%
Cd	CdO	14.2%
Co	CoO	27.2%
Cr	Cr2O3	46.2%
Cu	CuO	25.2%
Hg	HgO	8.0%
Mn	MnO	29.1%
Mo	MoO3	50.0%
Ni	NiO	27.3%
Pb	PbO	7.7%
Sb	Sb2O3	19.7%
Se	SeO	20.3%
Sn	SnO2	27.0%
V	V2O5	78.5%
Zn	ZnO	24.5%
Be	BeO	177.8%
Sc	Sc2O3	53.3%
Sr	SrO	18.3%
Ti	TiO2	66.8%
Tl	Tl2O	3.9%
W	WO3	26.1%
Si	SiO2	113.9%
Fe	Fe2O3	43.0%
Ca	CaO	39.9%
Al	Al2O3	88.9%
K	K2O	20.5%
Mg	MgO	65.8%
Na	Na2O	34.8%

* Carbon in sold residues is assumed to be 50% TOC (organic C) and 50% TIC (CO3) based on findings for bottom ash (see chapter 2.10 'Carbon in bottom ash' on page 24). Weight increase from oxidation is 0% for TOC (no oxidation) and 400% for CO3, averaging to 200%.

6.7 Combustion air volume

Combustion air is led to the combustion chamber to obtain the technical oxygen demand. Assuming ideal gas volumes and an oxygen content in air of 21%, the required air input is calculated:

(Combustion air volume; m^3 air/kg waste) = (technical oxygen demand; kg O/kg waste) / (32 kmol O2/ kg O) * (22.413837 m3/kmol) / 0.21

The technical oxygen demand is described in the previous chapter.

6.8 Raw flue gas volume

In the raw flue gas the combustion products and N_2 and O_2 remaining from combustion air are present. To calculate the volume of raw flue gas, all emissions to air, scrubber sludge and water emissions are assumed to be gaseous in raw flue gas. I.e. solid particles in dust and ash are not assumed to be gaseous.

(Raw flue gas volume; m^3 gas/kg waste) = (volume of combustion products; m^3 gas/kg waste) + (remainder of combustion air (N2 + O2))

(volume of combustion products; m^3 gas/kg waste) = $\sum$ [(gaseous species in emissions to air, scrubber sludge and water emissions; kg/kg waste) * 1000 / (molecular weight of species; g/mol)]

The remainder of combustion air after combustion is the inputted air volume minus the air oxygen that has been bound up in combustion products, i.e. the stoichiometric oxygen demand, which must be conveted from kg to m^3 using ideal gas volume:

(remainder of combustion air) = (Combustion air volume; m^3 air/kg waste) - (stoichiometric oxygen demand; kg O/kg waste) / (32 kmol O2/ kg O) * (22.413837 m3/kmol)

The combustion air volume is described in the previous chapter and the stoichiometric oxygen demand in the chapter before that.

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