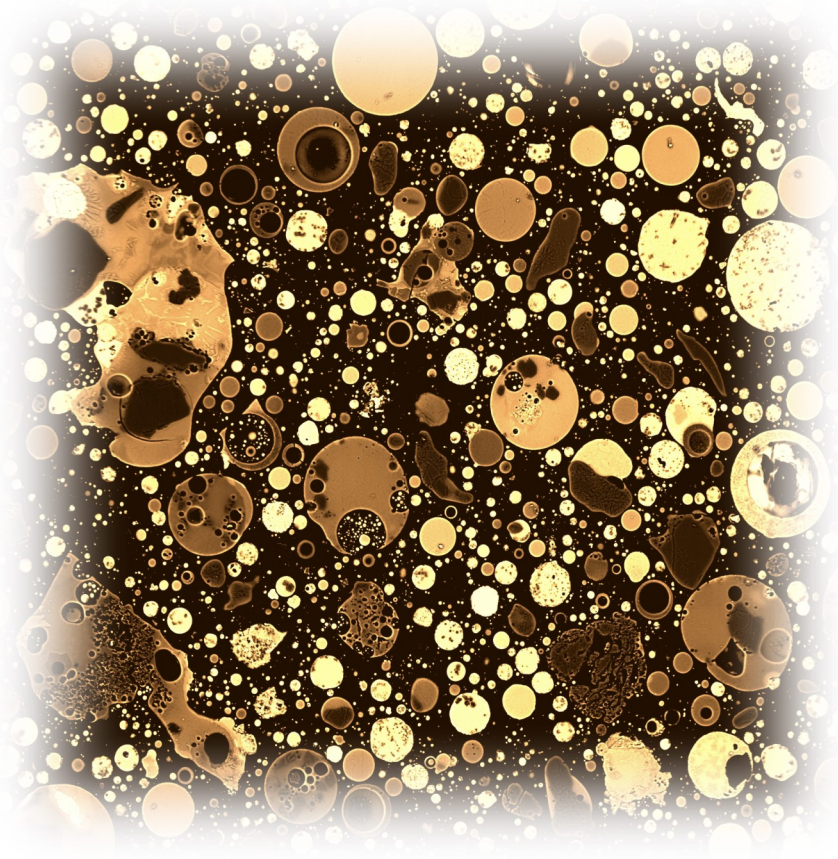
Life cycle inventories of municipal waste incineration with residual landfill & FLUWA filter ash treatment



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Title picture A false-color electron micrograph of a polished cross section of fly ash embedded in epoxy, fly ash from a coal power plant. Source: http://commons.wikimedia.org/wiki/File:Back-Scattered_Electron_Micrograph_of_Coal_Fly_Ash_small.tif by author wabeggs.

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1 Introduction

Goal and circumstance This study report elaborates life cycle process inventories for waste incineration of different waste fractions and looks at the technology currently employed in Swiss municipal waste incinerators. The process inventories are elaborated for the ecoinvent LCI database. It is an extension of the previous inventory reports on waste incineration (Doka 2003-III, Doka 2013) and should be read with the contents of those reports as a background. This report describes only the newly introduced aspects and data, but not the complete inventory procedure.

Developments in waste incineration Municipal solid waste incinerators (MSWI) produce a range of outputs from waste. Apart from energy gained from the utilisation of the waste's heating value, solid, liquid and gaseous outputs are created. The gaseous and liquid outputs – the flue gas and wastewater effluent – have been treated on-site to comply with legal emission thresholds to air and water. The solid outputs are bottom ash, and the air pollution control (APC) residues in the form of filter ashes and sludges from scrubber liquid treatment. The extraction of metallic scrap from bottom ash is commonplace in Switzerland: frequently magnetic ferrous scrap, but increasingly also non-ferrous metals like copper and aluminium are isolated and recycled. The unutilised solid remains must be landfilled at considerable cost. Due to increasing problems in erecting new landfills and their long-term risks there is increasing political, economic and environmental pressure to seek alternatives to landfilling.

The first priority in waste management must be the *reduction of waste*, by promoting more durable goods, reducing useless packaging and products, and facilitate re-use, direct recycling or post-consumer waste sorting. The perspective of waste incinerator operators is different, inasmuch their goal is to *fully utilize the available capacity* of their existing incinerator infrastructure. This is exemplified with the Swiss MSWI Josefstrasse in Zurich, which now only incinerates waste imported from abroad until 2020 when it will be decommissioned. Under the proviso that the annual flow of input waste is accepted as a pre-assigned and unavoidable quantity – i.e. several steps down in the waste hierarchy – the incinerator operators have the possibility and also the economic motivation to divert outputs from landfilling into secondary goods. The mentioned de-scrapping of bottom ash is a popular possibility. Filter ash is rich in metals which are hazardous pollutants in a landfill, like zinc, lead, copper, cadmium or tin. Since the 1980s there have been various approaches to gain secondary goods from APC residues. In Switzerland the FLUWA treatment has become popular. It produces a zinc-rich solid which can be recycled abroad in zinc furnaces. The inventories created here include the treatment of filter ash in the FLUWA process according to the typical technology mix in 2012.

Incorporation in the ecoinvent database A previous update of the datasets in ecoinvent for the waste incineration of 57 different waste materials was described in (Doka 2013) and those updated datasets are part of ecoinvent v3.1 since April 2014. They have the localisation GLO, i.e. represent a modern waste incineration as applied in many developed nations in the world (although based largely on data from Switzerland and other European countries). Creating a GLO dataset is a mandatory prerequisite in ecoinvent v3.x. To save database space, the updated datasets of 2013 were only created with a GLO localisation and no duplicates with a Swiss localisation (CH) were created.

In the present work new incineration datasets with a Swiss localisation are created. These include in part the aforementioned filter ash extraction procedure, which is frequent in Switzerland, but not abroad.[1] The filter ash treatment creates a recyclable zinc concentrate as an output. Since the GLO datasets created in 2013 did not contain any zinc concentrate output, they cannot be used as the

[1] Outside Switzerland, only two smaller MSWI plants have the FLUWA treatment: since 1998 in the MSWI Termizo (95 kt MSW/yr) in Liberec, Czech Republic, and since 2010 in the MSWI Ingolstadt (105 kt MSW/yr), Germany.

mandatory "forerunners" for the newly created CH datasets. In ecoinvent, any non-GLO datasets must feature the identical kind of reference products and co-products as their GLO counterpart. Therefore the new Swiss incineration datasets represent a new activity in the database. This is distinguished with the new suffix *"with fly ash extraction"* in the activity name, e.g. "treatment of municipal solid waste, municipal incineration with fly ash extraction". But also these new CH datasets need a mandatory GLO forerunner, although this activity is not occurring outside Switzerland[2]. Therefore also new GLO datasets are created with the new name. The fact that the activity is not occurring outside Switzerland is heeded with the fact that the production volume of the CH activities is set identical to the production volume in the GLO activities. In this manner the rest-of-the-world (RoW) datasets are not created during database linking and only the CH datasets remain in the linked database.

Since these inventories are – apart from the filter ash treatment – in large part based on (Doka 2013), the same time period for the inventories is used, which is 2006-2012.

[2] The new datasets represent a technology mix with 46.22% filter ash treatment (see next chapter). Although two FLUWA facilities exist outside Switzerland, a different geography with a share of 46.22% filter ash treatment (i.e. the Swiss technology mix) does not exist outside Switzerland. In this sense the inventoried process is unique in Switzerland. This is the consequence of inventorying *one national average technology mix* in waste incineration, also regarding other technology choices applied in energy production, DeNOx, bottom ash descrapping.

2 Generic technology mix for 2012

This report chiefly differentiates the treatments of APC residues (filter ash and scrubber sludge) in Swiss MSWI. Other technology aspects of the waste incineration, like DeNOx, gross energy utilisation etc. are unchanged and described in (Doka 2013).

A common fate of MSWI filter ash and scrubber sludge is *landfilling*. Usually these APC residues are solidified with cement to reduce leachability in the landfill. In Switzerland filter ash is landfilled separately from bottom ash, due to the larger pollutant potential of the former. Due to shortages in landfill space in the 1990s approximately 50% of the produced APC residues were exported annually as hazardous waste to *underground deposits* in old salt mines in Germany[3]. Switzerland maintains a policy goal that disposal of its waste should not take place abroad and the export of waste without recycling is considered a transient practice only. The practice of underground deposition has been declining to currently 25%. Underground deposition of filter ashes shall be outlawed with the new Swiss waste ordinance by prescribing a zinc and lead recycling (§33e in TVA 2014, BAFU 2014:28).

No underground deposition: In the technology mix inventoried here the underground deposition is not considered a viable option. Instead landfilling in a residual material landfill is used. This corresponds to the current legal target sink for APC residues, is in accordance with the previous inventory choices since 1996 and is in agreement with the current study commissioner.

FLUWA acidic filter ash leaching: In the FLUWA process the collected boiler and filter ashes of the incinerator are washed with the acidic scrubber liquid, which leaches a lot of the heavy metals from the ashes. The leaching liquid is precipitated into a metalliferous hydroxide sludge. The washed ash remainder is mixed with the incinerator's bottom ash. Tab. 2.1 gives the most recent data on the share of Swiss MSWI filter ashes treated with the FLUWA process calculated for the year 2012. Of the roughly 78 kilotonnes of filter ash produced annually 35.72% are treated in an internal FLUWA process and 10.50% are transported to other MSWI and treated with FLUWA externally. Internal treatment means that the filter ash is treated at the location of the incineration. External treatment leads to an additional transport.

No FLUREC: In one Swiss MSWI (Zuchwil SO) an extended process called FLUREC is operated routinely since December 2013 (KEBAG 2014:5). The FLUREC process is an extension of the existing FLUWA process and produces *pure zinc metal* directly at the MSWI site, instead of exporting the metalliferous hydroxide cake. The FLUREC process in Zuchwil is expected to treat 7500 tons of filter ash per year (including ash imports from other plants) and is expected to produce 1000 tons of pure metallic zinc per year, as well as 200 kg of a lead-rich precipitate recycled off-site (Schlumberger & Bühler 2013). Since this new process was only becoming fully operational in Decmeber 2013, which is outside the temporal scope of the inventories created here, and only trial runs were performed previously, it is not included in the technology mix here. In the future, the FLUREC process might become more relevant.

Residual landfill: filter ashes not treated in a FLUWA process are assumed to be mixed with sludges from the MSWI's own wastewater treatment, solidified with cement, and landfilled in a residual material landfill. This is the conventional fate for APC residues in inventories since 1996.

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[3] Usually the underground deposits in Herfa Neurode and Heilbronn. A small fraction was intermittently also delivered to the now-defunct recycling facility Citron (Centre International de Traitement et de Recydage des Ordures Novices) in Rogerville, France. The Citron site was closed down in December 2010 after police investigations due to severe risks to the public health.

Tab. 2.1 Data on Swiss filter ash treated with the FLUWA procedure.

Swiss MSWI plants 2012 [1]	**Specific filter ash generation** [2] t FA/t MSW	**Filter ash generation per year** [3] t FA/yr
With internal FLUWA treatment		
Bern BE	0.0172	2'001
Thun BE	0.0256	3'570
Posieux FR	0.0325	3'007
Niederurnen GL	0.0174	2'011
Trimmis GR	0.0154	1'559
Buchs SG	0.0200	2'781
Kirchberg (Bazenheid) SG	0.0134	2'625
Zuchwil SO	0.0114	2'648
Giubiasco TI	0.0200	3'547
Tridel/Lausanne VD	0.0225	4'072
With external FLUWA treatment		
Luzern LU	0.0200	1'875
Weinfelden TG	0.0142	2'063
Hinwil ZH	0.0219	4'236
All other MSWI without FLUWA	0.0226	41'890
Total	**0.020**	**77'885**
	Filter ash treatment mix	
	Share internal FLUWA treatment	35.72%
	Share external FLUWA treatment	10.50%
	Total share FLUWA treatment	**46.22%**
	Total share landfilling	**53.78%**

1 Plants with internal or external FLUWA treatment as of 2012 based on information contained in (Bühler & Schlumberger 2012:9) with one correction: MSWI Hagenholz (ZH) is not counted, as by 2012 the FLUWA treatment was commissioned, but only started operating in late 2014 (ERZ 2015).

2 Data based on latest available data for 2004 and 2006 (mean value) from (BAFU 2008:97). For non-reporting MSWIs a generic value of 0.02 kg filter ash/kg incinerated waste is used.

3 Based on specific filter ash production (the previous column) and incinerated waste masses for 2012 given in (Hügi 2012).

Technology mix: Technology mix means that a process or activity does not represent *one* particular technology choice but is a *mixture* of several choices[4]. For the technology mix applied in the present inventories this means that on average 46.22% of the generated filter ash are treated in a FLUWA process (internal or external) and the remaining 53.78% is landfilled in the conventional residual landfill. Of the FLUWA-treated filter ash, a share of 22.71% is first transported to another MSWI.

Datasets incorporate technology mixes. A share of 53.78% of any waste in the technology mix will be modelled as if incinerated in a conventional MWSI with landfilling of ashes as described in (Doka 2013). The remainder will be modelled as if incinerated in a MWSI with FLUWA. The characteristics of a plant with FLUWA technology by itself is described in the following chapters. The created unit process inventories will contain a weighted mixture of the two filter ash treatment technologies in one process as a technology mix.

4 Such technology choices have already ubiquitously employed in process inventories of MSWI, e.g. the mixture of different energy utilisations in produced heat vs. electricity , or the different technologies employed for the DeNOx stage.

3 Production volumes

For each of the 57 waste fraction incineration datasets, production volumes are given. The production volume here equates to the mass of a waste fraction incinerated annually in Switzerland. The production volumes are adapted from the GLO production volumes estimated in (Doka 2013), but based on an annual municipal waste mass of 3.02 million tonnes incinerated in Switzerland, instead of the global incinerated municipal waste mass of 200 million tonnes used for the global production volumes. The mass of 3.02 million tonnes is the average of incinerated municipal waste of the years 2006-2012, taken from (Hügi 2013a) and augmented with waste generated abroad, but incinerated in Switzerland of approximately 0.29 million tonnes (Hügi 2013b).

4 FLUWA process description

The core concept of the FLUWA filter ash treatment is to remove a large part of pollutants in filter ash with an acid extraction (acid leaching). As extraction liquid the incinerator's own flue gas scrubber liquid is used, which contains e.g. sulfuric and hydrochloric acid from scrubbing sulfur and chlorine from raw gas. The extraction step produces two material streams: the extraction liquid (filtrate 1) containing the extracted pollutants and the matrix rest, i.e. the washed, depleted solid bulk ash matrix.

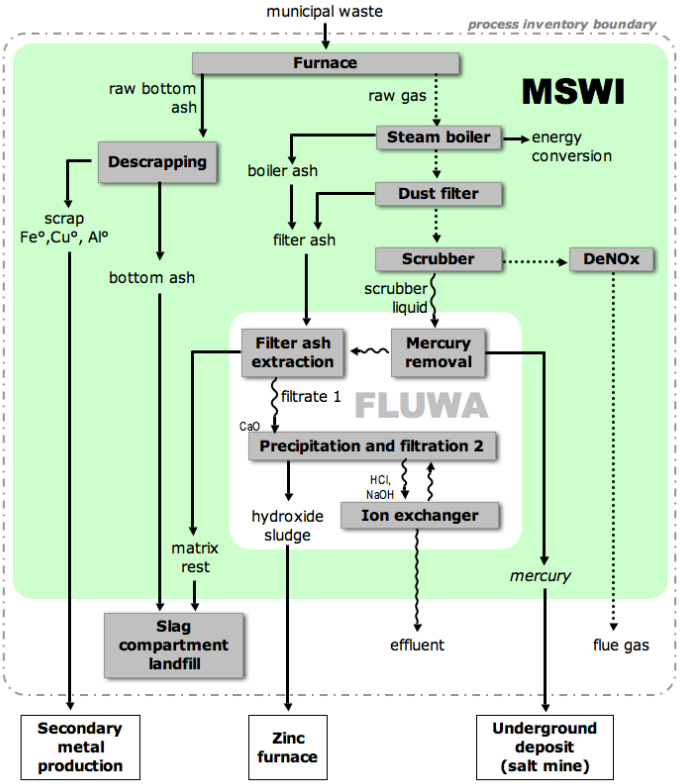

Abb. 4.1 Simplified scheme of the FLUWA process within the MSWI process and the process inventory boundary. The extraction liquid is especially rich in zinc and lead. Metals and sulfur are precipitated by adding burnt lime and filtered into a metalliferous hydroxide cake. This cake is recycled externally in Waelz kilns to secondary zinc and lead metal. The remaining water after the second filtration is treated internally with ion exchangers prior to discharge.

The solid matrix rest remaining after the initial filter ash extraction step has reduced concentrations of heavy metals and solubles and can be disposed together with the incinerator bottom ash without violating the criteria of the slag compartment landfill, which are comparatively less stringent than the criteria of the residual landfill, where untreated filter ash is traditionally landfilled.

The main pecuniary advantages of the FLUWA process are therefore:

- Filter ash and scrubber liquid can be used to produce secondary metals instead of landfilling them
- The landfilled matrix rest is largely stripped from pollutants and can be landfilled in a less costly type of landfill
- Neutralisation agents to treat acidic scrubber liquids are reduced by filter ash.

A disadvantage is that more wastewater and – for some elements – more heavily loaded wastewater is created. For instance chlorine and other salts originally in filter ash are washed off into wastewater.

Discharge of this wastewater can run short the gap given by plant's legal thresholds for wastewater discharge.

4.1 Waste-specific inventory model for FLUWA

The goal of the inventories presented here are to capture the burdens of the incineration different waste fractions, including subsequent treatment of secondary or tertiary waste. These waste-specific inventories are achieved by creating waste-specific models of the processes involved and applying different inputs waste fraction compositions. Waste-specificity here means that the different chemical elements present in a waste are heeded and their fate within the processes. For many parts of the waste incineration process chain such models are presented in (Doka 2007, 2013). In this report, the modelling of the FLUWA compatible with those previous reports is presented, which involves creating a set of transfer coefficients that describe how chemical elements move through the process on average. Also consumption of auxiliaries can be assigned to different mass flows. To simplify the presentation, the derived transfer coefficients for the FLUWA model are expressed relating to the FLUWA input, i.e. filter ash and scrubber liquid (while the transfer coefficients in the MSWI model generally relate to the municipal waste input into the furnace), while the functional unit of the created inventories remains 1 kilogram of wet waste as delivered to the MSWI plant.

The model is based as far as possible on published literature data detailing the observed and reported characteristics of the FLUWA process. This is the so-called "working point data" describing the typical behaviour of the process with the average municipal waste. The waste-specific inventories then represent only a part of the burdens and demands of the whole process, which are the parts assignable to a particular waste composition, but based on the average process behaviour.

4.1.1 Working point data

General considerations

From available publications and literature sources data on dry mass amounts and elemental compositions of the different input, intermediate and output materials of the FLUWA process was researched; see Tab. 4.2 on page 12. Calculating median values from the available data results in typical data for those materials, which is considered the working-point data. The use of a median value dampens the influence of extreme data points. Over 800 single data points were evaluated, 371 of them relating to the composition of the produced hydroxide sludge. With the typical masses and compositions, it is possible to establish average elemental transfer coefficients that occur during typical operation of the FLUWA process. For a waste-specific calculation, the obtained set of average transfer coefficients can then be combined with the waste-specific FLUWA input materials generated in the already established waste-specific MSWI model.

The FLUWA process is broken down into several steps as shown in Fig. 4.1.

Tab. 4.1 The steps of the FLUWA process with respective inputs and outputs

Inputs		FLUWA step		Outputs
B.1 Flue gas scubber liquid + ion exchanger	→	**1. Pre-treatment of scubber liquid** (demercurisation)	→	B.2 Treated scubber liquid + B.3 spent ion exchanger with mercury
A. Unwashed filter ash + B.2 Treated scubber liquid + flushing water	→	**2. Filter ash extraction and filtration 1**	→	C. matrix rest (washed ash) + D. filtrate 1
D. filtrate 1 + burnt lime (CaO) + Sodium hydroxide (NaOH)	→	**3. Hydroxide precipitation and filtration 2**	→	E. Metalliferous hydroxide sludge + Filtrate 2
Filtrate 2	→	**4. Water treatment** (ion exchanger)	→	F. Effluent

blue Materials with some literature data on dry mass amounts and elemental composition

grey Materials without any literature data

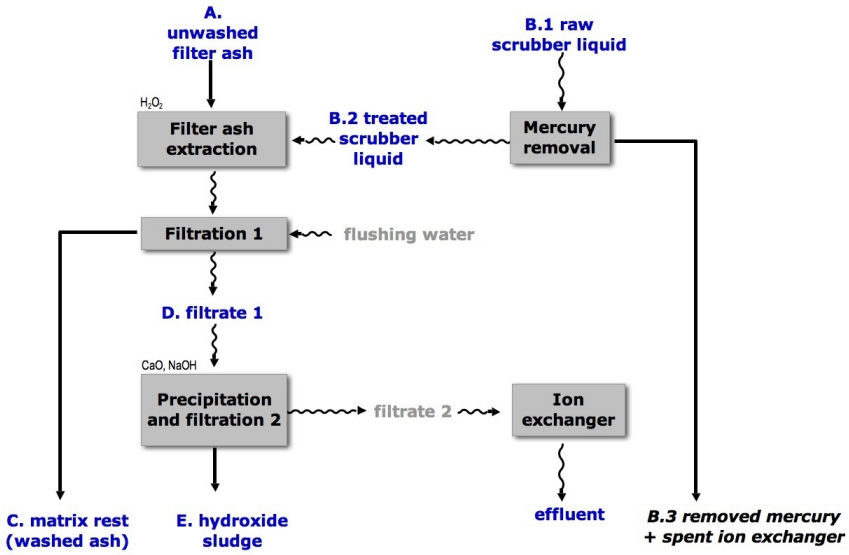

Fig. 4.1 Breakdown of the FLUWA process into a series of steps

Tab. 4.2 Literature sources to derive FLUWA transfer coefficients in this study

Material	Literature sources	Median mass flow per kg incinerated municipal waste
A. Unwashed filter ash	Bösch et al. 2011:Tab 2; Bösch et al. 2011:Tab A7.1; Bühler & Schlumberger 2011; Bühler & Schlumberger 2010:Tab 2; Schlumberger 2011:15; Bühler & Schlumberger 2011; Schlumberger & Bühler 2013:Fig 5+6; Schlumberger & Bühler 2013:Tab 1; Schlumberger & Bühler 2013:Fig 14; Syc et al. 2010:Tab 2; Doka 2013	0.02 kg dry mass
B. Scrubber liquid	Bühler & Schlumberger 2011; Doka 2013	0.07 L
C. Matrix rest	Bühler et al. 2007:3; Bühler & Schlumberger 2011:Tab 4; Schlumberger 2011:15; Schlumberger & Bühler 2013:Fig 14; Syc et al. 2010:Tab 4	0.0143 kg dry mass
D. Filtrate 1 *	Schlumberger 2010:Tab 1; Jutz & Schlumberger 2011:25; Schlumberger 2005:Tab 5	0.0777 L
E. Metal hydroxide	Schlumberger 2005:Tab 6; Bühler & Schlumberger 2010:Tab 6; Schlumberger 2014:4; Furgler 2014:15	0.001966 kg dry mass
F. Effluent	Bergomi 2014; ACR 2013; ACR 2012; Fornara 2011; KEBAG 2013; KEBAG 2012; KEBAG 2011; KEBAG 2010;	0.0777 L

* The flushing water used after extraction is approximated with pure water, i.e, it dilutes the filtrate 1, but does not add any element masses.

4.1.2 Pre-treatment of scrubber liquid (demercurisation)

Bühler & Schlumberger 2010 state that the demercurisation decreases the mercury concentration in the scrubber liquid from 1 – 10 mg/L to below 0.01 mg/L. Using the mean of those ranges a removal efficiency of 99.91% can be estimated, i.e. from 5.5 to 0.005 mg/L. This factor is used in the model to alter the mercury concentration in the treated scrubber liquid. Other elements are assumed to remain unaffected.

4.1.3 Extraction and precipitation

The demercurised scrubber liquid (B.2) is mixed with the raw filter ash (A) in the extraction step. The acid in the liquid extracts heavy metals from the ash, while calcium from the ash dissolves and precipitates with the sulfate from the scrubber to gypsum. The suspension is filtered into a solid (C. matrix rest) and a metalliferous liquid (D. filtrate 1). The metalliferous filtrate 1 of the extraction step is mixed with burnt lime to establish a high pH. A metalliferous hydroxide precipitate (E.) results, which is separated in a second filtration. The liquid phase remaining from the second filtration is treated with ion exchanger to remove the remaining pollutants. The removed pollutants in the ion exchanger regeneration solution output are recycled back into the FLUWA precipitation process. Since the literature data on hydroxide sludge is based on real operations, the effect of this recycling is already included in the established hydroxide compositions.

In earlier FLUWA operations, the matrix rest was sometimes returned into the MSWI's furnace. Since the matrix rest contains a lot of sulfur in gypsum this could lead to an additional sulfur loading of the flue gas and significantly increased expenditures for sulfur removal during scrubbing. This practice has therefore been discontinued and the matrix rest is combined directly with bottom ash instead.

Fig. 4.2 The matrix rest (washed filter ash) from the FLUWA process (from Schlumberger 2011)

Fig. 4.3 Hydroxide sludge sample from the FLUWA process (from Schlumberger 2014)

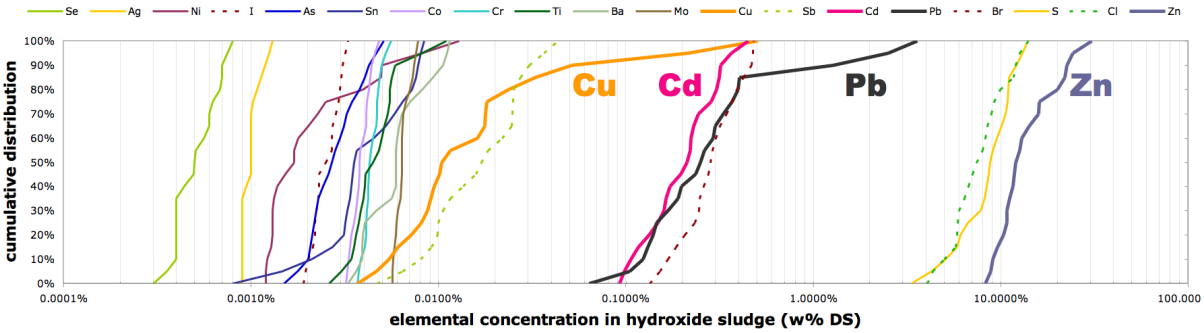

Fig. 4.4 Distribution of the literature values of the composition of FLUWA hydroxide sludge.

4.1.4 Calculation of FLUWA extraction and precipitation transfer coefficients

The behaviour of the filter ash extraction and filtrate precipitation is modelled in a summary fashion. Transfer coefficients are established based on the generated outputs alone – C. matrix rest, E. hydroxide sludge, and F. effluent. I.e. the sum of the outputs is taken to be equal to the input to filter ash extraction. This gives the most reliable data. Due to large variations in the available literature data a separate calculation of transfer coefficients for the extraction and precipitation steps from inputs and outputs did not yield trustworthy results.

Eq. 4.1
$$TK_{Matrix\ rest} = \frac{mass\ in\ matrix\ rest}{(mass\ in\ matrix\ rest + mass\ in\ hydroxide\ sludge + mass\ in\ \ final\ effluent)}$$

Eq. 4.2
$$TK_{Hydroxide\ sludge} = \frac{mass\ in\ hydroxide\ sludge}{(mass\ in\ matrix\ rest + mass\ in\ hydroxide\ sludge + mass\ in\ \ final\ effluent)}$$

Eq. 4.3
$$TK_{Effluent} = \frac{mass\ in\ effluent}{(mass\ in\ matrix\ rest + mass\ in\ hydroxide\ sludge + mass\ in\ \ final\ effluent)}$$

The transfer coefficients determine the fate of chemical elements. Oxygen mass in outputs is corrected based on oxidised masses of the chemical elements in the outputs. Based on the obtained total dry mass, additional water content is calculated, to arrive at the total wet mass of the outputs. Employed water concentration in the matrix rest output is 46.4% and 75% in the hydroxide sludge, based on (Bühler & Schlumberger 2011:Fig.11).

4.1.5 Extrapolations

The complied transfer coefficients are shown in Appendix A on page 23.

For ten elements literature data on all outputs was available and FLUWA transfer coefficients could be determined (S, Cl, F, Cd, Cr, Cu, Hg, Ni, Pb, Zn). For the rest some approximations were made.

For elements without any literature data, or only data for one output, direct approximations from chemically similar elements were made. Similarity was based on behaviour of the elements in acidic environments, since the crucial step in FLUWA is the extraction with acid. The approximation used is indicated in Appendix A on page 23. E.g. bromide is approximated with chloride, which is indicated by the text "like Cl". Elements fully approximated are B, Br, I, Ag, Ba, Mo, Se, V, Be, Sc, Sr, Ti, Tl,

W. For average incinerated waste these approximations make up 3% 2.4%, and 1.3% of the dry mass content of matrix rest, hydroxide sludge and effluent output, respectively.

Frequently literature data on matrix rest and hydroxide sludge is available, but data on the final effluent is missing. Here it was assumed that the FLUWA precipitation step has identical retention performance to a conventional MSWI wastewater treatment stage in separating precipitated solids from effluent. An element-specific amount of the mass entering the precipitation stage was assumed to end up in the final effluent, using conventional MSWI wastwater efficiencies. The transfer coefficient for hydroxide sludge (the precipitate) was corrected for the amount going into effluent; usually a small amount. This was done for C, N, As, Co, Mn, Sb, Sn, Si, Fe, Ca, Al, Mg.

For phosphorus the TK for hydroxide sludge was set identical to that of sulfur. Using the behaviour of phosphorus in a conventional MSWI wastwater stage a TK for effluent was derived (and the TK hydroxide sludge corrected). The reminder to 100% was used as the TK for the matrix rest.

For molybdenum a TK for matrix rest was estimated comparing literature data on FLUWA input and matrix rest output. For the other two outputs the remainder was split up into hydroxide sludge and effluent according to the behaviour of molybdenum in a conventional MSWI wastwater stage.

For sodium and potassium a TK for matrix rest and hydroxide sludge was available from literature data, but not for the effluent. The TK for hydroxide sludge was corrected to produce an effluent output based on the behaviour of *chlorine* in the FLUWA precipitation step. Using the conventional MSWI wastewater treatment performance here, the modelled hydroxide sludge would contain too much sodium and potassium. Since these are well-soluble elements, a wash-off from the hydroxide is likely.

4.2 Discussion of FLUWA transfer coefficients

The mean transfer coefficients for the FLUWA process established in this study are based on a broad compilation of literature data on material compositions and total mass flows. To a limited extent, they can be compared with transfer data given by BSH, the manufacturers of the FLUWA process, in (Bühler & Schlumberger 2010, Schlumberger 2011). There the efficiency of the FLUWA extraction step for four elements is given. The extraction step is only step 2 in Tab. 4.1 on page 11. The extracted part in this step is the fraction not going into the matrix rest. The extraction transfer coefficient of the present model can therefore be obtained as the full complement of the transfer coefficient into the matrix rest, see Eq. 4.4 below. The comparison is shown in Tab. 4.3 and Fig. 4.5.

Eq. 4.4 $$TK_{Filtrate\,1} = 1 - TK_{Matrix\,rest}$$

Tab. 4.3 Comparison of transfer coefficients of the extraction step of FLUWA with manufacturer's data

	Cadmium Cd	Copper Cu	Lead Pb	Zinc Zn
TK FLUWA filtrate 1 This study	79.03%	0.81%	7.52%	54.22%
FLUWA metal recovery (Schlumberger 2011)	80 – 95%	40 – 80%	40 – 90%	60 – 90%
FLUWA extraction efficiency (Bühler & Schlumberger 2010)	85 – 93%	20 – 45%	40 – 70%	60 – 85%

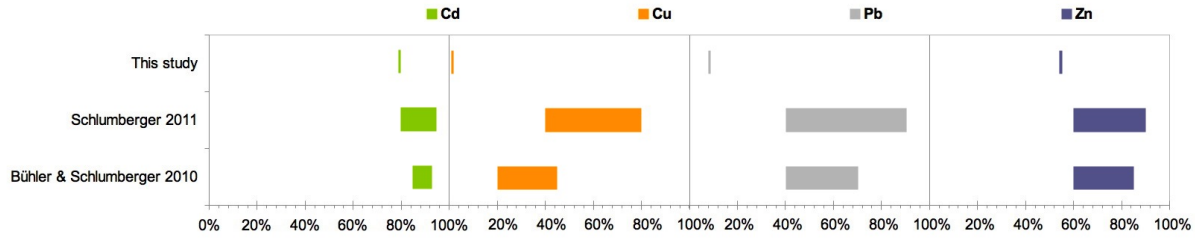

Fig. 4.5 Comparison of transfer coefficients of the extraction step of FLUWA with manufacturer's data

The transfer coefficients derived in the present study are generally lower than the ranges given by the FLUWA manufacturer. Especially copper and lead show very low extraction rates.

There are indications that the manufacturer uses too optimistic values. For instance (Bühler & Schlumberger 2010) state that the hydroxide sludge from 100'000 tonnes of waste would contain 60 tonnes of zinc. At 2 kg hydroxide sludge dry matter per tonne of waste (same source, Fig. 11), this would correspond to a zinc concentration of 30% in hydroxide sludge dry matter. This is however the *maximal* concentration value given by the same authors (same source, Tab.6). It therefore seems the stated separated zinc mass is based on *maximal* values, rather than *typical or average* values. In the field, one MSWI operator reports obtaining 17, resp. 21 tons of zinc from burning 100'000 tons of waste[5], clearly lower than the 60 t stated above.

It seems that even by using only figures given by the FLUWA manufacturers, their published extraction efficiencies can be called into question. Based on data on typical total mass and composition given in (Bühler & Schlumberger 2010) one can for example calculate following transfer coefficients into hydroxide sludge (where 100% is the input to the FLUWA extraction step). The calculation is shown in detail in Appendix B on page 24.

[5] In the MSWI Giubiasco 31 tonnes of zinc in hydroxide sludge are reported to be gained from burning 180'429 tonnes of waste in 2013 (Bergomi 2014), while in 2012 an annual total of 38 tonnes of zinc are gained from burning 177'331 tonnes of waste (ACR 2013).

Tab. 4.4 Transfer coefficients for the FLUWA process calculated on data given in (Bühler & Schlumberger 2010)

	Minimal [1]	Maximal [1]
Cd	54.4%	90.4%
Cu	1.7%	7.2%
Pb	4.7%	19.6%
Zn	37.3%	66.1%

1 Minimal and maximal values are obtained by assuming strong covariance or dependent uncertainties, e.g. implying hydroxide sludge with low zinc content derives from filter ash and scrubber liquid with low zinc content.

With the assumption that transfer into final effluent is relatively small, these transfer coefficients should correspond roughly to the extraction efficiency, i.e. transfer coefficients into filtrate 1. In their table 3 (Bühler & Schlumberger 2010) give following ranges for the efficiencies.

Tab. 4.5 Transfer coefficients for the FLUWA process given directly in (Bühler & Schlumberger 2010)

	Minimal	Maximal
Cd	85%	93%
Cu	20%	45%
Pb	40%	70%
Zn	60%	85%

As can be seen, the extraction efficiencies calculated from the detail data (Tab. 4.4) are generally lower than the efficiencies given directly by the same authors (Tab. 4.5). While for cadmium there is a fair overlap, zinc is clearly lower and lead and copper are very much lower. This is the same tendency that could be observed in Fig. 4.5 where also lead and copper have very low transfers.

These discrepancies also highlight the variable nature of the involved materials, where it becomes difficult to pinpoint typical system behaviour. This is also evidenced by the two ranges for copper extraction given by the FLUWA manufacturers themselves, which are hardly overlapping, i.e. (40 – 80% vs. 20 – 45%) in Fig. 4.5. Another aspect could be that the manufacturers might in some cases have been using older data. In the last 20 years the concentration of cadmium, copper, lead and zinc in Swiss municipal waste appears to have *decreased* in the range of 16% – 34% (Doka 2013:46, Morf 2006). Older FLUWA performance data might not be reproducible with the currently lower element flows into MSWI.

It has also to be borne in mind that the produced hydroxide sludge makes up only about 10% of the dry mass input to FLUWA and only about 0.2% of the initial input to the incinerator. This narrowing of the mass base tends to amplify the uncertainty already contained in the input materials onto the output compositions. The variability in the composition of the produced hydroxide sludge as derived from the literature survey (sources as stated in Tab. 4.2) is shown in Fig. 4.4.

The use of transfer coefficients can reduce this variability to a certain degree. Transfer coefficients found in this study appear reasonable as they appear to reflect chemically reasonable behaviour: Dissolvable elements like chlorine, fluorine, potassium, or sodium predominantly remain with the liquid phase flows; refractory elements like silicon, iron, aluminium, or magnesium largely remain with the solid phases. Also elements like As, Sb, or Cr have low extraction rates and remain predominantly with the matrix rest, which is in accordance with low solubility of oxianion-forming elements in acidic solutions.

In the present study the derived transfer coefficients in Tab. 7.1 on page 23 are used, since they are based on a large data base gathered from diverse literature sources trusted to depict in their median values the typical behaviour achieved in the field. The data base includes also data in publications by the manufacturer, i.e. by Anton Bühler and Stefan Schlumberger).

4.3 Auxiliaries consumption

Electricity demand

The FLUWA process requires 146.3 kWh of electricity per tonne of untreated filter ash input (Bösch et al. 2011:19). In the waste-specific model, 0.1463 kWh is assigned per kg of untreated filter ash arriving at the FLUWA process start. For example for 1 kg average municipal waste and 100% FLUWA this makes up about 0.0031 kWh, which represents roughly only 3% of the gross electricity demand of an average MSWI operation.

Since the FLUWA process includes its own effluent treatment, the energy and expenditures of the conventional MSWI wastewater treatment are reduced in the modelling of the technology mix. This is heeded by accordingly reducing the allocand mass arriving in conventional wastewater treatment. I.e. the mass diverted into the FLUWA process reduces the mass treated in conventional wastewater treatment and therefore electricity consumption (Doka 2013:20). The reduced mass in wastewater treatment affects also the auxiliaries used only in *wastewater treatment*: $FeCl_3$, TMT15, Polyelectrolyte, HCl.

Calcium oxide CaO

In a conventional MWSI calcium oxide is used to neutralise the acidic scubber liquid. With the FLUWA process a part of this neutralisation is effected by mixing the scrubber liquid with the alkaline filter ash (Bühler & Schlumberger 2010, BSH 2012). The operators at MSWI Emmenspitz (KEBAG) in Switzerland report a reduction in the consumption of CaO in the field of 47.2 kg per tonne of filter ash input[6].

In the technology mix this effect is heeded by reducing the conventional consumption of CaO according to the mass of filter ash input into the FLUWA process. Per kilogram of filter ash in FLUWA a reduction of 0.0472 kg CaO is heeded. For example for average waste and 100% FLUWA the reduction amounts to approximately 30%.

Hydrogen peroxide H_2O_2

Hydrogen peroxide is used in the extraction step to oxidise iron into its trivalent form, which precipitates and thus avoids transferring it into the filtrate. Per kilogram of filter ash in FLUWA a consumption of 0.0845 kg hydrogen peroxide H_2O_2 is given in (Bösch et al. 2011:19). This material is also allocated simply to the filter ash input into the FLUWA process.

[6] The operators note that in 2012 the processing of external filter ash had reduced the consumption of calcium oxide by 176 tonnnes compared to the previous year (KEBAG 2013:41). The added external filter ash amounted to approximately 3731 tonnes per year . Therefore one kilogram of filter ash can replace roughly 0.0472 kg CaO. In (Bösch et al. 2011:19) a fourfold reduction is given (0.1975 kg CaO per kg FA). This is an unreferenced figure, but probably based on a stochiometric calculation. In the present study the figure from the real operation at KEBAG MSWI Emmenspitz is used.

Hydrogen chloride HCl

Hydrogen chloride is used to balance the pH of the effluent prior to discharge. Per kilogram of filter ash in FLUWA a consumption of 0.0332 kg hydrogen chloride HCl is given in (Bösch et al. 2011:19). This demand is also allocated simply to the filter ash input into the FLUWA process and added to the HCl demand of the conventional part of the MSWI (WWT).

Sodium hydroxide NaOH

Sodium hydroxide is used to increase the pH after the acidic extraction and effectuate the hydroxide precipitation. Per kilogram of filter ash in FLUWA a consumption of 0.0241 kg sodium hydroxide NaOH is given in (Bösch et al. 2011:19). This demand is also allocated simply to the filter ash input into the FLUWA process and added to the NaOH demand of the conventional part of the MSWI (scrubber).

Mercury removal

According to (Bühler & Schlumberger 2010: Fig.11) the demercurisation treatment of the scrubber liquid produces 20 grams of used ion exchanger per tonne of filter ash input into FLUWA. In this figure ca. 1 gram of removed mercury is included. Therefore in the present model 19 kg of ion exchanger resin is inventoried for each kilogram of removed mercury. The efficiency of mercury removal was described above in chapter 4.1.2 'Pre-treatment of scrubber liquid (demercurisation)' on page 12.

Schenk (2011:17) notes that the mercury gained from FLUWA can potentially be recycled, but due to lack of mercury demand is currently not. Bans on the use of mercury, like the 2013 Minamata Convention by the UN or the 2003 Restriction of Hazardous Substances (RoHS) Directive by the EU, will probably amplify this situation further. The appropriate fate for the spent ion exchanger is therefore the underground deposit. For the current model, the disposal of spent ion exchanger charged with mercury is inventoried with the available approximation of "treatment of spent activated carbon with mercury, underground deposit".

Additional filter ash transport

In ecoinvent v3+, transport of materials is usually taken care of in a central fashion in market datasets (instead of letting the dataset authors lookup standard transport distances). This means that transport services must usually not be inventoried for input or output materials. However internal transports within the activity must be recorded. Some filter ash is not treated at its production site, but in a different incinerator plant. This leads to an additional transport, which must be recorded in the inventory, since within the database model, it is not subject to a market dataset.[7]

A share of 22.71% of the *treated* filter ash is first transported to another MSWI plant, cf. Tab. 2.1 on page 7. The transported mass is calculated waste-specifically based on the input waste composition, transfer coefficients into filter ash and transfer coefficients of the FLUWA process.

An average transport distance of 118 km is assumed based on the approximate locations of the generating and receiving facilities, weighted by the annually produced filter ash mass.

[7] This is similar to the internal transports of bottom ash to slag compartment and residual material to the residual material landfill. These are internal transports since the inventoried waste incineration activity also includes the landfilling of its residues, in order to reduce the number of single datasets to save database space.

4.4 Are dioxin emissions from landfills relevant in LCA?

The landfill models employed in ecoinvent to date have no fate modelling of *organic compounds*. Only landfill behaviour of *chemical elements* and their speciation is considered. With FLUWA the washed ash (matrix rest) is deposited together with bottom ash. Since the dioxin concentration in the former is much higher than in the latter, there is some concern that the larger dioxin load will lead to detrimental effects[8].

A coarse estimation is attempted here, to check if inclusion dioxin emissions from landfills is a relevant burden in a life cycle perspective. No detailed modelling of dioxin fate in landfills is performed, instead it is assumed that the characterisation factor for an emission of dioxin into *industrial soil* gives an appropriate damage estimate of dioxin in landfills. Any retention and degradation behaviour of the landfill is assumed to be represented by the LCIA soil behaviour. This approach tends to overestimate burdens, as in common LCIA models "soil" is typically the upper 20 centimetres of soil which is relatively exposed, while a landfill body is several meters underground with reduced dynamics regarding gas and water exchange, vegetation, and fauna. On the other hand, degradation of dioxin is likely to be reduced in deeper soil, which might balance out the slower transport dynamics in deeper soil.

It is estimated here how a consideration of the dioxin flows to landfill would change existing LCA results. Dioxin concentration in washed filter ash, i.e. the matrix rest, is estimated to be 2 micrograms TEQ per kg filter ash, based on (UMTEC 2009). Dioxin concentration in bottom ash is estimated to be 0.0145 micrograms TEQ per kg bottom ash, based on the mean of a range given in (Schlumberger 2005:9). Characterisation factors for dioxin emissions into *industrial soil* regarding human toxicity, freshwater ecotoxicity, and terrestrial ecotoxicity are 10'123'780, 49'1211, and 26'909 kg 1,4-DCB-Eq per kg dioxin TEQ respectively, for an infinite modelling time horizon (CML 2013). From Eco-indicator'99'HA an aggregated factor of 199'673 points per per kg dioxin to industrial soil is also used (Goedkoop et al. 2001).[9] As a reference burden, LCIA results for the incineration of *average municipal solid waste* are taken from ecoinvent v3.1, cut-off system model. Assuming 0.2 kg of bottom ash and 0.014 kg of matrix rest per kilogram municipal waste input, it is found that **the additional ecological burden from dioxin emissions is minor and would increase results at most by 0.11%**. The most susceptible of the investigated impact categories is terrestrial ecotoxicity. The increase for the Eco-indicator'99HA method is 0.031%. So, although the combined landfilling of treated filter ash with the bottom ash does increase the dioxin content of the latter by a factor of 9.6, in an LCA perspective of waste incineration this effect appears not crucial or a game-changer. This effect is also put into perspective by observing that also *untreated* filter ash would lead to dioxin emissions, only in another type of landfill.

It can therefore be estimated that the inclusion of dioxin emissions from landfills is unlikely to play an important role in LCA of municipal waste incineration. Specific waste fractions, especially those generating large amounts of filter ash, like for instance PVC, could be more affected. Also not included in this estimation are industrial wastes.

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[8] "Dioxin" stands for the sum parameter obtained by weighting the different dioxins and furans into toxicity equivalents (TEQ).

[9] The more recent ReCiPe LCIA method has no characterisation factor for dioxin in soil.

5 Results

This is only a technical report describing the newly elaborated base data for the additions to the incineration inventory model of (Doka 2013). The new incineration inventories including filter ash treatment are expected to be incorporated in ecoinvent v3.2 (state of affairs on September 2015). Inventory results are not yet available. Nevertheless some general observations can be made.

An obvious comparison would be the new results with filter ash treatment vs the prior results without filter ash treatment. Interesting aspects of this comparison would firstly be the differences due to the recyclable metals gained in the FLUWA treatment. On one hand usable recyclates are generated which – depending on the chosen allocation method – reduces the burden allocated on the waste disposal function. Another interesting comparison would be zinc generated from FLUWA recyclates vs. zinc from primary ore sources. Isolating the recyclates has also the effect that they do not end in landfill and therefore are not partly emitted, but kept in the technosphere.

The not recycled part of the filter ash has two fates: the solid residue (matrix rest) is landfilled with bottom ash in a slag compartment. Here it would be interesting to see the effects of changing the type of landfill from residual landfill to slag compartment. The slag compartment has a somewhat different emission behaviour than a residual landfill (cf. Doka 2003, Fig 12.1, p.93). It is expected for instance that oxianion-forming metals and semimetals like chromium, antimony, arsenic, molybdenium, or selenium have *better* retention behaviour in a slag landfill. On the other hand elements like cadmium or mercury have worse retention behaviour in the slag landfill. So FLUWA can also lead to additional emissions.

The other not recycled part of the FLUWA process is leaving the wastewater treatment as effluent and is emitted to water. Especially well soluble elements in filter ash will tend to be emitted to water. In common LCIA methods only fluorine might have some relevance here, due to toxicity, while other elements like chloride, potassium, sodium are relatively benign. Seeing that also in a residual landfill fluorine would be completely emitted over long time frames, the net effect of additional emissions to water might indeed be small. But also here effects depend much on waste composition.

Finally, additional expenditures for operating the FLUWA process constitute an additional burden over incinerators without filter ash treatment. Bösch et al. 2011 found that with the functional unit of only filter ash treatment especially hydrogen peroxide constitutes a considerable burden. Within the boundaries of this study, which looks at the whole incineration process and not only the filter ash treatment, the relevance of hydrogen peroxide will be "diluted".

How these effects balance out regarding the burden placed on waste disposal function ultimately depends much on the waste fraction incinerated, the concentration of elements in waste, and the applied allocation and LCIA method.

6 Abbreviations

APC	Air pollution control. The on-site treatment of raw flue gas of incinerators to reduce air and water pollutants.
FLUWA	Treatment of MSWI filter ash using scrubber liquids and producing a recyclable, zinc-rich hydroxide sludge. From German 'Flugasche' = fly ash and 'Wäsche' = scrubbing.
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incineration
TVA	The Swiss waste ordinance (German 'Technische Verordnung Abfälle')
t	metric ton = 1000 kilograms
kt	kilo ton = 1000 metric tons = 1 million kilograms
FA	Fly ash, filter ash. In this usually the sum of boiler ashes and filter ashes (from ESP or bag filter) is meant.
yr	year
WWT	Wastewater treatment, in this study usually the internal scubber liquid treatment in a conventional MSWI is meant.

7 Appendix A

Tab. 7.1 Transfer coefficients for the FLUWA process. 100% is the input to the FLUWA extraction step, i.e. filter ash and demercurised scrubber liquid.

Elem	TK Matrix rest		TK hydroxide sludge		TK final effluent	
O	88.79%	[1]	11.21%	[1]		
H	88.79%	like O	11.21%	like O		
C	88.79%	like O	5.6%	retrocalc from remainder to TK Matrix rest and Conventional MSWI-WWT	5.60%	retrocalc from remainder to TK Matrix rest and Conventional MSWI-WWT
S	65.44%	[1]	29.79%	[1]	4.77%	[1]
N			0.00%	retrocalc from TK Effluent and Conventional MSWI-WWT	100.00%	corrected for extrapolated TK MeOH
P	70.21%	remainder to 100%	29.23%	like S, [3]	0.562%	[2]
B	65.44%	like S	29.79%	like S	4.77%	like S
Cl	1.03%	[1]	5.28%	[1]	93.70%	[1]
Br	1.03%	like Cl	5.28%	like Cl	93.70%	like Cl
F	1.79%	[1]	5.44%	[1]	92.78%	[1]
I	1.03%	like Cl	5.28%	like Cl	93.70%	like Cl
Ag	99.19%	like Cu	0.81%	like Cu	0.00154%	like Cu
As	97.10%	[1]	2.90%	[3]	0.00000015%	[2]
Ba	99.75%	like Si	0.12%	like Si	0.12%	like Si
Cd	20.95%	[1]	79.03%	[1]	0.0148%	[1]
Co	75.87%	[1]	24.12%	[3]	0.00622201%	[2]
Cr	97.73%	[1]	2.23%	[1]	0.04%	[1]
Cu	99.19%	[1]	0.81%	[1]	0.001539%	[1]
Hg	98.94%	[1]	1.05%	[1]	0.01%	[1]
Mn	99.42%	[1]	0.57%	[3]	0.00830504%	[2]
Mo	43.67%	estimated from Input minus known outputs	55.53%	[4]	0.807%	[2], corrected for extrapolated TK Matrixrest
Ni	96.61%	[1]	3.36%	[1]	0.03%	[1]
Pb	92.47%	[1]	7.52%	[1]	0.00%	[1]
Sb	95.20%	[1]	2.40%	[3]	2.402%	[2]
Se	95.20%	like Sb	2.40%	like Sb	2.40%	like Sb
Sn	99.39%	[1]	0.30%	[3]	0.304%	[2]
V	97.73%	like Cr	2.23%	like Cr	0.04%	like Cr
Zn	45.78%	[1]	54.22%	[1]	0.001248%	[1]
Be	75.87%	like Co	24.12%	like Co	0.00622%	like Co
Sc	99.92%	like Ti	0.08%	like Ti	0.000829%	like Ti
Sr	91.45%	like Mg	2.74%	like Mg	5.81%	like Mg
Ti	99.92%	like Al	0.08%	like Al	0.000829%	like Al
Tl	96.61%	like Ni	3.36%	like Ni	0.0312%	like Ni
W	83.69%	like Ca	8.16%	like Ca	8.16%	like Ca
Si	99.75%	[1]	0.12%	[3]	0.123%	[2]
Fe	99.21%	[1]	0.78%	[3]	0.0078317%	[2]
Ca	83.69%	[1]	8.16%	[3]	8.157%	[2]
Al	99.92%	[1]	0.08%	[3]	0.0008286%	[2]
K	55.72%	[1]	2.36%	[5]	41.91%	[5]
Mg	91.45%	[1]	2.74%	[3]	5.806%	[2]
Na	42.01%	[1]	3.09%	[5]	54.90%	[5]

1 Derived from literature median data, cf. Tab. 4.2 on page 12

2 Derived from performance of conventional MSWI wastewater treatment and available TK hydroxide sludge 3 Corrected for extrapolated TK effluent

4 Corrected for extrapolated TK effluent and TK Matrixrest

5 remainder of matrix rest partitioned with the performance for chlorine retention in FLUWA WWT step

8 Appendix B

Calculation of FLUWA extraction efficiencies for four elements derived from data given in (Bühler & Schlumberger 2010).

Compositions of input and output materials are reproduced on the top part of the following table. Total mass amounts of these materials per kilogram incinerated municipal waste are quoted in the middle. At the bottom the mass flows of elements per kilogram incinerated municipal waste are calculated from the preceding data. At the bottom right finally transfer coefficients into hydroxide sludge are calculated and compared with the transfer coefficients for extraction given by (Bühler & Schlumberger 2010).

The observed discrepancies are discussed in chapter 4.2 'Discussion of FLUWA transfer coefficients' on page 15.

Compositions [1]		**Filter ash** Tab. 2 mg/kg DS	**Scrubber liquid** Tab. 1 mg/l		**Hydroxide sludge** Tab. 6 mg/kg DS		
Cadmium	**mean**	**600**	**2.25**		**4500**		
	min	550	0.5		3000		
	max	650	4		6000		
Copper	**mean**	**1275**	**5.5**		**600**		
	min	1200	2		200		
	max	1350	9		1000		
Lead	**mean**	**16500**	**55**		**21500**		
	min	15000	10		7000		
	max	18000	100		36000		
Zinc	**mean**	**42000**	**225**		**225000**		
	min	40000	50		150000		
	max	44000	400		300000		
Amount per kg MSW	Fig. 11, [3]	0.02 kg	0.07 L		0.002 (DS) kg		
		A	B	C = A+B	D	= D/C	
Mass flows per kg MSW [2]		**Filter ash** mg DS/kg MSW	**Scrubber liquid** mg DS/kg MSW	**Input to Extraction** mg DS/kg MSW	**Hydroxide sludge** mg DS/kg MSW	**TK Hydroxid sludge** calculated	**TK Extraction** Tab. 3
Cadmium	**mean**	**12**	**0.1575**	**12.1575**	**9**	**74.03%**	
	min	11	0.035	11.035	6	54.37%	85.0%
	max	13	0.28	13.28	12	90.36%	93.0%
Copper	**mean**	**25.5**	**0.385**	**25.885**	**1.2**	**4.64%**	
	min	24	0.14	24.14	0.4	1.66%	20.0%
	max	27	0.63	27.63	2	7.24%	45.0%
Lead	**mean**	**330**	**3.85**	**333.85**	**43**	**12.88%**	
	min	300	0.7	300.7	14	4.66%	40.0%
	max	360	7	367	72	19.62%	70.0%
Zinc	**mean**	**840**	**15.75**	**855.75**	**450**	**52.59%**	
	min	800	3.5	803.5	300	37.34%	60.0%
	max	880	28	908	600	66.08%	83.0%

1 The mean of compositions is calculated as the arithmetic mean of min and max value here.

2 The mean of mass flows is calculated based on total mass and mean composition.

3 Scrubber liquid volume based on 3500 kg liquid per 1000 kg filter ash given in (Schlumberger 2005:Fig.56). This number is uncritical for the four elements considered here.

9 References

ACR 2012 Azienda Cantonale dei Rifiuti (2012) Rapporto Ambientale 2011. Impianto Cantonale di Termovalorizzazione dei Rifiuti (ICTR), Azienda Cantonale dei Rifiuti (ACR), Giubiasco, Switzerland. http://www.aziendarifiuti.ch/Desktopdefault.aspx?tabId=84&languageId=1 (8 Feb 2015)

ACR 2013 Azienda Cantonale dei Rifiuti (2014) Rapporto Ambientale 2012. Impianto Cantonale di Termovalorizzazione dei Rifiuti (ICTR), Azienda Cantonale dei Rifiuti (ACR), Giubiasco, Switzerland. http://www.aziendarifiuti.ch/Desktopdefault.aspx?tabId=84&languageId=1 (8 Feb 2015)

BAFU 2008 BAFU (2008) Abfallwirtschaftsbericht 2008 - Zahlen und Entwicklungen der schweizerischen Abfallwirtschaft 2005–2007. Bundesamt Für Umwelt (Swiss EPA), Berne. http://www.bafu.admin.ch/publikationen/publikation/01009/index.html (5 Jan 2009)

BAFU 2014 Bundesamt für Umwelt BAFU (2014) Erläuterung zur Totalrevision der Technischen Verordnung über Abfälle TVA - 10.07.2014. Referenz/Aktenzeichen: N185-0625. BAFU, Berne. www.bafu.admin.ch/abfall/02202/12415/13332/index.html (15 Jan 2015)

Bergomi 2014 Bergomi T (2014) Rapporto Gestionale e Ambientale ICTR 2013. Impianto Cantonale di Termovalorizzazione dei Rifiuti (ICTR), Azienda Cantonale dei Rifiuti (ACR), Giubiasco, Switzerland. http://www.aziendarifiuti.ch/Desktopdefault.aspx?tabId=84&languageId=1 (8 Feb 2015)

Bösch et al. 2011 Bösch ME, Haupt M, Hellweg S (2011) Ökobilanzielle Untersuchung der sauren Wäsche von KVA Flugasche in der Schweiz. Endbericht (Version 1.7) 10.Okt 2011. ETH Zürich, Institut für Umweltingenieurswissenschaften, Gruppe für Ökologisches Systemdesign und Aveny GmbH, Zürich http://www.awel.zh.ch/internet/baudirektion/awel/de/betriebe_anlagen_baustellen/abfallanlagen/kehrichtverbrennung_kva.html (3 Oct 2012)

Bösch et al. 2014 Boesch ME, Vadenbo C, Saner D, Huter C, Hellweg S (2013) An LCA model for waste incineration enhanced with new technologies for metal recovery and application to the case of Switzerland. Waste Management Volume 34, Issue 2, February 2014, Pages 378–389 and Supplementary Material. www.fkit.unizg.hr/_download/repository/seminar_7.pdf (25 Feb 2015)

BSH 2012 BSH Umweltservice AG (2012) FLUWA - Filter & Flugaschenwäsche. FLUWA Referenzblatt. http://www.bsh.ch/upload/public/0/71/BSH-Umweltservice-AG-Referenzblatt-FLUWA-DE.pdf

Bühler & Schlumberger 2010 (BAFU) Bühler A., Schlumberger S. (2010) Schwermetalle aus der Flugasche zurückgewinnen: Saure Flugaschenwäsche - FLUWA Verfahren, ein zukunftsweisendes Verfahren in der Abfallverbrennung. In: KVA-Rückstände in der Schweiz - Der Rohstoff mit Mehrwert. 2010, Bundesamt für Umwelt (BAFU), Bern. http://www.bafu.admin.ch/publikationen/publikation/01538/index.html?lang=de&lang=de (27 Feb 2012)

Bühler & Schlumberger 2011 (ISWA) Bühler A., Schlumberger S. (2011) Metal recovery from air pollution control residues - Filter ash. 7th ISWA Beacon Conference on Waste to Energy in Malmö 3-4 November 2011 http://beacon-wte.net/index.php?id=38 and http://beacon-wte.net/Fileadmin/avfallsverige/Documentation_2011/2-5_BSH.pdf (28 Feb 2014)

Bühler & Schlumberger 2012 Bühler A., Schlumberger S. (2012) Urban mining: Metal recovery from fly and filter ash in Waste to Energy plants. BSH Umweltservice AG, Sursee, Switzerland. http://www.varmeforsk.se/files/program/askor/buehler_mindre.pdf (2 Oct 2014)

Bühler et al. 2007 Bühler A, Sigrist A, Häfliger B (2007) The acidic flyash washing process FLAWA. BSH Umweltservice AG, Sursee, Switzerland. http://www.bsh.ch/all/download/Flawa_EN.pdf (22 Jul 2007)

CML 2013 CML-IA Characterisation Factors update information version 4.2, released April 2013. Institute of Environmental Sciences (CML), Netherlands. http://cml.leiden.edu/software/data-cmlia.html (29 April 2014)

Doka 2003-II Doka G (2003) Life Cycle Inventories of Waste Treatment Services, part II: waste incineration. ecoinvent report No. 13, part III. Swiss Centre for Life Cycle Inventories, Dübendorf, 2003. http://www.doka.ch/13_II_WasteIncineration.pdf

Doka 2003-III Doka G (2003) Life Cycle Inventories of Waste Treatment Services, part III: Landfills - Underground Deposits - Landfarming. ecoinvent report No. 13, part III. Swiss Centre for Life Cycle Inventories, Dübendorf, 2003. http://www.doka.ch/13_III_Landfills.pdf

Doka 2013 Doka G. (2013) Updates to Life Cycle Inventories of Waste Treatment Services - part II: waste incineration.Doka Life Cycle Assessments, Zurich, 2013. Available at http://www.doka.ch/ecoinventMSWIupdateLCI2013.pdf

ERZ 2015 ERZ Entsorgung + Recycling Zürich (2015) Thermische Verwertung von Abfall Kehrichtheizkraftwerk Hagenholz. Tiefbau- und Entsorgungsdepartement Stadt Zürich, 6. Jan 2015. https://www.stadt-zuerich.ch/content/dam/stzh/ted/Deutsch/erz/Zuerich_Waerme/Publikationen_und_Broschueren/ZW_Broschuere_Hagenholz_1501.pdf (16 Jan 2015)

Fornara 2011 Fornara L. (2011) Rapporto Ambientale 2010. Impianto Cantonale di Termovalorizzazione dei Rifiuti (ICTR), Azienda Cantonale dei Rifiuti (ACR), Giubiasco, Switzerland. http://www.aziendarifiuti.ch/Desktopdefault.aspx?tabId=84&languageId=1 (8 Feb 2015)

Furgler 2014 W. (2014) 14 Jahre Hydroxidschlamm – ein Erfahrungsbericht. ZAR Informationsveranstaltung Erfolgreiche Ressourcenstrategie, 24. Oktober 2014, Zuchwil, SO, Switzerland. http://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Veranstaltungen/Info_2014/Walter_Furgler.pdf (3 Nov 2014)

Goedkoop et al. 2001	Goedkoop M, Spriensma R. et al. (2001) The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report. Third edition, 22 June 2001, Pré Consultants, Amersfoort, Netherlands.
Hügi 2012	Hügi M. (2012) Brennbare Abfälle in Kehrichtverbrennungsanlagen (KVA). Referenz/Aktenzeichen: K481-2565 of 4 Oct 2012. BAFU, Abteilung Abfall und Rohstoffe, Berne. http://www.bafu.admin.ch/abfall/01517/01519/12949/index.html?lang=de (1 Oct 2014)
Hügi 2013a	Hügi M. (2013) Gesamtmenge der Siedlungsabfälle und Recyclingquote. Document 264/2010-00259/07/04/L122-0995 of 4 Oct 2012. BAFU, Abteilung Abfall und Rohstoffe, Berne. http://www.bafu.admin.ch/abfall/01517/01519/12949/index.html?lang=de (1 Nov 2013)
Hügi 2013b	Hügi M. (2013) Importierte Siedlungsabfälle aus dem Ausland. Document 264/2010-00259/07/04/L112-2808 of 4 Oct 2012. BAFU, Abteilung Abfall und Rohstoffe, Berne. http://www.bafu.admin.ch/abfall/01517/01519/12949/index.html?lang=de (1 Nov 2013)
Jutz & Schlumberger 2011	Jutz M., Schlumberger S. (2011) Wertstoffrückgewinnung aus den Rückständen der Müllverbrennung und Reduktion der Abwasserbelastung - Erfolgreiche Forschungskooperationen, ein Beispiel aus der Praxis. GreentechEvent 2011 Ressourceneffiziente Wassertechnologien 20.Okt 2011, i-net Basel. http://www.inet-innovation.ch/Fileadmin/documents/inet/events/cleantech/111020-06_Jutz-SAM-Medox.pdf (28 Feb 2014)
KEBAG 2010	KEBAG (2013) Jahresbericht 2009. KEBAG, Kehrichtbeseitigungs-AG, Emmenspitz, Zuchwil. http://www.kebag.ch/cms/upload/pdf/Jahresbericht%2009.pdf (3 Mar 2014)
KEBAG 2011	KEBAG (2013) Jahresbericht 2010. KEBAG, Kehrichtbeseitigungs-AG, Emmenspitz, Zuchwil. http://www.kebag.ch/cms/upload/Jahresbericht_2010.pdf (3 Mar 2014)
KEBAG 2012	KEBAG (2013) Geschäftsbericht 2011. KEBAG, Kehrichtbeseitigungs-AG, Emmenspitz, Zuchwil. http://www.kebag.ch/files/Downloads/Geschaeftsbericht%202012.pdf (27 Oct 2014)
KEBAG 2013	KEBAG (2013) Jahresbericht 2012. KEBAG, Kehrichtbeseitigungs-AG, Emmenspitz, Zuchwil. http://www.kebag.ch/cms/upload/pdf/Jahresbericht_12.pdf (27 Oct 2014)
KEBAG 2014	Kehrichtbeseitigungs AG (2014) Geschäftsbericht 2013. April 2014. Zar Stiftung Zentrum für nachhaltige Abfall- und Ressourcennutzung. http://www.kebag.ch/files/Downloads/Geschaeftsbericht%202013.pdf (27 Oct 2014)
Morf 2006	Morf L. (2006) Chemische Zusammensetzung verbrannter Siedlungsabfälle Untersuchungen im Einzugsgebiet der KVA Thurgau. Report Nr. UW-620. Bundesamt für Umwelt, Bern. http://www.bafu.admin.ch/publikationen/publikation/00019/index.html (20 Sept 2008)
Schenk 2011	Schenk K. (2011) TVA-Revision – Normkonzept. Mai 2011. Bundesamt für Umwelt BAFU, Abteilung Boden. http://www.bafu.admin.ch/abfall/02202/12415/12418/index.html (15 Jan 2015)
Schlumberger & Bühler 2013	Schlumberger S, Bühler A (2013) Metallrückgewinnung aus Filterstäuben der thermischen Abfallbehandlung nach dem FLUREC-Verfahren. In: Thomé-Kozmiensky (Ed) "Aschen, Schlacken, Stäube", 2013, VIVIS Verlag, ISBN 978-3-935317-99-3 http://www.vivis.de/phocadownload/2013_ass/2013_ass_377_398_schlumberger.pdf (13 Jan 2015)
Schlumberger 2005	Schlumberger S (2005) Entwicklung und Optimierung eines Verfahrens zur selektiven Zinkrückgewinnung aus sauren Ascheextrakten der thermischen Abfallentsorgung. Dissertation, Department Chemie, Lehreinheit Anorganische Chemie, Technische Universität München. http://d-nb.info/978146255/34 auch unter https://mediatum.ub.tum.de/doc/601428/601428.pdf (28 Nov 2012)
Schlumberger 2010 (BAFU)	Schlumberger, S. (2010) Neue Technologien und Möglichkeiten der Behandlung von Rauchgasreinigungsrückständen im Sinne eines nachhaltigen Ressourcenmanagements, in KVA-Rückstände in der Schweiz - Der Rohstoff mit Mehrwert. 2010, Bundesamt für Umwelt (BAFU), Bern. http://www.bafu.admin.ch/publikationen/publikation/01538/index.html?lang=de&lang=de (28 Feb 2014) siehe auch Republikation bei BSH 2012 unter http://web.archive.org/web/20140228123155/http://www.bsh.ch/upload/public/0/71/BSH-Umweltservice-AG-Zinkrueckgewinnung-und-Ascherueckfuehrung-FLUREC-Verfahren.pdf (28 Feb 2014)
Schlumberger 2011	Schlumberger S. (2011) Wertstoffgewinnung durch saure Wäsche von KVA- Filterasche. Stand der Technik in der Abfall- und Ressourcenwirtschaft Tagung im Rahmen der Umwelt 11, 9. September 2011. Kanton Zürich, Baudirektion, Amt für Abfall, Wasser, Energie und Luft (AWEL) http://www.awel.zh.ch/internet/baudirektion/awel/de/betriebe_anlagen_baustellen/abfallanlagen/stand_der_technik/_jcr_content/contentPar/morethemes/morethemesitems/904_1315901058306.spooler.download.1320054848912.pdf/Vortraege_Umwelt11_Nachmittag.pdf (27 Feb 2014)
Schlumberger 2014	Schlumberger, S. (2014) KVA-Hydroxidschlamm - Vom Abfall zum Rohstoff. ZAR Infoveranstaltung 26 October 2014 http://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Veranstaltungen/Info_2014/Dr._Stefan_Schlumberger.pdf (3. Nov 2014)
Syc et al. 2010	Syc M, Keppert M, Pohorely M, Novák P, Puncochár M, Fiserová E, Pekárek V (2010) Fly Ash Treatment Technology in Modern Waste Incineration Plant. Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies, June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy. http://www.claisse.info/2010%20papers/l41.pdf (13 Jan 2015)
TVA 2014	Verordnungsentwurf Technische Verordnung über Abfälle (TVA) vom 10 Juli 2014. BAFU, Berne. www.bafu.admin.ch/abfall/02202/12415/13332/index.html (15 Jan 2015)
UMTEC 2009	Anon. (2009) Removal of Dioxin from Acid Washed Municipal Waste Incineration (MWI) Fly ash. Institut für Umwelt- und Verfahrenstechnik, Rapperswil, Switzerland. 14.01.2009 http://www.umtec.ch/uploads/tx_hsrpm/Factsheet_exDIOX_englisch.pdf (26 Jan 2015)