Life Cycle Assessment of municipal solid waste incineration with the PECK technology

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Commissioned by ARGE PECK, PSI Villigen

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The photo assembly on the front cover shows:

- Municipal solid waste (top left)

- Filter ash pellets prior to treatment in the Fluapur ash treatment process (center)

- Casting of recycled, secondary copper at Montanwerke Brixlegg, Austria (bottom right)

Summary

The study compares the environmental performance of the PECK waste incineration technology with a conventional grate municipal solid waste incinerator (MSWI). The PECK technology was developed by the ARGE PECK partnership, which includes the federal Paul Scherrer Institute PSI, Eberhard Recycling AG, CT Umwelttechnik, and Küpat AG. PECK differs from the MSWI mainly by staged high-temperature incineration and separation of several metal fractions from slags and ashes. The principal aim is to produce separate recyclable solid fractions by concentrating heavy metals in appropriate output products without additional energy input.

The study uses Life Cycle Assessment (LCA) procedures to register and compare the environmental burdens produced by both technologies. To account for the additional commodities delivered by PECK, an approach with expanded system boundaries was chosen. The included processes are waste collection, waste incineration, raw gas purification, slag and ash treatment, manufacture of raw metal from recyclates, landfilling of residues and long-term emissions of landfills. Amongst other burdens, the fate of important heavy metals like copper, zinc, cadmium, lead, chromium, mercury, nickel was modelled and assessed. Due to several data gaps, PECK emission data are extrapolated or calculated from models. The environmental interventions determined in the Life Cycle Inventory (LCI) were evaluated and weighted using the Life Cycle Impact Assessment (LCIA) methods Eco-indicator'99, CML'01 and Critical-Surface-Time'95. Several sensitivity calculations were performed including variations in PECK performance, in output product recyclability, and in landfill performance.

The study shows that PECK succeeds in its aim to produce a de-toxified mineral product from slag. Pollution from landfills is reduced as compared to grate-MSWI due to recycling of metals, especially copper, cadmium and zinc. Recycling also reduces mineral resource consumption and causes less burdens regarding *mineral* resource depletion. On the other hand, *energy* consumption is slightly higher in the PECK process, which leads to a decrease in net energy production from waste incineration, a higher demand of energy resources and a bigger burden regarding energy resource depletion. So there is a trade-off between a decrease in toxic pollution and reduced mineral resource consumption on one hand, and an increase in energy resource demand. However it can be shown that the advantages of PECK outweigh the small disadvantage of increased energy consumption. The LCIA methods Eco-indicator'99 and Critical-Surface-Time'95, which allow for a fully aggregated result accordingly show a result in favour of the PECK technology. Furthermore, earlier LCA results on the crucial role of including long-term leachate emissions from landfills were confirmed.

Future research should focus on running a pilot plant or trial facility with all three components of PECK interlinked to obtain detailed measurements of PECK outputs. The extrapolated copper content in the iron scrap is rather high and leads to substantial toxic releases. Steps to further isolate copper from the iron scrap should be considered, even a the expense of an increased energy demand. In that respect the wet treatment of slag instead of dry treatment should be reconsidered as an option. The mineral product can't satisfy the threshold limits currently set for inert landfill materials regarding zinc and copper.

Contents

Remark on displayed vs. significant digits

Figures in the tables of this report often feature several digits. This is not to imply that all the digits are significant or that the data displayed is very precise (it is mostly not). Showing several digits helps to minimise the avoidable accumulation of rounding mistakes along the chain of calculations performed here, and in possible future studies referring to this data.

Glossary

ABA	Abwasser-Behandlungs-Anlage. Waste water treatment facility in the MSWI, cf. IWWTS.
Case 'Lab'	Scenario regarding the performance of the PECK technology. The Case 'Lab' estimates the performance of the PECK technology as elemental transfer coefficients based on the information gathered from laboratory experiments and trial phases. An improved scenario is the Case 'Max'.
Case 'Max'	Scenario regarding the performance of the PECK technology. The Case 'Max' is based on the estimations made in the case 'Lab'. Additional performance improvements as anticipated be the ARGE PECK are taken into consideration.
CML'01	CML is the name of the Environmental Science Institute of the University of Leiden, Netherlands (Centruum voor Milieukunde Leiden). In 1992 the CML issued a widely used LCIA method, which was named after the Institute (CML'92). In 2001CML issued an extensive update of the method, which greatly improves on the older method and therefore needs to be named differently (CML'01)
ERAG	Eberhard Recycling AG
IWWTS	Incinerator Waste Water Treatment Sludge or scrubber sludge, solid remains of the waste waster treatment from flue gas cleaning (wet scrubber), output of the MSWI that needs to be landfilled. This is not the same as municipal waste water treatment sludge (MWWTS, sewage sludge) fed into the flue gas treatment part of PECK!
LCA	Life Cycle Assessment, a method to holistically evaluate the total environmental burden of a product or service.
LCI	Life Cycle Inventory, earlier stage of an LCA, which includes raw data collection on energy and material fluxes. Compare LCIA.
LCIA	Life Cycle Impact Assessment, later stage in an LCA, which evaluates the burdens associated with the energy and material fluxes established in LCI according to their environmental damage potential and performs relative weighting between similar burdens.
Mineral product	Output from the Eberhard mechanical slag treatment: 'De-scrapped' slag containing mostly silicon-rich oxidic material. Potential use as a filler in cement production or as residual landfill stabiliser.
MSW	Municipal solid waste
MSWI	Municipal solid waste incinerator (Kehrichtverbrennungsanlage KVA), here also used to denote a *conventional* grate-incinerator in contrast to the PECK technology. Of course in a broader sense PECK is also a MSWI.
MWWTS	Municipal Waste Water Treatment Sludge, or sewage sludge solid remains of the municipal waste waster treatment, used as input into the flue gas treatment part (Fluapur) of PECK as a carbon input.
PSI	Paul Scherrer Institute ,Villigen.
Recursion	Practice of feeding the output of a process back as an input into that same process. In the PECK technology there are such recursive feed-back loops. However, they have never been realised: experimental data is only available for the unconnected stand-alone module components of PECK. This data is denoted as being 'non-recursive', due to lack of feed-back loops.
UCTE	Union pour le transport de l'électricité. European power grid association.

TK   transfer coefficient (german 'Transfer-Koeffizient') A parameter which describes the relation between the amount of a chemical element present in a certain output and the amount of the same element present in the input. Used to describe element fates in incineration, landfill and metal furnace processes.

1 Introduction and goal

The aim of this report is to compare the environmental performance of the PECK waste incineration technology with a conventional grate municipal solid waste incinerator (MSWI). The PECK technology is a new patented concept to treat municipal solid waste and transform its contents to recyclable materials. The aim of the PECK technology is to provide a resource-efficient way of waste disposal by transforming heavy metal contaminations in incinerator remains to recyclable metal products. Remaining mineral material from PECK should be recyclable in cement production. The PECK technology should not be more costly than conventional grate incineration.

There are three principal components of the PECK technology

- the Küpat incinerator
- the Fluapur ash treatment and
- the Eberhard slag treatment

The Küpat incinerator is a staged high-temperature incinerator aimed at evaporating volatile metals like mercury, cadmium, zinc, lead and conditioning the remaining slag.

The Fluapur ash treatment extracts heavy metals from fly ash pellets in a fluidized-bed reactor. A recyclable hydroxide product rich in zinc, lead and cadmium is obtained.

The Eberhard slag treatment mechanically treats the Küpat slag and extracts copper and iron scrap. The remainder is the mineral product.

PECK was developed during the last years by the ARGE PECK partnership, which includes the federal research centre Paul Scherrer Institute PSI, and the private companies specialising in waste treatment technologies: CT Umwelttechnik, Eberhard Recycling AG, and Küpat AG.

The study shall show how PECK performs ecologically compared to a conventional grate MSWI. It shall identify important contributors to the total burden for optimisation and prioritisation.

2 Functional unit

In LCA the 'functional unit' is the service each of the examined technology options is performing. For waste disposal processes the primary service or function is the treatment and final disposal of MSW. As in earlier studies the functional unit is therefore – preliminarily – defined as the safe disposal of 1 kilogram of MSW [Zimmermann et al. 1996, Hellweg 2000].

The development in national waste management strategies led to technologies *not only* disposing waste as a service, but actually generating some benefit from the treatment of waste. In most MSWI today the excess heat from combustion is converted to heat or electricity and fed into corresponding energy grids. So the benefit or service one can expect from MSWI is not only the safe disposal of MSW, but also the generation of energy. A common practice is also the removal of iron scrap from bottom ash/incinerator slag. This iron scrap is however a low-value commodity. Nevertheless the contained iron is recycled and – after suitable treatment – represents a benefit.

The PECK process delivers all of the above services – it disposes of MSW, it produces excess energy and iron scrap. Additionally it produces two metal scrap fractions rich in copper, zinc and lead. Moreover, PECK also consumes a small amount of sewage sludge (MWWTS) in the Fluapur fly ash treatment.

So to make a fair comparison of the PECK process with other types of waste treatment, we need to define the 'functional unit' of this LCA as a fixed collection of services all the examined technology alternatives need to fulfil. If each alternative delivers the same services, the benefit is equal and *only then* a fair comparison of the associated burdens is possible[1].

Function	MSWI technology	PECK technology
Disposes of MS Waste	a	a
Disposes of sewage sludge MWWTS	-	a
Produces electricity	a	a
Produces useful heat	a	a
Produces iron scrap	a	a
Produces copper scrap	-	a
Produces zinc scrap	-	a
Produces lead recyclate	-	a
Produces mineral product	-	a

Table 1   Functions of the MSWI technology and the PECK technology

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[1] Obviously it would be tremendously unfair and meaningless to compare an alternative X (which produces the service A) directly with an alternative Y (which produces the service A *and* B *and* C) and conclude that X is less burdening than Y, and not heeding the fact that X generates less service or benefits than Y.

2.1 System expansion

System expansion is one possibility to deal with comparisons of *multifunctional* processes[2]. Consider two technologies 1 and 2, both performing some service *A* (e.g. disposal of 1kg MSW). But additionally technology 1 also performs a service *B* (e.g. production of energy); and technology 2 also performs a service *C* (e.g. production of compost), cf. Figure 1. These two technology cannot be seen as interchangeable alternatives and *cannot be compared directly*, as they do not perform the same services. Technology 1 lacks the service *C*; Technology 2 lacks the service *B*.
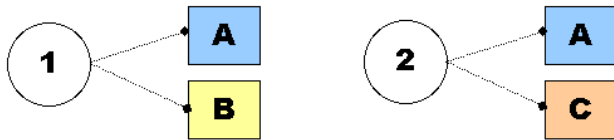

Figure 1   Basic situation when comparing two multifunctional processes 1 and 2.

To guarantee that the comparative assessment of technologies 1 vs. 2 compares true and valid alternatives, the system boundaries of both technologies have to be *expanded* to include processes that perform these lacking services. To assess technology 1 the system needs to be expanded by a complement process *c* performing the service *C*; to assess technology 2 the system needs to be expanded by a complement process *b* performing the service *B*, cf. Figure 2. Each complement process *c* or *b* is added to the systems in such amounts, that the resulting **cluster of services A+B+C** is equal for both systems. The complement processes *c* and *b* should be typical or average sources that perform the required service[3].
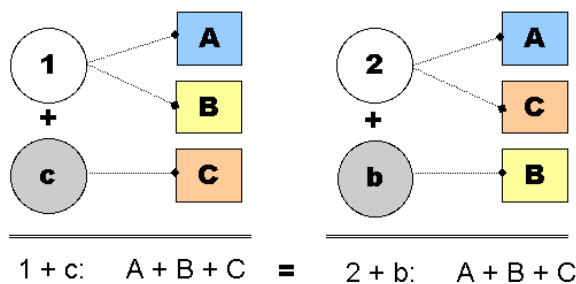
Figure 2   Fair comparison of two multifunctional processes 1 and 2 using system expansion by complement processes c *and* b*, respectively.*

Both expanded systems *(1+c)* and *(2+b)* now perform the same cluster of services *A+B+C* and hence their environmental impacts can be compared in a fair manner. The cluster of services *A+B+C* represents the *functional unit* of the expanded system (cf. footnote 4 on page 5).

For the comparison of the PECK technology several services can be identified. The basic structure of the comparison is shown in Figure 3. As explained, the important notion is

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[2]   Multifunctional processes are processes that produce more than one desired service or benefit.

[3]   To avoid further complications, the complement processes should possibly be monofunctional processes, i.e. one producing one desired benefit or service.

that both systems provide comparable services or fulfil the same functions. Therefore, the systems can be compared impartially.
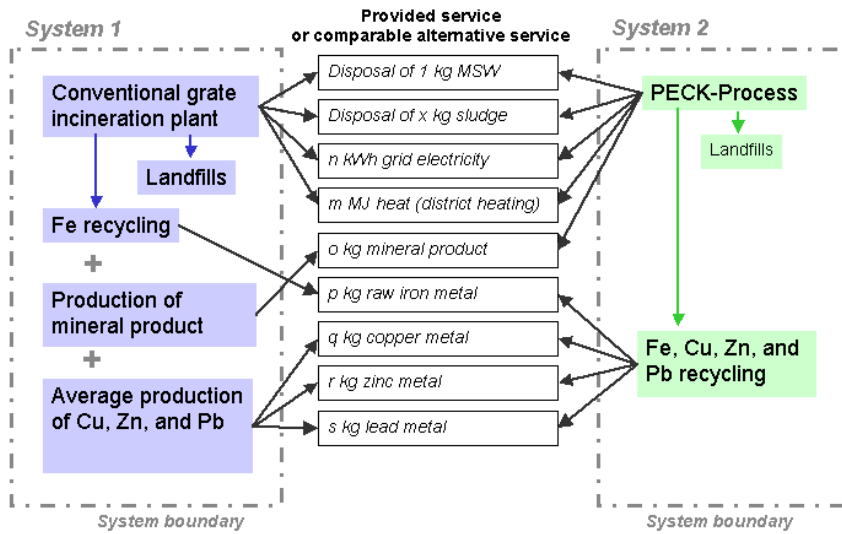
Figure 3   *Compared systems for the PECK technology (on the right) and the conventional MSWI technology (on the left). Both systems deliver the same services. To do that, the systems need to be complemented with certain processes originally not associated with the incinerators.*
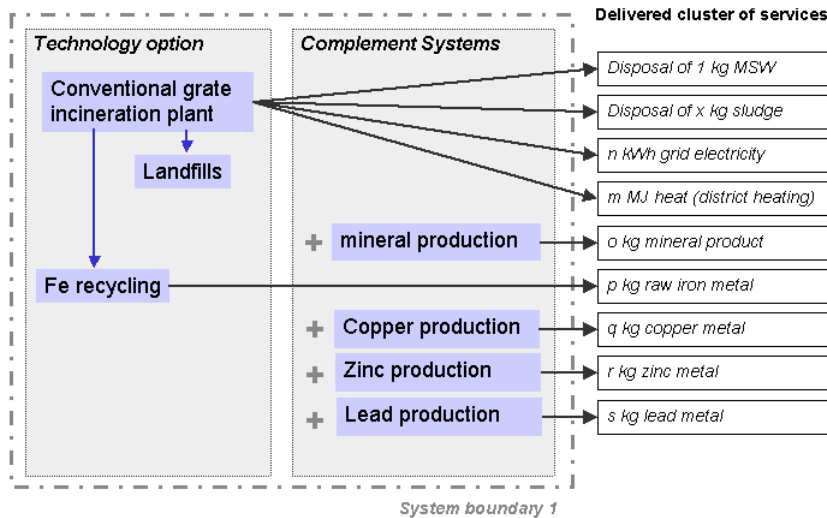
Figure 4   *System boundary for the assessed MSWI technology, divided into MSWI-related parts (on the left) and complementary systems that help to achieve the required cluster of services (on the right).*

2.2 The cluster of services

The definition of the cluster of services, as explained in chapter 2.1 'System expansion' above, is of course crucial to the meaning of the result of the LCA and should bear

some relation to the cluster of services under examination[4]. The leading topic of the PECK technology is resource efficient treatment of waste. As much waste as possible shall be recycled as usable materials or energy. The theoretical maximum to recycling is 100%, i.e. all material or energy is recycled. In practice 100% recycling is usually not feasible. However, any deviation from 100% recycling rate, i.e. any landfilling, deposition or emission of material must be seen as a loss. The lost materials are withdrawn from the production process and need to be replaced with material from other sources. A 100% recycling rate can be used as an objective benchmark to describe recycling performance[5]. The cluster of services hence contains the production of the maximum possible amount of the considered materials (iron, copper, zinc, lead, minerals) present in the waste input. Additionally the cluster of services contains the production of the 'maximum possible' amount of energy from the waste input as a typical mixture of electricity and heat[6].

The definition of the service cluster is displayed in Table 2. The actual amounts are derived from the average waste input composition[7]. The amount for consumed sewage sludge MWWTS is derived from Case Max of the PECK technology which features the largest input of MWWTS.

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[4]   This 'cluster of services' is sometimes also called 'product basket' or 'function basket'. It can also be defined as the 'functional unit of the expanded system'.

[5]   'Benchmark' is used here in the sense of a 'measuring stick', not in the sense of a 'goal to be achieved'.

[6]   The term 'maximum possible' is controversial. A modern MSWI converts 18% of the energy in waste to electricity and 37% to useful heat [Hellweg 2000]. This is the gross production, disregarding the MSWI's own energy consumption. Assuming typical power generation and furnace efficiencies of 33% and 87% [ESU 1996b], respectively, one can see that 55% (= 18%/33%) of the heating value was converted to electricity and 43% (= 37%/87%) of the heating value was converted to useful heat, i.e. 98% of the heating value was actually engaged to generate useful energy. The exact mixture of electricity vs. heat can be varied within certain limits. But it can be concluded that a modern MSWI treats the energy content of waste almost equally efficient as present power plants and furnaces, i.e. almost all energy is being engaged in energy production. The generation of 18% electricity and 37% useful heat as defined in the service cluster represents therefore the *present* 'maximum possible' amount of energy products from the waste input. An unambiguous and absolute, but *theoretical* maximum of the energy extractable from one kilogram of waste would be 89'000 million megajoules = 89 petajoules, i.e. Einstein's mc^2 [Frischknecht et al. 1998]. This illustrates that energy contents that are *meaningful* to human's scope of action are always based on a subjectively chosen energy conversion *technology*.

[7]   The total waste input includes also the small amount of municipal sewage sludge MWWTS.

Type of service	Delivered service	Amount	Unit	Comment
Waste disposal services	Disposal of municipal solid waste MSW	1	kg MSW	Primary function of MSW disposal
	Disposal of sewage sludge MWWTS	0.0210	kg MWWTS dewatered to 5% from 65%	Co-service performed by PECK technology in the flue ash treatment (maximum amount per 1kg MSW)
Energy services	Generation of electricity	2.15	MJ electricity	18% of the lower heating value in MSW & MWWTS converted to electricity [Hellweg 2000]
	Generation of heat	4.43	MJ heat	37% of the lower heating value in MSW & MWWTS converted to useful heat [Hellweg 2000]
Resource services	Iron	0.0318	kg Fe	Total amount of iron in MSW + MWWTS is recycled
	Copper	0.0012	kg Cu	Total amount of copper in MSW & MWWTS is recycled
	Zinc	0.00134	kg Zn	Total amount of zinc in MSW & MWWTS is recycled
	Lead	0.000509	kg Pb	Total amount of lead in MSW & MWWTS is recycled
	Mineral material	0.354	kg	Total amount of mineral material (Ca, Si, Al, K, Na, Mg, O) in MSW & MWWTS is recycled

Table 2   Definition of the service cluster. This is the functional unit. All options examined in this study must fulfil all these services.

Not all technology options are able to fulfil all services to the same extent. E.g. a normal MSWI does not produce any copper scrap. But since the service cluster calls for the production of 1.2 grams of copper metal, this copper amount must be added coming from some copper producing facility. As explained in the chapter 2.1 'System expansion', if a process X is not able to fulfil a service defined in the service cluster – partially or completely – a different source for that service must be included in the assessment of X *as a complement*.

Delivered services		Cluster of services (constant for every option)	PECK process Case Lab	complement process
Waste services	MSW disposal	1000 grams =	1000 grams	⊕ 0 grams
	MWWTS disposal	21 grams =	13 grams	⊕ 8 grams
Energy services	Electricity	2.1 MJ =	1.7 MJ	⊕ 0.4 MJ
	Useful heat	4.4 MJ =	3.8 MJ	⊕ 0.6 MJ
Resource services	Iron scrap	32 grams =	19 grams	⊕ 13 grams
	Copper scrap	1.2 grams =	0.4 grams	⊕ 0.7 grams
	Zinc scrap	1.3 grams =	0.9 grams	⊕ 0.4 grams
	Lead scrap	0.5 grams =	0.4 grams	⊕ 0.1 grams
	Mineral material	354 grams =	161 grams	⊕ 192 grams

Table 3   *Sum of the services delivered in the Case Lab and the according contributions delivered by the PECK process and the necessary complements, respectively.*
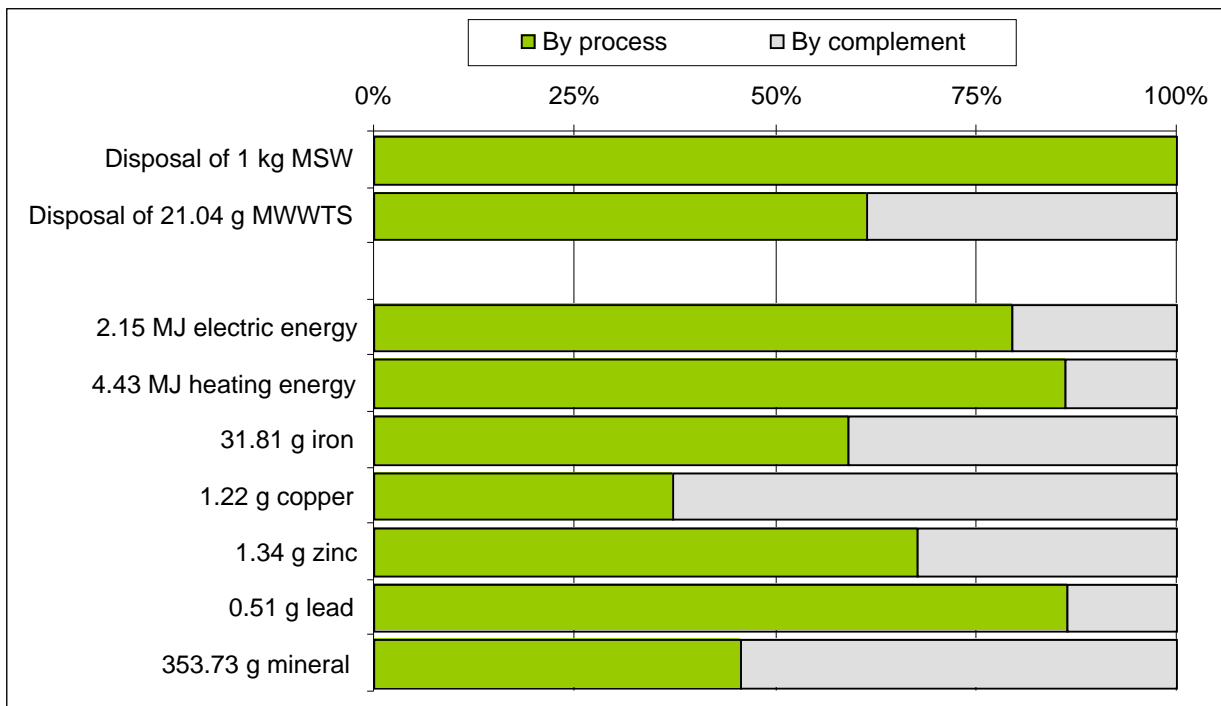
Figure 5   *Services delivered according to the required cluster of services (text on the left) and the according shares (split columns) delivered by the PECK process and the necessary complements, respectively. For the Case Lab.*

An option therefore not only includes the activities of the examined waste treatment technology (e.g. the waste incinerator plant) but also the complement processes necessary to deliver the full list defined in the service cluster (e.g. a conventional source for copper). These complement processes are also called 'reference systems' in LCA terminology.

The choice of these complementary processes is somewhat subjective, but common sense suggests following characteristics of these processes:

- Complementary processes should deliver the same or closely related quality of the service.
- Complementary processes should not be an extreme – ecologically very burdened or very favourable – source for that service. It should represent an average source.
- Complementary systems should not be an unusual or exotic source for that service.

E.g. as most Swiss MWWTS is incinerated for disposal, it would be an extreme choice to select an agricultural application of sludge[8] as an complementary disposal route of MWWTS.

To show the influences on the choice of the complementary system, sensitivity analysis can be applied using different choices. Table 4 shows the chosen complementary systems for the components of the service cluster.

Type of service	Delivered service	Complement system delivering the service as a complementary source	Second complement system as sensitivity
Waste disposal services	Disposal of municipal solid waste MSW	–	–
	Disposal of sewage sludge MWWTS	sewage sludge incineration in modern MSWI	–
Energy services	Generation of electricity	UCTE grid electricity	Swiss grid electricity, national & import mix
	Generation of heat	Industrial natural gas furnace	Industrial fuel oil furnace
Resource services	Iron	Raw iron (from primary iron ore)	–
	Copper	Copper metal from usual, average industrial sources	–
	Zinc	Zinc metal from usual, average industrial sources	–
	Lead	Lead metal from usual, average industrial sources	–
	Mineral material	Sand from natural sources for building purposes	Burnt lime CaO (in case of hydraulic activity of the mineral product)

Table 4   Chosen complement processes or reference systems for the various components of the service cluster.

For the assessment of the usual, average industrial sources of metals, the typical recyclate input rates were heeded. The recyclate input rate signifies the average

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[8]   Moreover, this practice will soon be abolished in Switzerland.

amount of secondary metal sources that are used to produce new metal[9]. The recyclate input rates are taken from [ESU 1996b] and are 40% for copper, 12% for zinc and 50% for lead.

The exact amount defined in the service cluster is actually of minor importance to the final ranking of the technology options. I.e. if the reference amount of e.g. copper were 50 grams higher, then *all* technology options would have to generate those 50 grams from complementary sources. So the resulting total burdens of *all* technology options would be increased by the burden for those 50 grams of copper. The *ranking* of the results is not affected, though the *relative* importance of the several contributions to the result can be influenced.

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[9] The recyclate input rate is 'ton scrap metal input to production per ton *new* metal produced'. In contrast, the *recycling rate* – which is often reported – is 'ton recycled scrap metal per ton of *waste* metal'. When demand for a metal is continuously expanding, there is usually less waste metal than new metal due to time lags between metal consumption and cost-consumer metal discarding. The time lag is dependent on the lifetime of the metal products. Under these conditions the recycling rate is higher than the recyclate input rate.

3 Scope of the assessment

As in former related LCAs like e.g. [ESU 1996a, Hellweg 2000], the waste incineration process is assessed complete with the necessary downstream and upstream processes. Upstream processes for waste incineration include municipal waste collection or direct transport, production of auxiliary materials like burnt lime (quicklime, CaO), MSWI plant infrastructure.

Downstream processes for waste incineration are landfilling or subsurface deposition of incineration remains like slag and ashes. For the PECK process the landfilled amount is reduced significantly, but not avoided completely, since scrubber sludge IWWTS will be solidified and landfilled. A small amount of hazardous waste Originates from the mercury trap.
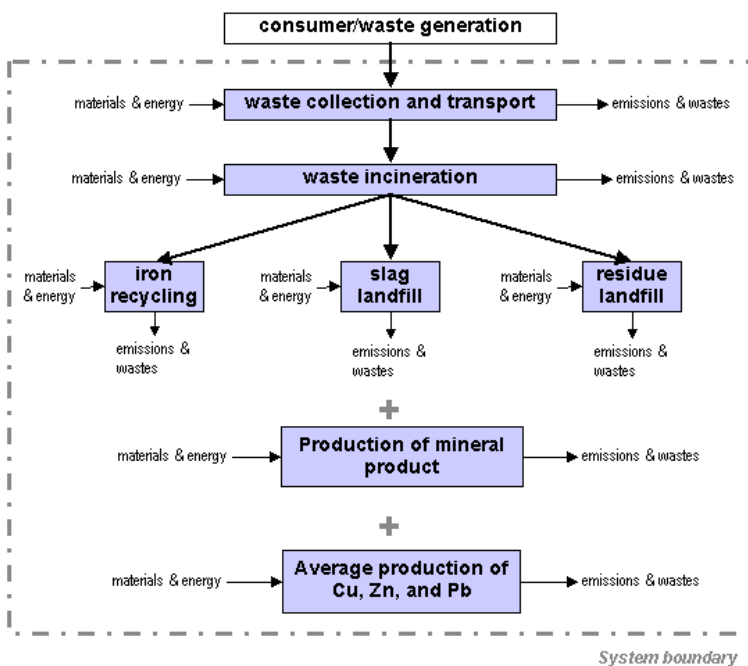
Figure 6   *System boundary for the MSWI technology. Compare with Figure 3 on page 4. On every step materials and energy are consumed and emissions and wastes are generated. All these flows and their respective burdens are assessed.*

The recycling of metals from waste incineration outputs is included up to a point, where the quality of the metal is equal to conventional sources. This point is expected to be reached after manufacture of raw metal products. The final manufacture of metal products, their distribution, subsequent use and disposal is *not* included in the present assessment. This applies also for recycled slag products: burdens from the use phase of those recycled products e.g. as building materials or blasting abrasives are not included (cf. Figure 17 on page 41).

3.1.1 Landfill leachate emissions

Landfills can emit pollutants for very long time spans. Simulations in [Hellweg 2000] calculate several ten thousand years. For the LCA, a distinction is made between short-

term emissions which occur during the human control and maintenance of the landfill[10] and the long-term emissions occurring after that period. The assessment includes short- and long-term emissions of the landfilled remains. Short-term landfill behaviour is extrapolated from measured leachate emissions [ESU 1996a]. Total long-term transfer coefficients are estimated from leaching and availability tests of average slags and ashes [ESU 1996a].

A majority of landfill experts agrees that landfills are not final repositories and that – given enough time – ultimately *all* contents in a landfill are released to the environment through leachate (e.g. Bäverman et al 1999, Bjoerklund 1998, Finnveden 1999, Sabbas et al 1998, Sundqvist et al. 1997, Leuenberger 1999). As a sensitivity test, complete long-term release of all elements from landfills can be calculated (cf. chapter 6.6.3 'Sensitivities on landfill performance' on page 75).

3.2 Characterisation of the PECK process

To assess the performance of the PECK process it is necessary to know the chemical composition of its output products[11]. Some information on product compositions are available from laboratory experiments. ARGE PECK also gives information in the form of targeted transfer coefficients (partition coefficients) for some chemical elements like zinc, copper, lead, and cadmium [PECK 2001].

Transfer coefficients (or TK) must be listed for each output product and each chemical element under consideration. Transfer coefficients signify how a chemical element in the input is distributed to the various output products. The amount of any chemical element in the waste input is defined as 100% i.e. the sum of all transfer coefficients across all outputs for one specific element must always be 100%.

3.2.1 Process model methodology

The information on products composition and transfer coefficients must be consolidated into one consistent system description.

a) One prerequisite of that system description is that it should be consistent with reasonable MS waste compositions encountered today;

b) the other prerequisite would be mass conservation

ad. a) In the transfer coefficients approach to waste treatment the waste composition is causally connected to the output products via transfer coefficients, i.e. multiplication of the input waste composition with the transfer coefficients gives the masses of chemical elements in the output products[12]. From this, the chemical composition of the output products can be calculated.

ad. b) mass conservation means that the sum of transfer coefficients for each chemical element is 100%, i.e. sum of inputs = sum of outputs. If the chemical composition of an

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[10] These short-term time frames are 75 years for slag landfills, and 40 years for residue landfills ('Reststoffdeponie').

[11] Output products of the PECK process are air emissions, treated slag (mineral product), iron scrap, copper product, treated filter ashes (zinc hydroxide product), water emissions and wastewater treatment sludge.

[12] Transformations like oxidation or the input of auxiliary substances must be heeded accordingly.

output is known, the combination of chemical composition and total output mass must be consistent with waste compositions, i.e. no transfer coefficient for any single element can exceed 100%. All output masses have to be balanced accordingly.

For this study the information given by ARGE PECK had to be consolidated in the above sense. PECK tries to achieve certain goals in terms of output quality. Accordingly, the observed output compositions were taken as a starting point for balancing the system performance. Typical Swiss waste composition was obtained from recent studies by [Belevi 1998 and personal communication Belevi 2001].

3.3 Performance cases for the PECK process

To show the influence of the PECK performance on the LCA results two main cases of PECK performance are distinguished. The performance Case Lab and the performance Case Max.

3.3.1 Performance Case Lab

The performance of the PECK process in the 'Case Lab' is based as far as possible on measured elemental compositions of output products collected during testing and trial phases of laboratory tests of PECK components, hence the name 'Lab'. The Küpat waste incineration process was measured 1991 to 1994 in Basel in test runs as an expansion of a regular MSWI. The Fluapur fly ash treatment process was extensively studied and tested at PSI and CTU. The Eberhard slag treatment process is implemented by ERAG. ERAG has several years of practice in mechanical slag treatment. Since not all necessary data was available as of September 2001 some extrapolations had to be made using data on transfer coefficients of regular MSWI (detailed information in chapter 4.2 'Transfer coefficients calculations for PECK Case Lab' on page 20ff.). The 'Case Lab' represents the current state of development for the PECK component cluster as a combination of the observed performance of its three composing processes.

This performance 'Case Lab' is an educated best guess of the probable and observed performance of the PECK component cluster.

3.3.2 Performance Case 'Max'

ARGE PECK hopes to improve the PECK process in the future and is confident that certain performance levels can be reached. These performance levels – in the form of transfer coefficients of copper, zinc, cadmium and lead for mineral product, zinc product and copper product – are outlined in [PECK 2001] and are reproduced in Figure 7. The case 'Max' represents a optimised performance of the PECK process. For the 'Case Max' the performance described in the 'Case Lab' is modified in such a way as to meet these goals while maintaining overall system characteristics as far as possible.
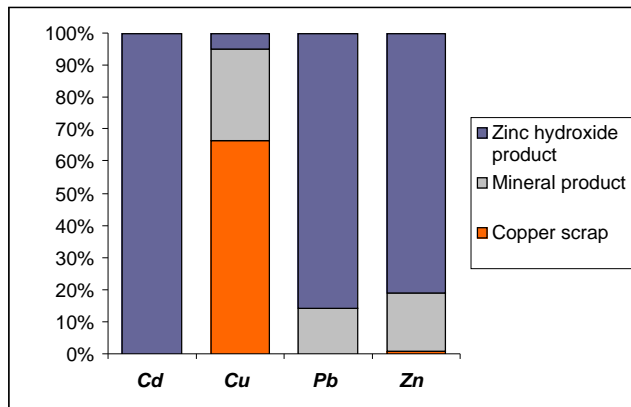
Figure 7   *Transfer coefficients for four elements in the 'Case Max' [PECK 2001].*

ARGE PECK expects to reduce nitrogen oxide emissions from incineration by 50% due to staged air combustion [PECK 2001]. This has not been checked in the Küpat trials and will only be included in the 'Case Max'. The reduction halves the fuel NO_x emissions to air, the thermal NO_x emissions and also the consumption of ammonia in the DeNOx equipment of the flue gas treatment.

3.3.3 Recursion in the system

The three components of the PECK technology – Küpat incinerator, Fluapur ash treatment and Eberhard slag treatment – have been tested separately under laboratory conditions or in test trials. The PECK technology is a combination of these three components. An important feature is that the components do not process waste material in a strictly successive order. There are some material feed-backs between the system components, i.e.

- the treated ash remains from the Fluapur process is fed back to the Küpat process, and

- a small amount of a copper-rich transient product is transferred from the Eberhard slag treatment to the Fluapur ash treatment.

The PECK system is a *recursive* system with feed-back loops. However, information on the PECK technology is only available for the unconnected and *non-recursive* PECK components. Since no PECK plant has been realised yet, future optimisations and feedback effects of the interlinked processes could not yet be measured. Future optimisations might improve the performance observed here, but unforeseen problems with feedback effects not observable from the single components performances might also deteriorate PECK performance.
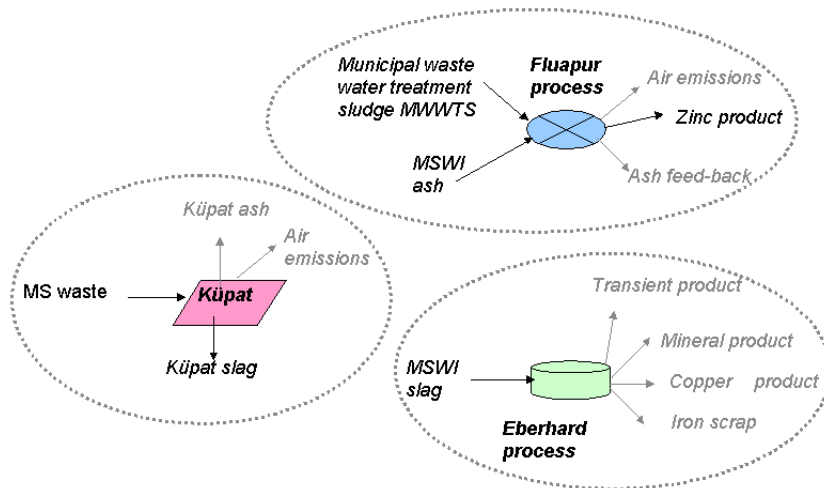
Figure 8　　　　　*The three components of the PECK technology, as they have been currently tested as separate installations. Black arrows indicate known tested or measured material fluxes. Gray arrows indicate unknown fluxes.*
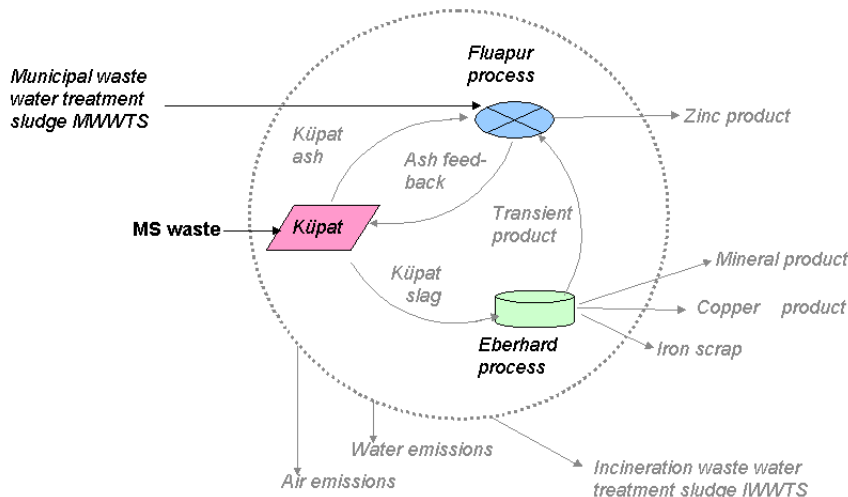
Figure 9　　　　　*The PECK technology as the suggested cluster of the three constituting components, which has currently never been assembled this way. Black arrows indicate known measured material fluxes. Gray arrows indicate unknown fluxes.*

For a valid assessment of the proposed system these feed-back loops have to be taken into account. In the following, information referring to the stand-alone components of PECK is denoted as being 'non-recursive', while results from model calculations of the PECK system including feed-backs is denoted as 'recursive', cf. chapter 4.2 'Transfer coefficients calculations for PECK Case Lab' on page 20ff.

4 Life Cycle Inventory LCI

As the standard grate MSWI is the basis for some calculations of the PECK process, the description of the LCI starts with the MSWI process.

4.1 Characterisation of the modern MSWI reference process

As a comparison for the PECK technology, a municipal waste incinerator with grate technology was chosen. This is the standard incineration technology for municipal waste in Switzerland. The plant is equipped with a wet scrubber flue gas treatment and a DeNOx process with selective catalytic reduction of nitrogen oxides (SCR high-dust).

The fate of the waste in the incinerator is determined by transfer coefficients. The set of transfer coefficients used is shown in Table 5. Emissions and output products are calculated from the waste composition multiplied by the transfer coefficients. This method allows to account changes in the waste composition. E.g. the MSWI in this study is not burning average MSW, but approximately 1% of MWWTS too. The transfer coefficient method accounts for a correct assessment of the changed composition and the changed emissions that are to be expected.

Several auxiliary materials are used in the flue gas scrubber. The demand of those materials is allocated to specific elements or sum totals of specific elements which cause the use of these auxiliary materials, cf. Table 8. The demand of those materials is ultimately calculated depending on the waste composition and the transfer coefficients. Again this method allows a correct assessment of the changed composition and the changed demand in auxiliary materials.

Some emissions were not attributed to specific waste components, as they are independent of waste composition and are determined by incineration technology and management. These so called process-specific emissions and expenditures are shown in Table 6 and Table 7. The data of these latter two tables are used as an approximation for the PECK technology as well, as no PECK-specific data is available and the overall importance of these burdens is small.

All LCI data of the MSWI are taken from [Zimmermann et al. 1996, Hellweg 2000].

	Air emissions	Slag	Fly ash	Electrostatic precipitator ash	Water emissions	Flue gas treatment sludge IWWTS
	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg
H_2O	1000	0	0	0	0	0
O	701.811543	288.017276	1.5647972	7.82398598	0	0.7823986
H	1000	0	0	0	0	0
C	977.154982	19.4265047	0	3.3985218	0.00999565	0.00999565
S	1.99304358	582.45737	0	279.026101	66.76696	69.7565253
N	989 [13]	10	0	0	1	0
P	1	880	25	94	0	0
B	0	0	0	0	0	0
Cl	0.00940497	191.172734	0	11.2859618	791.888918	5.64298092
Br	3	110	10	877	0	0
F	0.5	615	0	307.5	56	21
J	0	0	0	0	0	0
Ag	0	0	0	0	0	0
As	0.0000102	550	30	380.9	0.1	39
Ba	0.24180422	972.676123	5.31969283	21.7623798	0	0
Cd	0.05426039	17.8869896	0	363.544595	0.4340831	618.080072
Co	0.00003175	850	10	120	0.01	20
Cr	1.3021E-05	904.022626	5.61271192	78.5779668	0.56127119	11.2254238
Cu	0.00402737	891.261126	0	100.680116	0	8.05473143
Hg	2.8192E-05	188.410408	1.70860967	299.006692	8.54304834	502.331242
Mn	5.445E-06	860	10	120	0.01	10
Mo	2	867	21	110	0	0
Ni	2.1857E-05	949.857143	18.0000001	32.1428316	0	0
Pb	0.02241331	436.271686	0	512.144086	0.01120665	51.5506082
Sb	2.428E-06	385.902206	11.3721814	512.771658	0.11372181	89.8402328
Se	3.6133E-06	339.187015	93.1915748	516.704923	0.08471961	50.8317681
Sn	1.01538864	614.152318	15.2308295	345.232136	0.01015389	24.3693273
V	0.1	889.89	10	90	0.01	10
Zn	0.0122411	253.158224	0	612.055019	0.122411	134.652104
Si	0.74735512	973.842571	8.22090628	17.1891677	0	0
Fe	0.00932803	971.913313	0	26.1184737	0.09328026	1.86560526
Ca	1.04346437	913.392458	22.956216	62.6078619	0	0
Al	0.95754065	909.991179	22.0234348	67.0278452	0	0
K	3.00611517	669.327331	47.0958043	280.570749	0	0
Mg	1.01987389	938.807567	15.2981083	44.8744511	0	0
Na	1.73373672	928.916795	17.3373672	52.0121015	0	0

Table 5   Transfer coefficients for the MSWI relating to an input of MSW and MWWT sludge. No rounding to significant digits.

---

[13] Of the nitrogen emitted to air, 1.8% are emitted as fuel NO_2, 0.36% as N_2O, 0.01% as CN, 0.091% as NH3, and the rest as N_2.

Process-specific emissions of a modern MSWI		... per kg waste
Carbon monoxide CO	g	0.1635
Methane CH$_4$	g	0.00576
Non-methane hydrocarbons NMVOC	g	0.0278
Thermal NO$_x$	g	0.18
NH$_3$ Ammonia emissions from abatement of thermal NO$_x$	g	0.009
Benzene	g	0.00038
Toluene	g	0.00077
Pentachlorobenzene	g	0.00000179
Hexachlorobenzene HCB	g	0.0000007
Pentachlorophenol PCP	g	0.00000006
Benz(a)pyrene	g	8.1E-09
Dioxins, Furans PCDD/F in ng TEQ	ng	3

Table 6   Process-specific emissions for the MSWI.

Process-specific auxiliary materials of a modern MSWI		... per kg waste
Water	g	1000
Ammonia for abatement of thermal NO$_x$	g	0.5
Process-specific infrastructure of a modern MSWI		**... per kg waste**
Steel	g	1
of which hi-alloyed	g	0.02
of which non-alloyed	g	0.98
Concrete (without reinforcement)	g	10
Bitumen	kg	0.0002
Gravel and sand	g	2.5
land use (area type II (modified) to IV (built))	m2a	1.69E-05
land use (area type III (cultured) to IV (built))	m2a	1.69E-05

Table 7   Process-specific auxiliary and infrastructure materials for the MSWI.

Auxiliary material M	Allocand A	grams M per gram A
Sodium hydroxide, NaOH	S in IWWT	2.5
	N in IWWT	0.47796
	P in IWWT	0.43171
	Cl in IWWT	0.18876
	Br in IWWT	0.08375
	F in IWWT	0.35218
Burnt lime, CaO	N in IWWT	2.69074
	P in IWWT	2.43034
	Cl in IWWT	1.0626
	Br in IWWT	0.4715
	F in IWWT	1.98265
TMT[14]	Hg in IWWT	3.53582
	Cd in IWWT	6.3095
Hydrogen chloride, HCl	All elements in IWWT	0.00191
Polyelectrolyte	All elements in IWWT	0.00319
Ironchloride, FeCl3	All heavy metals in IWWT	0.57984
		MJel/kg recycled Fe
Electricity demand for iron recycling	Recylcled iron	0.1125

Table 8   Waste-specific auxiliary material consumptions for the MSWI.

4.1.1 Iron scrap separation

According to [Lichtensteiger 2001], a large fraction of iron is oxidized, which limits the amount of iron separable from the slag with magnetic separation. It is assumed that 66% of the iron content is separated from the slag[15]. Together with the magnetic iron some other elements are removed from the slag. The assumed iron scrap composition is displayed in Table 9. The respective amounts were subtracted from the raw slag. The fate of the iron scrap is assessed in the blast furnace. The remaining slag is landfilled in a slag compartment[16].

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[14] TMT or TMT 15 is trimercapto-S-triazine, $Na_3N_3S_3$.

[15] The raw slag composition is determined by waste composition and the transfer coefficient for slag.

[16] Slag compartments are separate and isolated sections in Swiss sanitary landfills where exclusively incinerator slags are landfilled.

Element	W-%	Source
O	12.260%	Difference to 100%
S	0.076%	Zeltner 2001
P	0.080%	Hoeffken et al 1988
Cr	0.120%	Hoeffken et al 1988
Cu	1.357%	Zeltner 2001
Mn	0.240%	Hoeffken et al 1988
Ni	0.105%	Hoeffken et al 1988
Sb	0.021%	PECK iron scrap cf. Table 15
Sn	0.067%	Zeltner 2001
V	0.025%	PECK iron scrap cf. Table 15
Si	3.095%	PECK iron scrap cf. Table 15
Fe	81.533%	Zeltner 2001
Al	1.022%	PECK iron scrap cf. Table 15

Table 9   Iron scrap composition of the MSWI.

4.2 Transfer coefficients calculations for PECK Case Lab
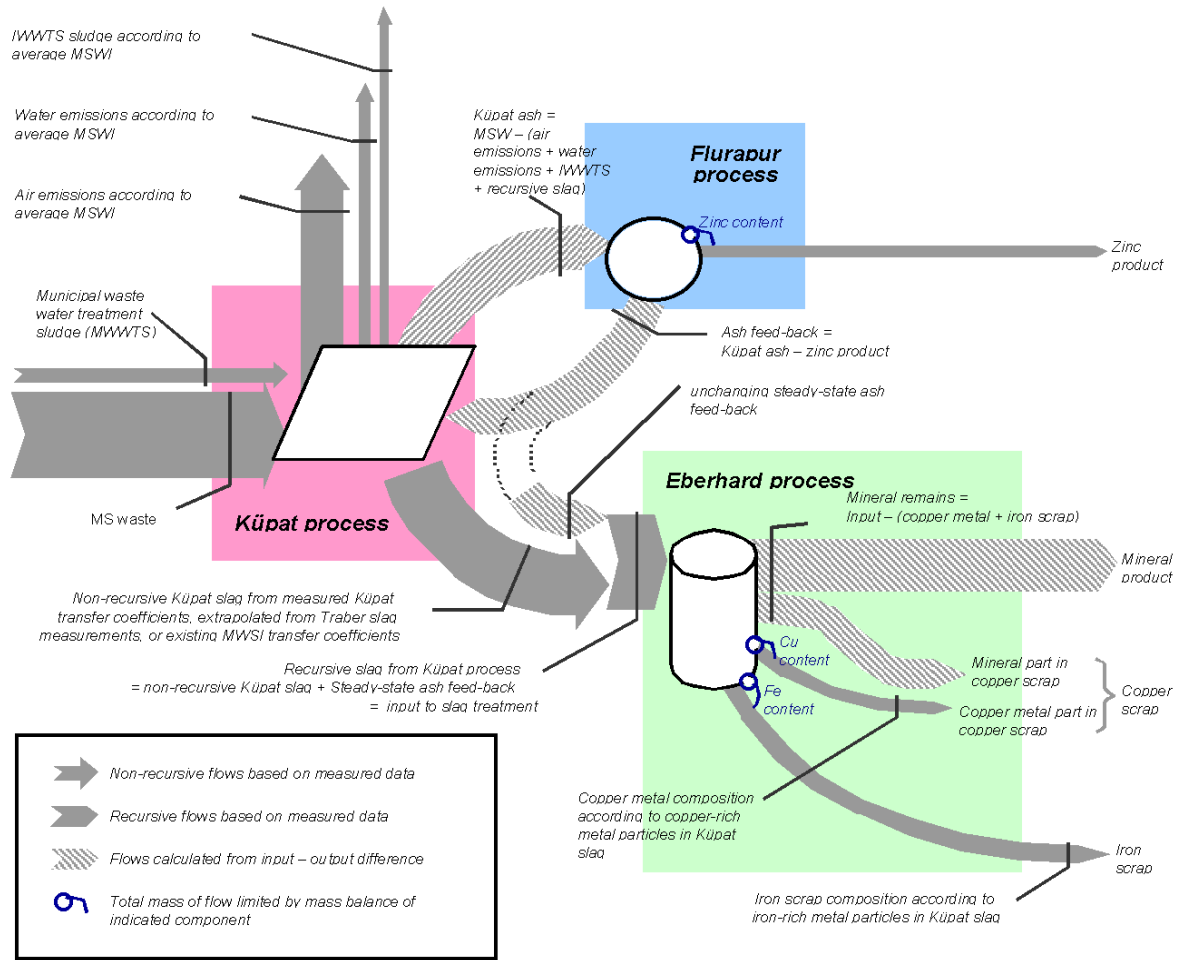
Figure 10   Overview of the calculations performed to calculate the transfer coefficients for the Case Lab of the recursive PECK assembly. Explanations in the text below.

4.2.1 Step 0: Simplifications

4.2.1.1   Air emissions

According to ARGE PECK, the direct emissions of pollutants to air and water of the PECK technology are roughly equal or better than a modern grate MSWI technology. Therefore the transfer coefficients for releases to air, waste water and scrubber sludge (IWWTS) are adopted from existing data for a modern MSWI with SCR high-dust gas purification system [Hellweg et al. 2002][17]. Air emissions are supposed to include also the air emissions from ash treatment.

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[17]   The PECK technology features a mercury trap to remove mercury from the raw gas flow. Without a mercury trap a significant amount of mercury ends up in the IWWTS. To account for the mercury removal, the transfer coefficient to IWWTS for mercury (which is about 50% in a MSWI without a mercury trap) is lowered to 1% of that value, i.e. 0.5%.

At incineration temperatures above 1200°C there is a risk of increased production of hexavalent Chromium [Wallmann 1999]. Cr-VI is much more toxic than the more abundant Cr-III. ARGE PECK expects to reach incineration temperatures of 1250°C (bed) to 1400°C (Flue gas) [PECK 2001]. A share of 2% of Cr-VI in the chromium air emissions of PECK was assumed. This is an inconsequential assumption, as the burden of PECK's Cr-VI air emissions is negligible in the end result (i.e. < 0.0004%).

4.2.1.2   Sewage sludge input

Dewatered sewage sludge (MWWTS) is used in the Fluapur process as an input (cf. Table 10). The amount is very small, approx. 1% as compared to the MSWI input. This additional source increases the contents of certain trace metals only by a few percent, e.g. instead of 0.144 ppm Hg as in MSW, the total waste input contains 0.149 ppm Hg. These variations are well within the confidence level of waste analyses and are of negligible influence. As for the reaction paths in the Fluapur process, it can be expected, that the burnable components of MWWTS (C, H, N, S etc.) do not react notably different as in grate incineration (bed temperature in the Fluapur fluidised bed reactor is 900°C). Therefore the WWT sludge is modelled as if being an input along with the MSW to the Küpat process.

4.2.1.3   Transient product

The transient product transferred from the slag treatment process to the ash treatment process is not part of the calculations. Very little is known about this product, but its total mass is expected to be very small: According to ARGE PECK the transient product is expected to be only 5% of the total inputs to the ash treatment process. This product could potentially carry significant amounts of copper to the ash treatment process as it is expected to have more than twice the mass of the copper product. According to [PECK 2001] the mass of the transient product is approximately 2.4 times the amount of the copper scrap mass, or approximately 5 grams per kg waste input. Assuming that the transient product has the same composition as the copper scrap product, the increase of copper input to the ash treatment via this route would be more than a factor 7 (740%). However, the increase in cadmium, lead and zinc would be only 0.005%, 0.186%, and 0.659% respectively. The increases in chlorine would be 36%. This might be significant regarding dioxin emissions of the Fluapur process. As explained in chapter 6.5.3 'Zinc hydroxide product' on page 66, copper catalyses the production of dioxins. The combined increase of copper and chlorine, as calculated in the above estimates, could be increasing dioxin emissions above dioxin levels measured in trials without any transient product input. In the trail runs, Fluapur decreases dioxin levels in filter ash by a factor of 271 (from 3.6259 ng TEQ/kg down to 0.0134 ng TEQ/kg) [Jakob et al. 1999].

To conclude, too little is known about this product to include it in the calculations. The only recursion left in the modelled system is the treated ash fed back to the incinerator process (cf. Figure 11).

	Average MSW	Average MWWT sludge, de-watered	Average waste input to PECK (MSW + MWWTS)
Input mass to PECK	100.000%	1.29%	100.941%

Table 10   *Total masses of input products to the PECK process, 'Case Lab', from recursive calculation.*

	Average MSW	Average MWWT slugde, de-watered	Average waste input to PECK (MSW + MWWTS)
H_o	15.451	12.2265	15.42
H_u	11.742	10.8934	11.73
H_2O	22.8826%	5.000%	22.7146%
O	25.7102%	32.944%	25.7762%
H	4.8250%	6.177%	4.8374%
C	33.4230%	21.660%	33.3115%
S	0.1119%	0.924%	0.1195%
N	0.3124%	2.565%	0.3334%
P	0.0894%	1.710%	0.1045%
B	0.0007%	0.000%	0.0007%
Cl	0.6866%	0.380%	0.6837%
Br	0.0014%	0.000%	0.0013%
F	0.0056%	0.001%	0.0056%
J	0.00000%	0.000%	0.0000%
Ag	0.00007%	0.000%	0.0001%
As	0.00006%	0.000%	0.0001%
Ba	0.0149%	0.000%	0.0148%
Cd	0.00117%	0.001%	0.0012%
Co	0.00013%	0.001%	0.0001%
Cr	0.0315%	0.013%	0.0313%
Cu	0.1213%	0.042%	0.1205%
Hg	0.000144%	0.001%	0.0001%
Mn	0.0259%	0.000%	0.0257%
Mo	0.00020%	0.000%	0.0002%
Ni	0.0107%	0.006%	0.0107%
Pb	0.0502%	0.033%	0.0501%
Sb	0.0023%	0.000%	0.0022%
Se	0.0000%	0.000%	0.0000%
Sn	0.0073%	0.000%	0.0073%
V	0.0009%	0.000%	0.0009%
Zn	0.1311%	0.149%	0.1313%
Si	4.8510%	7.257%	4.8731%
Fe	3.0014%	8.626%	3.0537%
Ca	1.4062%	5.985%	1.4488%
Al	1.2420%	2.409%	1.2528%
K	0.2060%	0.209%	0.2060%
Mg	0.3378%	0.380%	0.3381%
Na	0.5144%	3.527%	0.5424%

Table 11   Compositions of inputs to the PECK process for 'Case Lab' in weight-%, heating values in MJ/kg.
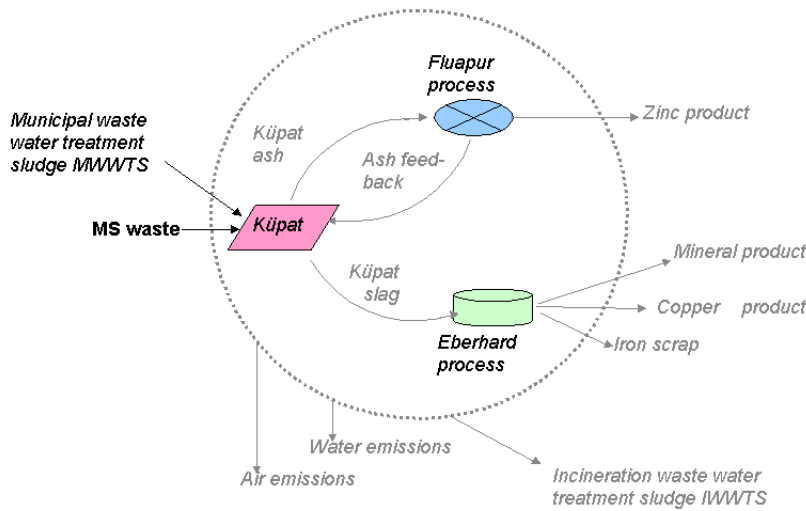
Figure 11   *Model structure of the PECK technology cluster. Note that compared to Figure 9 on page 14 the transient product (from Eberhard slag treatment to Fluapur ash treatment) is neglected. Also the sewage sludge MWWTS is treated as an input to the Küpat process and not the Fluapur process.*

4.2.2 Step 1: calculate Küpat raw slag

The Küpat process has the aim of concentrating volatile heavy metals like zinc, lead, cadmium etc. in the incinerator ashes and removing those metals from slag. Some transfer coefficients for Hg, Cd, Zn, Pb, Cu, Cr, and Ni from the Küpat trials in Basel are given in [Biollaz et al. 1999a, 1999b]. These figures can be used to model the system and are reproduced in Table 12. For other elements, different data sources have to be used.

i	*Transfer coefficient to Küpat slag*
Hg	1.0%
Cd	0.2%
Pb	8.0%
Zn	18.0%
Cu	87.0%
Ni	75.0%
Cr	76.0%

Table 12   *Measured transfer coefficients to Küpat slag from [Biollaz et al. 1999a, 1999b].*

Detailed compositions of untreated Küpat slag C_{iS} are given in [Traber 2000]. Traber compares this composition also to average MSWI slag $C_{iS\emptyset}$ of the same period in time.

This data can be used to modify the *known* transfer coefficient data of the average MSWI process for slag to obtain *extrapolated* transfer coefficient data for raw slag of

the Küpat process. Composition of a product and transfer coefficients for that product are connected through the following equations:

C_{iS} = Concentration of a certain element i in Küpat slag

M_{iS} = mass of a certain element i in Küpat slag = $C_{iS} \cdot M_S$
where M_S = total mass of raw slag from Küpat process

TK_{iS} = transfer coefficient of a certain element i to Küpat slag = M_{iS} / M_i°
where M_i° = total mass of element i in waste input

Similarly the parameters for an average MSWI are:

$C_{iS\varnothing}$ = Concentration of a certain element i in average MSWI slag

$M_{iS\varnothing}$ = mass of a certain element i in average MSWI slag = $C_{iS\varnothing} \cdot M_{S\varnothing}$
where MS = total mass of raw slag from average MSWI process

$TK_{iS\varnothing}$ = transfer coefficient of a certain element i to average MSWI slag =
$M_{iS\varnothing} / M_{i\,\varnothing}^\circ$
where $M_{i\,\varnothing}^\circ$ = total mass of element i in waste input

We can define a factor P_i which is the ratio of the transfer coefficient for Küpat slag divided by the transfer coefficient for average MSWI slag:

$$P_i = TK_{iS} / TK_{iS\varnothing}$$

If the transfer coefficients to average MSWI slag are known, multiplication with P_i gives us the transfer coefficient to Küpat slag[18].

$$TK_{iS} = P_i \cdot TK_{iS\varnothing}$$

The equation above can be written as:

$$TK_{iS} = M_{iS} / M_i^\circ = C_{iS} \cdot M_S / M_i^\circ = P_i \cdot C_{iS\varnothing} \cdot M_{S\varnothing} / M_{i\,\varnothing}^\circ$$

We can assume two things:

First, the total mass of element i in waste input will be equal for the Küpat or average MSWI process, i.e. the waste composition is equal for both processes. In the measurements by Traber there is no feed-back of mineral remains from the ash treatment. The contribution from WWT sludge can be neglected. Therefore,

$$M_i^\circ = M_{i\,\varnothing}^\circ$$

The second assumption is that the total slag masses are similar in the Küpat and the average MSWI process. Actually the MSWI slag masses are slightly bigger: PECK 2001 assumes the values of 25% raw slag output for PECK and 22% raw slag output for MSWI. It can be approximated that the slag masses are equal for both processes. Therefore,

$$M_S = M_{S\varnothing}$$

This simplifies the equation for P_i to:

$$P_i = TK_{iS} / TK_{iS\varnothing} = C_{iS} / C_{iS\varnothing}$$

Values for P_i were calculated using the measured data for C_{iS} and $C_{iS\varnothing}$ from Traber 2000 and are given in Table 13. Elements with a P_i of >1 are concentrated in the slag

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[18] The use of an extrapolation factor P_i is more suitable than the use of the (older) slag composition from Traber's measurements together with current MSW composition, since the waste composition has changed since the early 90ties. The extrapolation factor P_i indicates the characteristic change of slag transfer coefficients when changing from the usual MSWI to Küpat incineration.

through the Küpat process; elements with a P_i of <1 are depleted in the slag through the Küpat process as compared to average MSWI slag. These factors are used to extrapolate the known transfer coefficients to slag from a modern MSWI to the transfer coefficients to slag for the Küpat process (cf. Table 13). The obtained non-recursive slag composition is not final as we will have to heed recursive material flows from the ash treatment process (cf. Step 3).

	Elements that are <u>depleted</u> in the Küpat slag	Extrapolated transfer coefficient to slag		Elements that are <u>concentrated</u> in the Küpat slag	Extrapolated transfer coefficient to slag
i	P_i	TK_i	*i*	P_i	TK_i
S	0.107	6.243%	V	1.128	98.989%
C	0.298	0.579%	Ca	1.147	99.896%
Fe	0.361	35.091%	Mg	1.221	99.898%
Zr	0.420	–	Ba	1.230	99.976%
Na	0.683	63.463%	P	1.261	99.900%
K	0.746	49.903%	Al	1.484	99.904%
Mn	0.812	69.817%			
Si	0.948	92.351%			

Table 13   *Extrapolation factors* P_i *when changing from a modern MSWI to Küpat incineration and derived transfer coefficients to slag (Stand-alone Küpat, not recursive).*

For the remaining elements (O, N, Cl, Br, F, Ag, As, Co, Mo, Sb, Se, Sn) the transfer coefficients of a modern MSWI are adopted.

The extrapolation leads to a desired decrease of carbon and sulfur in the slag. It is assumed that the depleted carbon will end up in the air emissions (as CO_2) and the depleted sulfur will end up in the IWWTS (i.e. as sulfate SO_4^{2-}).

4.2.3 Step 2: calculate slag treatment products

Raw slag is but an intermediate product in the PECK process. The Küpat slag will be treated in the Eberhard slag treatment with the aim to produce recyclable outputs in the form of a copper-rich product, iron scrap and mineral product. Additionally a small amount of a transient product ('Mittelprodukt') is produced by the Eberhard slag treatment which is fed into the filter ash treatment (Fluapur process)[19].

Unfortunately no direct measurements of any of the Eberhard outputs are available. However, [Traber 2000, p.63] also characterises compositions of various metallic particles in the untreated Küpat slag (cf. Table 14). Although not entirely representative, in absence of any other measured data on the Eberhard products, these metal compositions can be used to extrapolate the compositions of the metallic Eberhard products (copper metal scrap and iron scrap).

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[19] This transient product is not considered in the model calculation due to lack of data.

	KU01-22	KU01-27	KU01-28	KU02-26	KU03-31	KU03-32	KU03-33	KU03-35	KU04-41	KU04-43	KU04-46	KU04-52	KU-06-67	KU-06-69	KU07-74	KU07-83
	Fe-Si-Ti	Fe	Fe	Fe-Si-Al	Cu-Al	Cu-Al	Cu-Fe	Fe-Si	Si	Fe	Fe-Si-Al	Fe-Si-Al	Cu	Al-Zn	Fe	Al
S	0.00%	0.08%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.00%	0.00%
Ag	0.00%	0.00%	0.00%	0.00%	0.09%	0.10%	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%	0.00%	0.00%	0.00%	0.00%
Cr	2.98%	0.00%	0.00%	0.12%	0.00%	0.00%	0.07%	0.07%	0.00%	0.32%	0.03%	0.04%	0.00%	0.00%	1.24%	0.00%
Cu	0.83%	0.83%	0.11%	1.27%	88.36%	84.47%	30.31%	4.17%	0.00%	2.20%	5.41%	3.64%	100.88%	1.04%	0.41%	0.05%
Mn	3.03%	0.00%	0.00%	0.17%	0.24%	0.32%	1.37%	1.72%	0.00%	0.26%	0.10%	0.03%	0.00%	0.00%	0.24%	0.15%
Ni	0.08%	0.26%	0.03%	0.06%	0.54%	1.05%	1.76%	3.00%	0.00%	0.08%	0.52%	0.53%	0.00%	0.00%	0.10%	0.00%
Pb	0.00%	0.00%	0.00%	0.15%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.55%	0.00%	0.00%	0.00%	0.07%
Sb	0.00%	0.00%	0.04%	0.00%	0.40%	0.98%	0.10%	0.00%	0.00%	0.00%	0.03%	0.55%	0.00%	0.00%	0.00%	0.00%
Sn	0.06%	0.31%	0.00%	0.00%	1.04%	2.46%	0.31%	0.00%	0.04%	0.00%	0.08%	0.21%	0.00%	0.04%	0.00%	0.00%
V	0.65%	0.00%	0.00%	0.06%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.23%	0.00%
Zn	0.06%	0.00%	0.07%	0.07%	0.23%	0.18%	0.09%	0.00%	0.00%	0.09%	0.29%	1.20%	0.00%	27.61%	0.00%	1.52%
Si	34.43%	0.00%	0.03%	46.20%	1.06%	1.16%	14.50%	18.98%	99.61%	1.30%	7.59%	9.94%	0.03%	0.56%	0.09%	0.12%
Fe	31.26%	86.64%	99.32%	39.22%	0.38%	2.61%	50.31%	71.13%	0.05%	86.44%	41.72%	36.43%	0.00%	0.03%	71.37%	0.16%
Al	0.18%	0.00%	0.00%	10.38%	7.57%	7.76%	2.61%	0.77%	0.04%	0.00%	44.65%	45.55%	0.11%	70.30%	0.00%	98.56%
Ti	27.54%	0.00%	0.00%	1.81%	0.00%	0.00%	0.00%	0.03%	0.00%	0.14%	0.09%	0.24%	0.00%	0.03%	5.15%	0.00%
sum	101.10%	88.12%	99.60%	99.51%	99.91%	101.09%	101.43%	99.87%	99.74%	90.83%	100.51%	98.94%	101.02%	99.66%	78.83%	100.63%

Table 14   16 quantitative electron microprobe measurements of metallic particles in Küpat slag [Traber 2000, p.63]

A *weighted* average of the measurements in Table 14 can produce compositions with a predominant metal. E.g. weighting copper-rich probes high in this average gives an average composition which is high in copper *but also contains metal traces which are common to occur together with copper* according to Traber's measurements. Thus not a pure copper product is calculated – which would be greatly optimistic in the case 'Lab' – but a copper product, which shows the typical trace contaminants of copper particles from Küpat slag. This copper product is used to characterise the metallic part in the copper scrap product (another part is made up from oxidic mineral product). In analogy, a probable composition of iron scrap metal can be extrapolated by giving iron-rich measurements high weights in the average. The weighting factor for each measurement in these weighted averages was set proportional to the concentration of copper in the measurement to the power of 4 (for copper particles), respectively the concentration of iron to the power of 4 (for iron particles).

The compositions of the copper and iron scrap can be used to calculate the composition of the remaining mineral product by difference from the input. The input to the slag treatment is calculated as the Küpat raw slag (without recursions, cf. step 1) *plus* the final fed-back ash from the ash treatment (with recursions), which won't leave the system by way of the zinc product (cf. step 3 below). The composition of the Küpat raw slag can be calculated from average MSW composition and the transfer coefficients for Küpat slag obtained above (cf. chapter 4.2.2 'Step 1: calculate Küpat raw slag' on page 24). A certain mass of copper scrap and iron scrap can be obtained from this

input. However, heeding mass balances, the amount of metallic scrap products is limited by the metals present in the input, e.g. one cannot obtain more copper than is available from the input. The amount of copper metal product is limited by the copper present in the slag input. Similarly, the iron scrap obtainable from slag is limited, not by iron, but by nickel. Roughly 60% of the total iron content in the raw slag is transferred to the iron scrap product.

Also the Eberhard process is not expected to remove *all* copper from slag. Even according to the anticipated transfer coefficients proposed by ARGE PECK (Case 'Max', cf. Figure 7), only about 66.7% of the copper of the MSW input is transferred to the copper scrap product and a fair fraction of 28.5% remains in the mineral product. Therefore the ratio of the copper transfer coefficients to the copper scrap and the copper transfer coefficients to the mineral product is – at least – 2.3 (= 66.7/28.5).

The copper metal product cannot be obtained in pure form, but it is heavily contaminated with oxidic mineral product. For the optimised PECK process (Case Max), it is expected that a fraction of 66% to 76% of the final copper product obtained from the Eberhard process consists of mineral product [Biollaz 2001]. Therefore, every gram of metal in the copper product, brings along 1.9 to 3.1 grams of mineral material. Due to lack of more accurate data the metal-to-mineral ratio is assumed to be 24/76 for the case 'Lab'.

The masses of mineral product output per kilogram MSW can be calculated from the masses of the input to the Eberhard process and subtracting the masses of copper scrap metal, the masses of mineral product in the copper scrap and the masses of iron scrap.

Transfer coefficients for copper product (metal and mineral part) are then calculated from the masses of the metal and mineral part in the copper product divided by the masses in average MSW. Accordingly, transfer coefficients for iron scrap are calculated from the masses of iron metal product divided by the masses in MSW.

Transfer coefficients for mineral product are the complement of copper product and iron scrap to the masses of the input to the Eberhard process.

For a number of elements no information about their concentration in metal particles is available (i.e. B, Ba, Br, Ca, Co, F, J, K, N, Mg, Mo, Na, P, Se). These elements all remain in the mineral product, as there is no information about their removal from the slag.

For a smaller number of elements no information at all can be estimated regarding their behaviour in the PECK process (i.e. B, Br, Co, F, J, Mo, N, Se). For these elements air and water emissions will be calculated according to an average MSWI. The rest ends up in the mineral product.

kg/kg	Copper metal particle	Iron metal particle	Zinc product
O		0.07031945	0.27553373
H			0.01650783
S	2.8372E-12	0.00016359	
Cl			0.01054624
Ag	0.00048905	1.9178E-06	8.9096E-05
As			7.8017E-05
Cd			0.00485387
Cr	2.7346E-06	0.00201668	0.00882794
Cu	0.93212531	0.01881573	0.06202386
Hg			6.16E-07
Mn	0.00148317	0.0028017	
Ni	0.00406233	0.00418906	0.00623202
Pb	4.4823E-09	4.8037E-05	0.18390684
Sb	0.00343813	0.00020296	0.0028156
Sn	0.00873394	0.00073031	0.00916418
V	2.178E-11	0.00024425	
Zn	0.00107548	0.00056716	0.37772527
Si	0.00642825	0.03045854	
Fe	0.00918109	0.85940015	0.03848703
Al	0.04023276	0.01004045	
Sum	1.00725225	1	0.99679213

Table 15   *Compositions of copper and iron particles (weighted averages from Table 14) and zinc product from [Biollaz 2001, Jakob et al. 1999] from measurements of stand-alone, non-recursive PECK components. Values for Ag, As, Sb and Sn were added based on the assumption that these volatile elements will have a transfer coefficient of at least 30% or higher for the zinc product.*
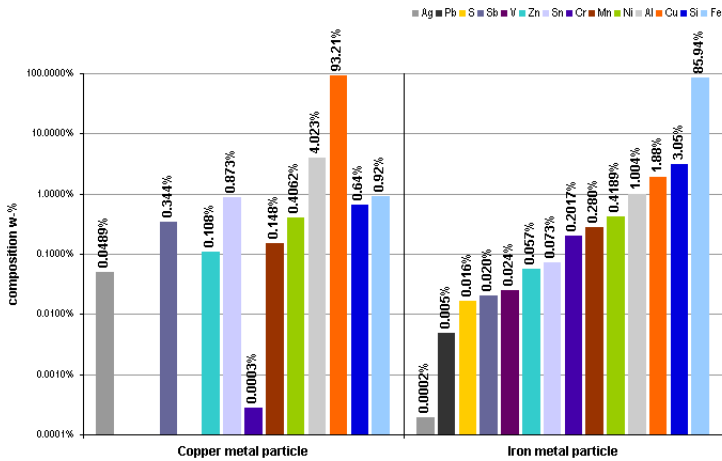
Figure 12   Compositions of metallic particles in Küpat slag. Weighted average for a copper-rich and an iron-rich fraction based on measurements in [Traber 2000].

According to [Zeltner 2001] measurements for remelted MSWI iron scrap showed concentrations of copper in the range of 0.65% – 2.65%, of tin 0.04% – 0.1% and of sulfur 0.039% – 0.11%. Apart from sulfur (which is not relevant to the LCA result) the ranges agree with the concentrations extrapolated for iron scrap in Table 15.

4.2.4 Step 3: Calculating the Fluapur ash treatment

In a first order approximation the input to the ash treatment system are the waste masses that neither go to raw slag or sludge (IWWTS), nor air or water emissions. Since all those fluxes are known or can be calculated, the first order ash masses can be calculated by difference.

This ash product consists of the fly ash and the boiler ash. In the Fluapur treatment a zinc hydroxide product is obtained from the ash. For this zinc product composition measurements exist from Fluapur standalone trials (i.e. fed with MSWI ash, no recursive system). This information can be used to characterise the performance of the Fluapur step in the form of transfer coefficients. The remaining masses that do not go into the zinc product are fed back to the incinerator.

Here the recursion in the system occurs: the fed-back ash gets another chance to be transferred to the Küpat incinerator slag and subsequently being processed in the Eberhard slag treatment, on the other hand ash components could again be transferd to the incinerator ash ensuing recurrent treatment in the Fluapur ash treatment process and a possible exit by way of the zinc product. Therefore this recursive step influences *all* solid output products of the PECK system. The recursions were included in the modelling of the PECK processes. A recursive loop from Fluapur ash input to → fed-back ash to → repeated Fluapur ash input was cycled until a steady state of the

mass fluxes was reached[20]. The final (i.e. steady state recursive and heavy metal depleted) fed-back ash represents those parts in the ash that possibly won't leave the system by way of the zinc product. It must therefore leave the system by way of the slag treatment[21]. Accordingly the final masses of the fed-back ash are added to the raw slag calculated from the Küpat process with an average MSW input, and both – MSW raw slag and the final fed-back ash – are processed in the slag treatment (cf. Step 2).

No information about the mercury content of the zinc product is available from the trial measurements. This is unfortunate, since mercury sets the most severe criteria for zinc products to be accepted in the zinc recycling: a maximum level of 0.002 w-% or 20 ppmw is the threshold of Berzelius Freiberg zinc recycling plant. With a mercury content in the waste input of 1.54 ppm, already a rather low transfer coefficient of 3.51% to the zinc product is enough to reach that threshold[22]. However, the assumptions regarding the performance of the mercury trap (cf. chapter 4.5 on page 35) allow a maximal quota of approx. 0.1% of all mercury to be transferred to the zinc product; i.e. more than 30 times below the threshold.

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[20] It is implied here that the (re-)distribution of the elements in the fed-back ash occurs according to the transfer coefficients determined for the Küpat incineration process (cf. Step 1). This is debatable, since the fed-back ash is mostly mineral and unburnable, but the transfer coefficients were determined for mostly burnable MSW. On the other hand the ash was volatilised in the incineration process and was transferred to the raw gas indifferent of its mineral nature as fly ash. However, in absence of any detailed information the transfer coefficients for average waste are the best way also to characterise the fate of the fed-back ash.

[21] Recursion increases the transfer coefficients of elements by hardly significant amounts, i.e. most of the 'first order' fed back ash will ultimately end up in the slag treatment.

[22] The total mass of the zinc product being 2.46 grams per kilogram waste input.

4.3 Modelled transfer coefficients and output compositions

kg/kg in input	Copper scrap	Iron scrap	Mineral product	Zinc hydroxide product
H_2O	0	0	0	0
O	0.002465923	0.005856483	0.286536994	0.002546659
H	0	0	0	0.000809049
C	7.83826E-05	0	0.009107953	0
S	0.002888417	0.002939643	0.335630191	0
N	8.53252E-05	0	0.009914675	0
P	0.008523987	0	0.990476013	0
B	0.008532519	0	0.991467481	0
Cl	0.001696087	0	0.197083073	0.003679536
Br	0.008506922	0	0.988493078	0
F	0.007871249	0	0.914628751	0
J	0	0	0	0
Ag	0.335354149	0.058207267	0.202970865	0.40346772
As	0.005522081	0	0.641658557	0.313719351
Ba	0.008530456	0	0.99122774	0
Cd	2.1289E-05	0	0.00247375	0.9774507
Co	0.008361783	0	0.97162818	0
Cr	0.006665721	0.138098527	0.774058869	0.069390175
Cu	0.37452347	0.335129531	0.160827177	0.121461058
Hg	8.69032E-05	0	0.00991615	0.000974943
Mn	0.009211194	0.234095099	0.746683701	0
Mo	0.008515454	0	0.989484546	0
Ni	0.018325585	0.840802955	0	0.140871439
Pb	0.000673279	0.002059089	0.078233583	0.86744982
Sb	0.076794635	0.194932491	0.299736484	0.338582433
Se	0.008098073	0	0.940985435	0
Sn	0.061292321	0.215499848	0.391421778	0.306391183
V	0.003545083	0.574411085	0.411933832	0
Zn	0.001882361	0.009274012	0.172800254	0.68125662
Si	0.008474758	0.013417815	0.97736007	0
Fe	0.003460834	0.60416114	0.385288207	0.005122769
Ca	0.008523616	0	0.99043292	0
Al	0.009913836	0.017205341	0.97192328	0
K	0.00850687	0	0.98848702	0
Mg	0.008523817	0	0.99045631	0
Na	0.008517726	0	0.989748537	0

Table 16   *Transfer coefficients for chemical elements in the PECK process for four output products, 'Case Lab', from recursive calculation.*

kg/kg in input	air emissions	water emissions	sludge IWWTS	mercury trap
H2O	1	0	0	0
O	0.70181154	0	0.0007824	0
H	1	0	0	0
C	0.99079367	9.9957E-06	9.9957E-06	0
S	0.00199304	0.06676696	0.58978175	0
N	0.989	0.001	0	0
P	0.001	0	0	0
B	0	0	0	0
Cl	9.405E-06	0.79188892	0.00564298	0
Br	0.003	0	0	0
F	0.0005	0.056	0.021	0
J	0	0	0	0
Ag	0	0	0	0
As	1.02E-08	0.0001	0.039	0
Ba	0.0002418	0	0	0
Cd	5.426E-05	1.4036E-05	0.01998596	0
Co	3.175E-08	0.00001	0.02	0
Cr	1.3021E-08	0.00056127	0.01122542	0
Cu	4.0274E-06	0	0.00805473	0
Hg	2.8192E-08	0.00854305	0.00502331	0.97545718
Mn	5.445E-09	0.00001	0.01	0
Mo	0.002	0	0	0
Ni	2.1857E-08	0	0	0
Pb	2.2413E-05	1.1207E-05	0.05155061	0
Sb	2.428E-09	0.00011372	0.08984023	0
Se	3.6133E-09	8.472E-05	0.05083177	0
Sn	0.00101539	1.0154E-05	0.02436933	0
V	0.0001	0.00001	0.01	0
Zn	1.2241E-05	0.00012241	0.1346521	0
Si	0.00074736	0	0	0
Fe	9.3225E-06	9.3225E-05	0.0018645	0
Ca	0.00104346	0	0	0
Al	0.00095754	0	0	0
K	0.00300612	0	0	0
Mg	0.00101987	0	0	0
Na	0.00173374	0	0	0

Table 17   Transfer coefficients for chemical elements in the PECK process for four output products, 'Case Lab'.

Composition kg/kg	Copper scrap	Iron scrap	Mineral product	Zinc product
O	0.31561658	0.07031945	0.416008	0.270808578
H	0	0	0	0.016145831
C	0.01296555	0	0.01708962	0
S	0.00171356	0.00016359	0.00225861	0
N	0.00014125	0	0.00018618	0
P	0.00442268	0	0.00582944	0
B	3.0192E-05	0	3.9795E-05	0
Cl	0.00575796	0	0.00758945	0.010378683
Br	5.671E-05	0	7.4748E-05	0
F	0.00021841	0	0.00028788	0
J	0	0	0	0
Ag	0.00011778	1.9178E-06	8.0864E-07	0.000117197
As	1.6983E-06	0	2.2385E-06	7.97954E-05
Ba	0.00062539	0	0.00082432	0
Cd	1.2396E-07	0	1.6339E-07	0.004707026
Co	5.9946E-06	0	7.9014E-06	0
Cr	0.00103766	0.00201668	0.00136685	0.008933694
Cu	0.22415	0.01881573	0.00109186	0.060121521
Hg	6.345E-08	0	8.3632E-08	6.0249E-07
Mn	0.00117517	0.0028017	0.0010806	0
Mo	8.1894E-06	0	1.0794E-05	0
Ni	0.00097326	0.00418906	0	0.006187712
Pb	0.00016744	4.8037E-05	0.00022069	0.17841364
Sb	0.00085235	0.00020296	3.7738E-05	0.003108022
Se	1.2735E-06	0	1.6786E-06	0
Sn	0.0022142	0.00073031	0.0001604	0.009154173
V	1.6069E-05	0.00024425	2.118E-05	0
Zn	0.00122714	0.00056716	0.00127785	0.36730889
Si	0.20507552	0.03045854	0.268276	0
Fe	0.05247612	0.8594	0.06626841	0.064534639
Ca	0.0613225	0	0.08082794	0
Al	0.06167227	0.01004045	0.06858388	0
K	0.00870134	0	0.01146906	0
Mg	0.01431233	0	0.0188648	0
Na	0.02294348	0	0.03024134	0

Table 18   Compositions for output products in the PECK process, 'Case Lab', from recursive calculation. Based on average waste input composition.

4.4 Comparison transfer coefficients 'Case Lab' vs. 'Case Max'

The only changes between the Case Lab and the Case Max regarding transfer coefficients occur for the elements Zn, Pb, Cd and Cu. In the Case Max the transfer coefficients from Figure 7 (cf. page 13) are used.
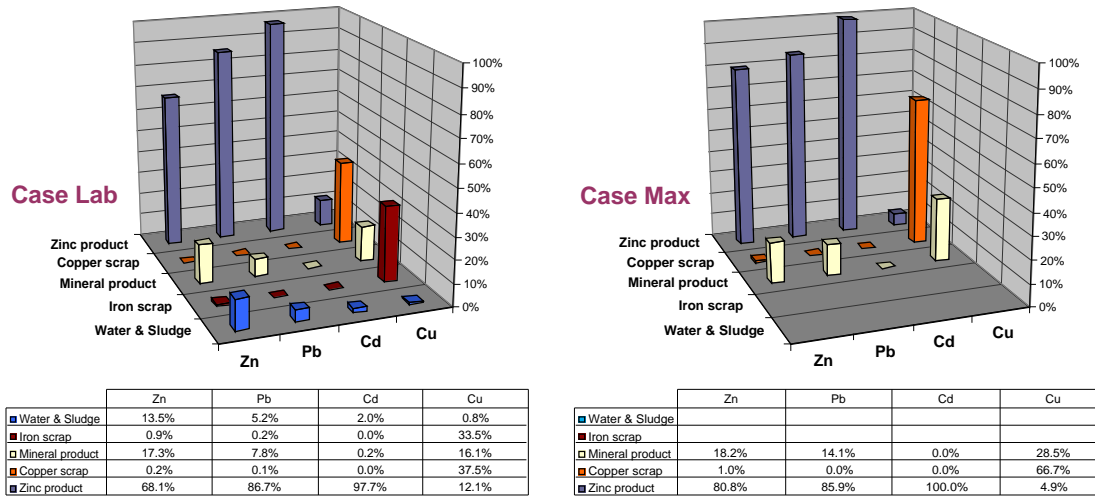

	Zn	Pb	Cd	Cu
■ Water & Sludge	13.5%	5.2%	2.0%	0.8%
■ Iron scrap	0.9%	0.2%	0.0%	33.5%
□ Mineral product	17.3%	7.8%	0.2%	16.1%
□ Copper scrap	0.2%	0.1%	0.0%	37.5%
■ Zinc product	68.1%	86.7%	97.7%	12.1%

	Zn	Pb	Cd	Cu
■ Water & Sludge				
■ Iron scrap				
□ Mineral product	18.2%	14.1%	0.0%	28.5%
□ Copper scrap	1.0%	0.0%	0.0%	66.7%
■ Zinc product	80.8%	85.9%	100.0%	4.9%

Figure 13   *Extrapolated (Case Lab) and expected (Case Max) transfer coefficients for four elements to five outputs. 'Water and Sludge' consists of scrubber sludge IWWTS plus emissions to water. Case Max is based on [PECK 2001]; no transfer coefficients to iron scrap and waste water are given.*

The comparison of the Case Lab and Case Max in Figure 13 shows that the two cases are quite similar, i.e. the extrapolated performance based on the trials (Case Lab) is already quite close to the expectations of ARGE PECK (Case Max).

The quite low transfer coefficient of copper to copper scrap in Case Lab (TK = 37.5% instead of 66.7% in Case Max) is due to the fact that the iron scrap exhibits copper contaminations. Almost equal amounts of copper are transferred to the iron scrap and to the copper scrap, respectively (TK = 33.5% resp. 37.5%). Some zinc is lost to the scrubber sludge.

4.5 Mercury trap and further flue gas treatment in PECK

The PECK technology features a mercury trap. The mercury trap removes mercury from the raw flue gas. It is assumed here, that absorption on activated carbon is used. The carbon has to be doted with SO_2 in order to bind the mercury as $HgSO_4$. It is assumed that 97.5% of the mercury in waste is transferred to the mercury trap, which corresponds with a removal efficiency of 99.9% from flue gas[23]. The carbon-mercury ratio is approx. 450 by weight, as established from descriptions of MSWI operations in [Studley and Wattis 2001]. With a mercury content of 1.5ppm, one kilogram of MSW generates 0.67mg of hazardous waste, that is deposited in subsurface deposits.

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[23] 1% of mercury is transferred to slag, 1.36% to waste water and IWWTS. Most of the remaining mercury (approx 0.1%) is assumed to be transferred to the zinc product.

Mercury from such a trap could also be recycled or adsorbed with ion exchangers which would reduce the mass of deposited hazardous waste. This is however not considered here. Since the contribution of deposited hazardous waste to the total result is small, this assumption is not decisive.

All other flue gas treatment processes are expected to be similar to conventional MSWI. To calculate the demand of auxiliary materials in PECK, the specific consumption figures from MSWI c.f. Table 8 on page 18 are used, except for the electricity demand for iron recycling, which is already heeded in the Eberhard process.

4.6 Fluapur ash treatment process

The Fluapur ash treatment extracts volatile heavy metals like zinc, lead, cadmium from fly ash and concentrates them in the hydroxide product (called zinc product, as the major metal is zinc). In the process ash is pelletised together with dewatered sewage sludge and dried (cf. cover photo). Hydrochloric acid (HCl_{aq}) is distilled from excess acid from the plants flue gas wet scrubber system. In a fluidised bed reactor the HCl extracts heavy metals from the ash pellets as gaseous metal chlorides. A small amount (2%) of the incinerators raw flue gas is used to heat the reactor. The gas stream is quenched, the metal chlorides are altered to metal hydroxides, and filtered. The filtrate is recycled for HCl. The filter cake is the final zinc product.

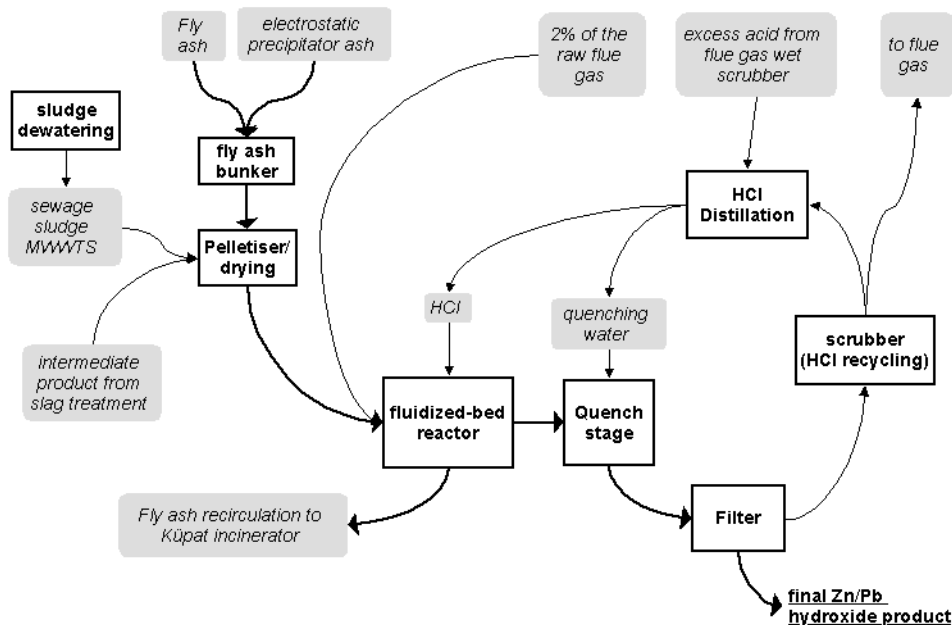The input of dewatered sludge to Fluapur is 290 grams per kilogram of filter ash input [PECK 2001].

Figure 14   Process scheme of the Fluapur ash treatment. Principal material flows are bold.

4.6.1 Energy demand

The energy demand figures in Table 19 were calculated from data given in [Jakob 1998] from experimental trials.

Raw flue gas is used for heating the reactor. However the gas needs to be heated additionally from 800°C to 1050°C. This is accomplished with a natural gas burner. This natural gas demand will be inventorised as such and not as a decrease in net energy production from PECK. Approximately 1.2% of the raw flue gas is diverted to Fluapur. This reduces the raw gas available to the PECK plant to produce energy. The electric and thermal energy efficiencies of PECK are therefore reduced to 98.8% of their initial values.

The entries C, D and E in Table 19 reduce the net energy production of the PECK plant. and do not lead to a direct consumption of energy carriers or additional emissions.

The estimated electricity demand for dewatering the sewage sludge by centrifuge is negligibly small (<1%).

Process	Energy	Unit	
A. Reactor heating	raw flue gas	% of total	1.2%
B. Additional heating of raw flue gas	useful heat natural gas	MJ / kg ash input	1.60
C. All processes	electricity	MJ/kg ash input	0.54
D. Pellet dying	process steam	MJ/kg ash input	0.98014
E. HCl distillation	process steam	MJ/kg ash input	5.5686

Table 19   Specific energy demands in Fluapur ash treatment

4.6.2 Other inventory data

Other data on infrastructure, auxiliary materials or emissions – apart from the material fluxes established in chapter 4.2 'Transfer coefficients calculations for PECK Case Lab' on page 20 – is not available and is neglected here, as the importance to the end result is probably small.

4.7 Eberhard slag treatment process

The Eberhard slag treatment has raw slag as an input and produces four outputs: mineral product, iron scrap, copper scrap and an intermediate product. The intermediate product is fed back to the Fluapur ash treatment. The other three products are recycled.
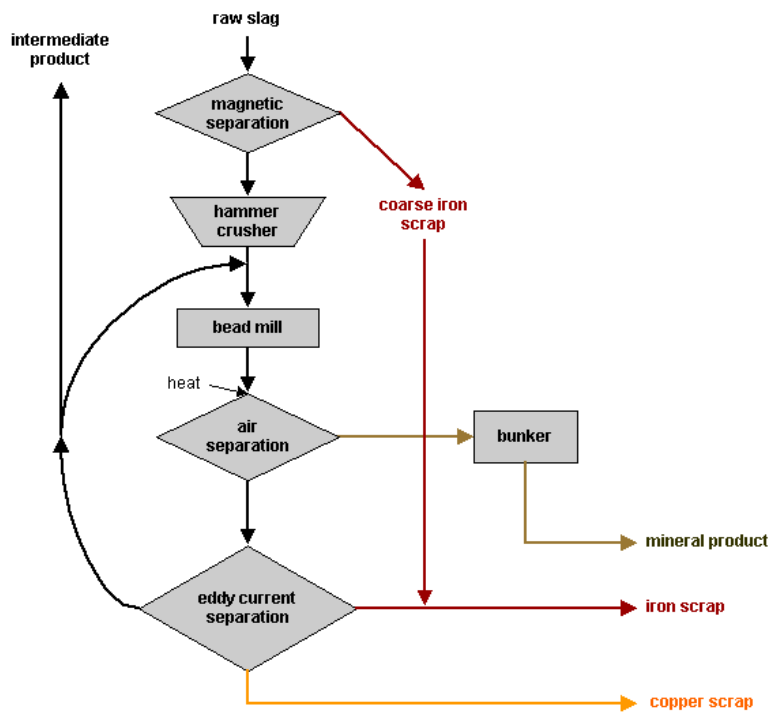
Figure 15   *Process scheme of the Eberhard slag treatment.*
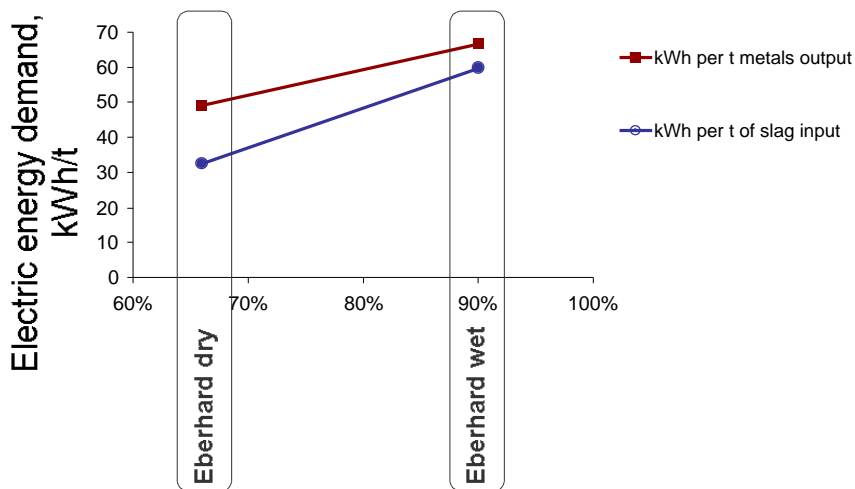
4.7.1 Energy demand

Two types of Eberhard slag treatment process are imaginable. A dry process, that first crushes slag to 1mm fragments and then uses mechanical and magnetic devices to separate iron rich and copper-rich products from the remaining mineral fraction[24]. This process can separate about two thirds of the metals present in the slag and has an electrical energy demand of approx. 30–35 kWh/ton slag input [Bunge 2001].

The second type would be a wet process that includes a bead mill (Kugelmühle) and a sequence of wet separation processes. The wet process can separate about 90% of the metals present in the slag and has an electrical energy demand of approx. 60 kWh/ton slag input [Bunge 2001].

Both processes use about two thirds of the energy input to crush (and grind) the slag and one third for the separation of the metal parts.

By comparison, a modern MSWI separates only the magnetic iron fraction and uses approx. 2.5 kWh/ton slag input [Zimmermann et al. 1996].

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[24] Separation consists of magnetic separation, density sorting, eddy current separation and optical sorting.

Figure 16   *The figure shows how the total energy demand for processing slag (kWh/t slag) increases with increasing quota of metal separation (lower line). Also the specific energy demand per ton of separated metal increases (top line).*

According to [Bunge 2001] of ERAG a wet separation seems to be too demanding in terms of investments and costs for the PECK purpose. A dry process will be the most likely option. Accordingly an electrical energy demand of 32 kWh/ton is chosen.

Two thirds of the energy input is used to crush and grind the slag and one third for the separation of the metal scrap [Bunge 2001]. The material input is 200 grams slag per kg waste (including 24 grams of iron and copper scrap). Therefore, the specific energy consumption figures amounts to 0.077 MJ_{el} per kg slag input and 0.326 MJ_{el} per kg metal for iron and copper.

4.7.2 Other inventory data

Other data on infrastructure, auxiliary materials (e.g. mill beads) or emissions – apart from the material fluxes established in chapter 4.2 'Transfer coefficients calculations for PECK Case Lab' on page 20 – is not available and is neglected here, as the importance to the end result is probably small.

4.8 Secondary metal production

4.8.1 Allocation issues in secondary metal production

During secondary metals processing the generated slags are often sold as co-products. Applications include road construction, building material filler, landfill material or sand blaster abrasive.

In LCA, co-products usually should bear a certain portion of the total burdens associated with the generating process, i.e. the total burdens of the process are allocated to its various output products. Allocation weights should be based on

1) relevant physical features of the products; or on

2) their economical value.

Since the products are diverse in functionality, i.e. refined metals vs. mineral sags, an allocation on physical features seems not feasible[25]. The economical value of the slags is bound to be negligible compared to the value of the metals[26]. It is concluded therefore that the burdens of secondary metals processing are fully allocated to the desired metal product. Usable slags bear no burdens. Landfilled slags however bear the burden of landfilling and are assigned to the metal production.

Note in Figure 17 that the Wälz furnace receives Zinc bearing material in form of PECK zinc hydroxide and zinc/lead dust from secondary copper processing. Also note that the lead product is produced indirectly via the Wälz furnace-Lead furnace route. The processes on the far right are outside the indicated system boundary and their burdens are not included in this assessment.

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[25] Allocation according to masses would certainly be unfair.

[26] E.g. sand blasting abrasive – as a specialised product with distinct properties – is valued at approximately 80 USD/ton; copper metal at 1700 USD/ton. Secondary copper production generates approximately 540 kilogram of slag per ton of copper. The resulting values generated are 44 USD for blasting abrasive and 1700 USD for copper. Allocation according to economical weights would contribute only 2.5% of all burdens to the slag/blasting abrasive and 97.5% to the copper, i.e. the allocation would hardly have any noticable effect.
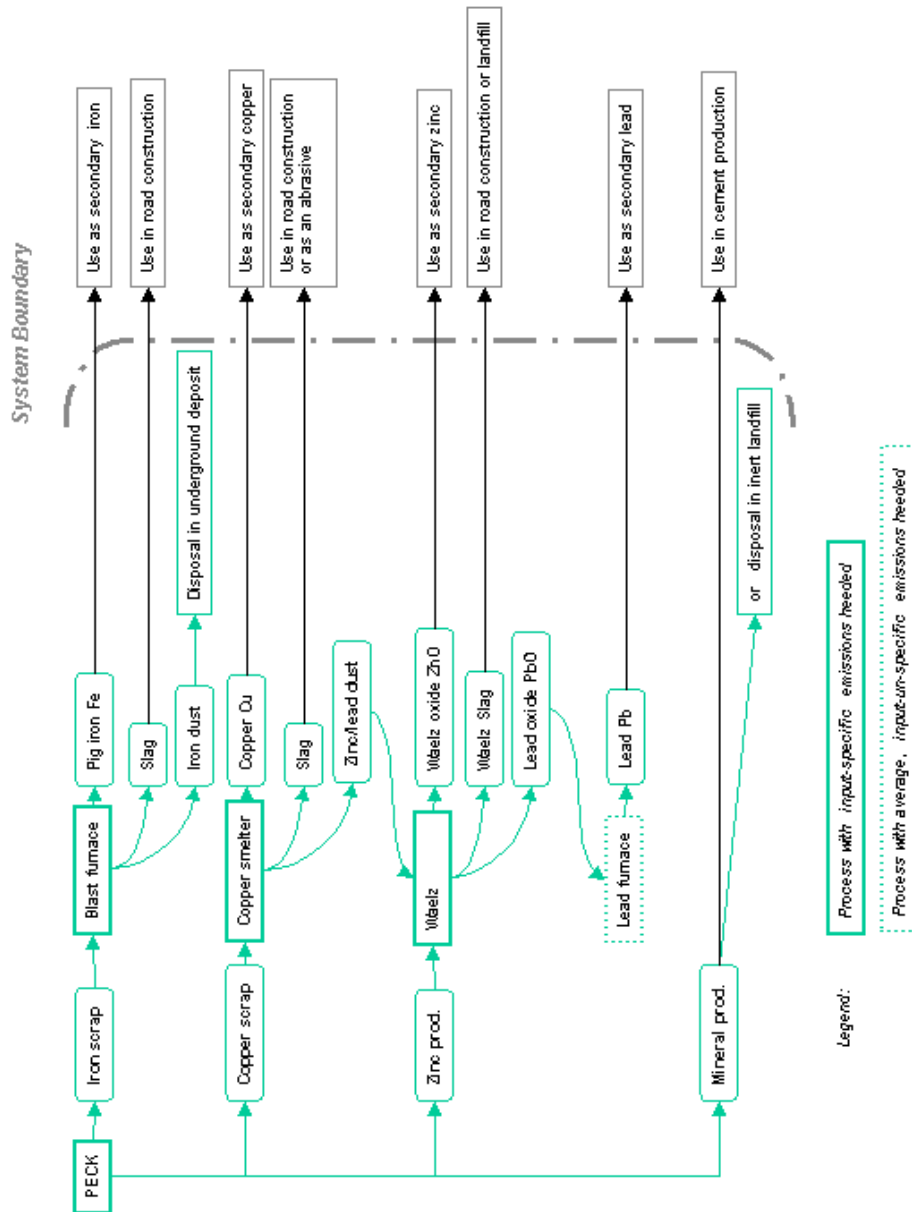
Figure 17   *Necessary processes for the secondary materials production from PECK outputs. Downstream flows and connections.*

4.8.2 Iron blast furnace

The iron scrap from conventional MSWIs is not entirely metallic. About 50% of the scrap is oxidised during incineration. Due to that fact MSW iron scrap cannot be

recycled in electric arc furnaces (EAF) which are generally fed with iron scrap. MSW iron scrap needs to be treated and smeltered in blast furnaces [AGW 1990b, p.6–13][27].

Blast furnaces produce pig iron ('Roheisen') from treated iron ores[28] by reduction with mostly coke fuel. The blast furnace production process is described in [ESU 1996b]. Emissions to air and water reported in [ESU 1996b] are taken from early 90ties publications and are probably based on 80ties data. Some new information for existing, modern iron facilities like sinter plants, pelletiser plants and blast furnaces in the EU can be found in [IPCC 2000-a]. In this study, the respective data in [ESU 1996b] was updated with the information of modern plants from [IPCC 2000-a]. Where no updated figure was available, the data from [ESU 1996b] was used[29].

The emissions reported in the above sources are generic, i.e. average, typical figures. Specialists agree that the emission levels from furnaces are strongly dependent on feed materials. However, quantitative data on the behaviour of different elements is not available. To obtain an input specific emission profile, information on the trace metal compositions of the feed materials (iron ore, coke, heavy fuel oil, natural gas) were assembled from various sources[30]. Thus, the total input of an element to pig iron production could be determined. Knowing the emissions to air and water the transfer coefficients can be calculated in the form of TK_i = (emissions of element i) / (total input of element i). These transfer coefficients can be used to determine input-specific emission contributions of pig iron production, when the composition of the iron scrap input is known.

For some elements, the input is not dominated by the iron feed, but also perceptibly influenced by fuel materials (coke, heavy fuel oil, natural gas). The combustion of those fuels leads to additional process-specific emissions. The total emission profile of pig iron production is the sum of the input-specific emissions determined by the iron scrap and the process-specific emissions from fuels combustion.

Slag from iron blast furnace is used as a co-product in road construction. Fine dust residue is rich in iron and is disposed in subsoil deposits.

A share of 2% Cr-VI emissions was applied for the total chromium emissions from the iron blast furnace. This emission is generally unimportant in the fully aggregated results, but account for 3%–6% in the Human Toxicity Potentials HTP score.

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[27] According to [Zeltner 2001] MSWI iron scrap in Switzerland is recycled in electric arc furnaces EAFs. The input to these EAFs is 100% scrap. MSWI iron scrap can only be added in small percentages due to high contents of copper and tin. Cleaner scrap from other sources is needed to dilute those contaminants. MSWI iron scrap is accepted to EAFs as a no value commodity, i.e. price is zero [Zeltner 2001]. On average, EAFs feature less emissions than blast furnaces. However, it is not feasible to inventorise the *input-specific* emissions streams of EAFs (i.e. calculate transfer coefficients in the from of emissions / input) as their scrap input has huge and erratic variations in composition. The blast furnace is chosen as recycling sink for iron scrap in this assessment, and this is likely to be a more burdening recycling option than EAFs, but a probable sink for other countries than Switzerland. The problem of assuming a blast furnace for recycling instead of a EAF is alleviated somewhat since modern blast furnaces were used for the inventory.

[28] Treatment of the iron ore consists of pelletising with coke or sintering with bentonite mineral.

[29] Blast furnaces are huge installations with considerable investment costs involved. Technology turnover rates are hence bound to be small.

[30] [ESU 1996] and public information from several iron ore traders.

4.8.3 Zinc oxide furnace (Wälz furnace)

The hydroxide product from PECK is rich in zinc and lead. It is expected to be processed by Wälz kiln furnaces producing zinc oxide and lead oxide. Wälz kiln furnaces usually process zinc rich dusts coming from iron recycling, so-called Electric Arc Furnace dusts, EAF dusts [31]. The EAF dust is mixed with coal and fluxing agents and fed to the kiln. The feed is reducing and oxidizing simultaneously in the kiln, thus generating two marketable products —a mixed zinc/lead oxide and an inert iron-rich slag. The zinc/lead oxide is refined to extract zinc and lead. Slag is used as a co-product in landfill construction or road construction.
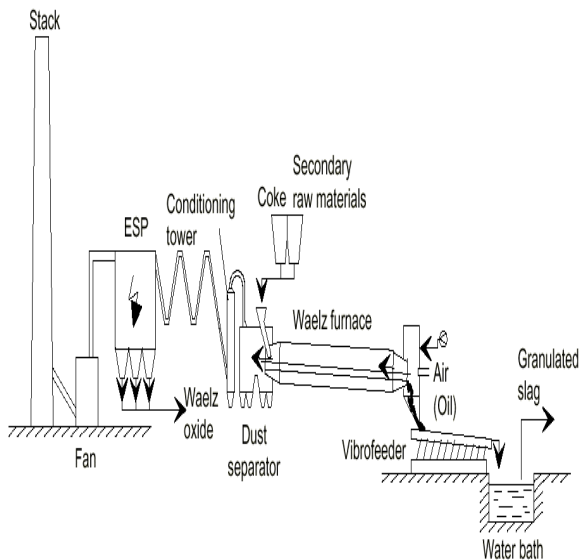

Figure 18   Waelz kiln scheme

Berzelius Umwelt Service B.U.S. oparates a Wälz kiln in Freiberg, Germany, with a capacity of 60'000 tons of EAF per year. A detailed material and energy flow inventory is listed in their environmental report [BZF 2000]. The typical ranges of metals in EAF dust are known from various sources [Janis 2000, BZF 2000, Dutrizac et al. 2000]. Together with the air and water emission data from [BZF 2000], elemental transfer coefficients for a chemical element *i* can be derived in the form of (emission of *i*) / (input of *i* in EAF dust)[32]. Thus, it is possible to calculate input-specific emissions from the Wälz process, when the composition of the zinc-bearing input is known.

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[31] Electric Arc Furnaces process iron scrap by direct reduction in an electric arc. Zinc from corrosion coatings of iron is evaporated and collected as EAF dust.

[32] The Wälz process has also other inputs than EAF dust, like coke or fuel oil. The contribution to the input of metals to the process by those materials is in the order of less than 0.1 percent. I.e. essentially all metals are entered as EAF dust. Other sources can be neglected.
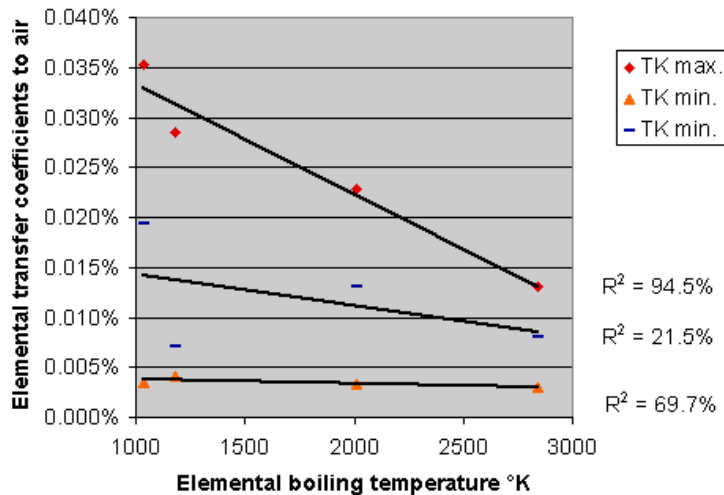
Figure 19   *Correlation of upper, lower and medium values for transfer coefficients (TK) for air emissions of Zn, Pb, Cu and Cd in the Wälz process with their respective elemental boiling temperature. The deviating element at approx. 1200°K is zinc, i.e. the desired product of the Wälz process.*

For volatile metals like zinc, cadmium, mercury and lead the calculated transfer coefficients to air show not excellent, but some remote correlation with the boiling temperature of the element as shown in Figure 19. This is not surprising as the operating temperature of Wälz kilns is 1200°C, i.e. 1473°K. The kiln is designed to refine zinc *by volatilisation* and collecting the generated zinc oxide dust. Thus low-boiling elements are prone to be transferred to the gas phase. Air emissions consist mainly of fugitive dust from the kiln. In absence of detailed data this correlation can be used to obtain approximations for transfer coefficients of additional volatile metals like antimony, thallium, tin etc[33].

The lead in the PECK hydroxide product is separated and reduced in a lead furnace (cf. below).

4.8.4 Copper smelting and converting

Secondary copper is produced by pyro-metallurgical processes. The process stages used depend on the copper content of the secondary raw material, it's size distribution and the other constituents. Special care is needed to remove organic material in the feed (cable insulation, oils and lubricants) to avoid the formation of dioxins, as copper is strong catalyst of dioxin formation.

A furnace such as a converter is used to smelt impure scrap to produce black copper and a zinc-rich filter dust. The stages used for secondary copper production are generally similar to those for primary production but the raw material is usually oxidic

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[33] These additional transfer coefficients are heeded for completeness of the assessment, i.e. in order to not ignore any potentially important emission. However, the contribution to the total burden in the final result from these elements is lower than 0.2% and hence not of noticeable relevance.

or metallic and process conditions are therefore not constant. Smelting of secondary raw materials therefore often uses reducing conditions.

The company Montanwerke Brixlegg in Austria uses oxidic copper scrap with copper concentrations between 15% and 70% to produce 'black copper' in a smelting furnace. They would be the designated recipients of PECK copper scrap.

Data on average process-specific air emissions of secondary copper furnaces can be found in [CORINAIR 1999-3]. The production process is heeded up to the generation of converter copper.

Information on the usual average compositions of copper scrap input was not obtainable. It is therefore not possible to derive any transfer coefficients from mass balances as featured in the secondary zinc and iron production. One single average transfer coefficient for copper of 0.0085% can be derived from an average of 85 grams of copper emissions per ton of secondary converter copper produced [CORINAIR 1999-3].

To produce educated guesses on transfer coefficients in absence of any measurements, the correlation found in secondary zinc production between transfer coefficients and the elemental boiling temperature is used. It is assumed that the emission characteristics of secondary zinc production and secondary copper production as described by the elemental transfer coefficients is comparable[34]. It can be expected that the increase in transfer coefficients with decreasing elemental boiling temperature is similar, i.e. that the *slope* of the correlation line displayed in Figure 19 is approximately applicable to secondary copper production too. If so, this slope can be used to calculate approximations on other transfer coefficients, anchoring at the known point for copper[35]. From the boiling points of other volatile metals their transfer coefficients can thus be derived[36].

A zinc rich dust is generated as a residue in secondary copper production. This dust will be processed as secondary zinc source, i.e. the Wälz kiln. For the assessment of the processing of the PECK copper scrap, it is expected that the following metals will be completely transferred to the residual dust: Ag, As, Ba, Cd, Co, Cr, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, V, Zn. The dust is then treated as an additional input to the Wälz kiln together with the PECK zinc product[37].

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[34] Indeed, both processes achieve purification by volatisation. The transfer coefficient to air for copper in secondary zinc production is 0.008% is very similar to that of secondary copper production (0.0085%) although they were derived from unrelated data backgrounds.

[35] The transfer coefficient of copper is 0.0085% and the boiling point is 1180°K. A slope of $-3.15 \cdot 10^{-8}$ per °K (i.e. $-3.15 \cdot 10^{-6}$% per °K) from the medium line in Figure 19 is used to extrapolate the transfer coefficients of other metals.

[36] This procedure is certainly daunting, to put it mildly. It is included in the assessment in order not to ignore any potentially important emissions. It will probably capture the order of magnitude of transfer coefficients correctly. However, the contribution to the total burden in the final result from the guessed elements is lower than 0.006% and hence not of noticeable relevance.

[37] The additional input to the Wälz kiln via that route is small compared to the input from the PECK zinc hydroxide product. I.e. total mass of input increases by 0.5%; the zinc input increases by 0.28%. Significant increases occur only for antimony, tin, selenium and mercury.

Slag is mainly generated from Si, Fe, Ca, Al, K, Mg, Na and O. Montanwerke Brixlegg sell the slag as sand blaster abrasive.

No water emissions from copper production are considered.

4.8.5 Secondary lead production

The secondary lead smelter produces lead from secondary sources. The PECK technology does not produce a *separate* lead product, but lead is recycled indirectly by way of the smelting of the zinc hydroxide product in a Waelz kiln. Lead-rich Waelz kiln dust is used as an input to the secondary lead smelter (cf. Figure 17).

As no PECK-specific composition of the Waelz kiln dust could be calculated, the emissions from the secondary lead smelter were assumed to be equal to the average emissions from the secondary lead smelter with an average lead scrap input. I.e. no elemental transfer coefficients were calculated for the secondary lead smelter. Information on secondary lead smelter burdens were combined from [ESU 1996b, IPCC 2000-b, CORINAIR 1999-3].

4.8.6 Overview of data sources concerning metal production

Metal	Data source for _primary_ metal production	Represented technology	Data source for _secondary_ metal production	Represented technology
Iron		Sinter, pelletizing and blast furnace plants to produce pig iron		Sinter, pelletizing and blast furnace plants to produce pig iron
	IPCC 2000-a	Average of current EU plants	IPCC 2000-a	Average of several current EU plants
	ESU 1996b	Average of 80ies plants	ESU 1996b	Average of 80ies plants
Zinc				Wälz furnace and hydroelectrical purification
	Corinair 1999-3	Typical average values for primary zinc processing (early 90ies publications)	BZF 2000	Detailed data from one existing plant, B.U.S. Freiberg, Germany
	FEI 1999	Data for one existing plant, Outokumpu Zinc, Finnland in 1997		
	ESU 1996b	Average of 80ies plants		
Copper	Corinair 1999-3	Typical average values for primary copper processing with extended emission control[38] (end 80/early 90ies publications)	Corinair 1999-3	Typical average values in EU for secondary copper processing (early 90ies publications)
	CSIRO 2000	Energy for primary copper processing (90ies publications)	IPCC 2000-b	Average of several current EU plants
	ESU 1996b	Average of 80ies plants		
Lead	IPCC 2000-b	Average of several current EU plants	Corinair 1999-3	Typical average values in EU for secondary lead processing
	Corinair 1999-3	Typical average values in EU for primary lead processing	ESU 1996b	Average of 80ies plants
	ESU 1996b	Average of 80ies plants		

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[38] Extended emission control includes flue gas treatment with electrostatic precipitator ESP, wet scrubber, and fabric filters with an efficiency of 99.9%.

5 Impact assessment methods (LCIA)

Inventory stage of LCA reveals material releases to and extractions from the environment. These material releases are in the form of kilogram per functional unit and bear no ecological significance as such. In a next step these material flows are grouped, weighted and valuated according to their environmental damage potential. As environmental damages are also called 'impacts', this step is also called Life Cycle Impact Assessment or LCIA. LCIA tells us how much damage can be caused by the assessed system.

The damages assessed in LCIA were historically focussed on toxic air pollutants like lead, or nitrogen and sulfur oxides. Other damaging emissions like greenhouse gases and ozone depleters were added. Today LCIA methods assess a multitude of air, water and soil pollutants, use of energetic and mineral resources, and land use. Damages are usually threefold: damages to human health, damages to non-human life (ecosystems) and damage to resources.

5.1 Subjectivity in valuation

Many LCIA methods have been and are still being developed. There is no consensus in the LCA community on which particular valuation method to use. There is consensus however, that the method should be based on natural sciences as far as a possible. Methods exist which model e.g. the fate of pollutants in the environment with painstaking detail to calculate realistic figures on pollutant fate, exposure and damages to human and non-human life. Also, it is obvious that a method that heeds many different substances is less prone to overlook important damages than a method with only a few key pollutants.

There is some disagreement on whether LCA results should be aggregated in to one single 'eco-damage' value. It is now generally accepted that such full-aggregation is impossible without value judgements. Such value judgements cannot be based on natural sciences alone but involve morals and ethics (e.g. on what constitutes an ecological damage). Fully-aggregated LCA results are therefore not 'objective', i.e. different value judgements might lead to different results (cf. Figure 20).
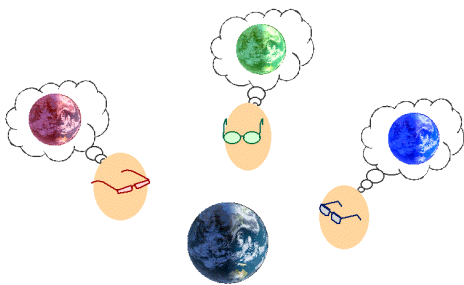

Figure 20   Differing perceptions and predispositions can lead to contrasting judgement between different people regarding the same issue.

An understandable solution here is that the stakeholders, i.e. the persons using the LCA to make an informed decision or a representative panel should apply their value judgement to aggregate the results. Stakeholders are often puzzled to come up with

detailed information about whether e.g. one person-day spent in a hospital while having an environmentally induced asthma attack is more, less or equally important as the destruction of 100 square-meters of rare swamp land. In this situation stakeholders often wish that LCA professionals come up with appropriate and well-informed value judgements. Accordingly, a lot of LCIA methods include valuation right away or provide default weighting sets.

While 'subjectivity' is debatable it is not 'arbitrary' or without structure. Social sciences can reveal structures in the value judgements of individuals, groups or even nations. 'Cultural theory' has established so-called 'cultural archetypes' that behave in a typical and consistent manner concerning value judgements [Thompson et al. 1990]. While any real-life individual is usually a mixture of these archetypes, they bring structure into the difficult topic of subjective value judgements.

LCIA methods like Eco-indicator'99 have integrated the differing viewpoints of three 'cultural archetypes' considered relevant in decision-making processes. Eco-indicator'99 provides a threefold set of weighing factors for the Individualist, the Hierarchist and the Egalitarian archetypical perspectives derived from their differing viewpoints on what constitutes an environmental damage. Comparing the three results can be used to establish *if* different archetypes would disagree over the result of an LCA study. If an LCA result is the same for all archetypes, it is less prone to be doubted. If an LCA result is not the same for all archetypes a discussion must ensue on which archetypal perspective is appropriate to the decision makers.

Cultural Archetypes – structure in the disagreement over ecological problems

The 'Hierarchist', the 'Individualist' and the 'Egalitarian' are so-called 'cultural archetypes'. These are model-persons that feature different biases and beliefs concerning value judgements, moral and ethical questions of individuals and societies. While any real-life individual is usually a mixture of these archetypes, they bring structure and consistency into the difficult topic of subjective value judgements. Different cultural archetypes were established in social sciences, based on surveys [Thompson et al. 1990]. Three archetypes that are important to decision-making were determined in [Hofstetter 1998]: the Hierarchist, the Egalitarian and the Individualist[39].

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[39] Two other archetypes (the 'Fatalist' and the 'Hermit') are believed to be non-deciding individuals either because of apathy or detachment from social matters.

Figure 21   The Individualist, the Egalitarian and the Hierarchist: three model personalities that exhibit archetypal perspectives regarding value judgements.

Important distinguishing features regarding environmental concerns are e.g. that the Individualist has a risk-seeking personality: He/she has a short-term perception of problems and belittles damages to future generations. Only damages that are actually observable are of concern to the Individualist and he/she focuses on the benefits of risky endeavours. The Individualist is an optimist, who thinks that technical problems to environmental solutions will allow us to continue and expand the present lifestyle in the future. On the other hand the Egalitarian has a risk-avoiding personality: He/she has a long-term perception of problems and judges damages to future generations at least as important as damages to the present generation. Apart from observable damages the Egalitarian also heeds suspected or uncertain environmental damages. The Egalitarian tends towards pessimism and thinks that continuation of the present lifestyle will lead to insurmountable problems in the future, which is the reason for him/her to urge changes now. The third archetype, the Hierarchist, generally takes an intermediary position between the Individualist and the Egalitarian: The Hierarchist believes in the systems established by society and tries to moderate or consolidate extreme positions and also believes in compromise. The Hierarchist's goal is to maintain the social system and in that he/she shows also traditionalist dispositions. Damages to future generations are equally important for the Hierarchist as damages to the present generation. He/she is risk-accepting and balances risks versus the benefits of risky endeavours. As a firm believer in the hierarchic, scientific system the Hierarchist heeds damages that are proven and scientifically established, but discounts damages of an uncertain or merely suspected nature.

5.2 Eco-indicator'99

Ecoindicator'99 is a damage-oriented LCIA weighting method. Eco-indicator'99 starts at the damages that occur when environmental impacts take place. The things we want to protect, when engaging in environmental protection are the 'safeguard subjects'. These safeguard subjects are damaged by environmental impacts.

The damages to the following safeguard subjects were defined in Ecoindicator'99:

- Damage to Human Health
- Damage to Ecosystem Quality

- Damage to Resources

In some LCIA methods a panel is asked to weigh ten or more subjects; this number is clearly too high. The subjects to be weighted should be easy to explain to a panel. In most LCIA methods the panel is asked to weigh rather abstract impact categories. It is very difficult to give a meaningful assessment.

Consequently, damage models were developed that group inventory results into three damage categories (cf. below). More information on the weighting applied in Eco-indicator'99 is given in chapter 5.1 'Subjectivity in valuation' on page 48.

A limiting assumption is that emissions and land uses with local or regional impacts and all subsequent damages are assumed to occur in Europe. Only damages to resources and damages created by climate change, ozone layer depletion, air emissions of persistent carcinogenic substances, inorganic air pollutants that have long-range dispersion, and some radioactive substances are assessed on a global scale [Goedkoop et al. 1999].

5.2.1 Damages to Human Health

Damages to Human Health are expressed as DALY (Disability Adjusted Life Years). Models have been developed for **respiratory and carcinogenic effects**, the effects of **climate change, ozone layer depletion** and **ionising radiation**. In these models for Human Health four sub steps are used:

1) Fate analysis, linking an emission (expressed as mass) to a temporary change in concentration.
2) Exposure analysis, linking this temporary concentration to a dose.
3) Effect analysis, linking the dose to a number of health effects, like the number and types of cancers.
4) Damage analysis, links health effects to DALYs, using estimates of the number of Years Lived Disabled (YLD) and Years of Life Lost (YLL).

5.2.2 Damages to Ecosystem Quality

Damages to Ecosystem Quality are expressed as the percentage of species that have disappeared in a certain area due to the environmental load. This definition is not as homogeneous as the definition of Human Health:

Ecotoxicity is expressed as the percentage of all species present in the environment living under toxic stress (PAF). As this is not an observable damage, a rather crude conversion factor is used to translate toxic stress into real observable damage.

Acidification and **eutrophication** are treated as a single impact category. Here the damage to target species (vascular plants) in natural areas is modelled.

Land-use and land transformation is based on empirical data of the occurrence of vascular plants as a function of the land-use type and the area size. Both the local damage on the occupied or transformed area as well as the regional damage on ecosystems is taken into account.

5.2.3 Damages to Resources

Resource extraction is related to a parameter that indicates the quality of the remaining **mineral and fossil resources**. In both cases the extraction of these resources will result in higher energy requirements for future extraction.

5.2.4 Weighting in Eco-indicator'99 across damage categories

Eco-indicator'99 has integrated the differing viewpoints of three 'cultural archetypes' considered relevant in decision-making processes. Eco-indicator'99 provides a threefold set of weighing factors for an Individualist, a Hierarchist and an Egalitarian perspective derived from their differing viewpoints on what constitutes an environmental damage. In Eco-indicator'99 there are also three different *default* weighting sets for each of the three archetypes that can be used to aggregate the three damage categories (Ecosystem damage, Human Health, Resources) into one single value. These *default* weighting sets were derived from a Swiss panel of LCA experts. Instead of applying one fixed weighing set, there is also the possibility to compare the results in a graphical method comprising *all possible* weighting sets using a mixing triangle chart. This type of chart is featured in chapter 6.3.1 'Discussion of trade-offs toxicity vs. energy' on page 61. More background information on the weighting applied in Eco-indicator'99 can be found in chapter 5.1 'Subjectivity in valuation' on page 48.

5.3 The CML'01 method

The CML'01 method was developed by the Centre of Environmental Science[40] in the University of Leiden, Netherlands [Guinée et al. 2001]. It is an extensive update of an older approach – CML'92 – to characterise many different environmental impacts.

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[40] 'CML' is in Dutch ' Centruum voor Milieukunde Leiden'.

Environmental Damage category	Characterisation value categories in CML'01
Global warming / Climate change	Global warming potentials GWP for various time horizons
Stratospheric ozone depletion	Ozone layer depletion potentials ODP for various time horizons
Toxic releases damaging humans	Human toxicity potentials HTP for various time horizons
Toxic releases damaging fauna living in freshwater	Freshwater aquatic ecotoxicity potentials FAETP for various time horizons
Toxic releases damaging fauna living marine water	Marine aquatic ecotoxicity potentials MAETP for various time horizons
Toxic releases damaging fauna living freshwater sediments	Freshwater sedimental ecotoxicity potentials FSETP for various time horizons
Toxic releases damaging fauna living marine water sediments	Marine sedimental ecotoxicity potentials MSETP for various time horizons
Toxic releases damaging fauna living in/on soils	Terrestrial ecotoxicity potentials TETP for various time horizons
Ozone creation in the troposphere by hydrocarbons VOC, carbon monoxide and NO_x ('Summersmog')	Photochemical Oxidation Potentials POCP Maximum Incremental Reactivity MIR Maximum Ozone Incremental Reactivity MOIR Equal Benefit Incremental Reactivity EBIR
Acidifying releases ('Acid rain')	Acidification potentials AP
Excess fertilising of freshwater bodies leading to oxygen depletion	Eutrophication potentials EP
Radioactive releases damaging humans	Ionising radiation damage potentials
Air releases with odours detectable by humans	Malodorous air potentials (1/odour threshold values)
Depletion of limited primary mineral and energy resources	abiotic depletion potential ADP
Occupation of land by man	land use competition LUC

Table 20   Environmental damage categories in CML'01

Until recently, fate and exposure modelling was only partially or not included at all in LCIA factors for toxic releases. For CML'01 a model for including fate (i.e. the transport, distribution and immission) and exposure (uptake of toxics in humans and fauna) in its characterisation factors has been developed: the global, nested multi-media fate, exposure and effects model USES-LCA. USES-LCA is based on the Uniform System for the Evaluation of Substances 2.0 (USES 2.0) by RIVM, cf. Figure 22. USES 2.0 is a variant of EUSES, a European Union decision-supporting instrument which enables public authorities, research institutes and chemical companies to assess rapidly and efficiently the risks attached to new and existing substances. USES-LCA was used to calculate ecotoxicity and human toxicity potentials for 181 different substance releases to air, freshwater, marine water, agricultural soil or industrial soil.
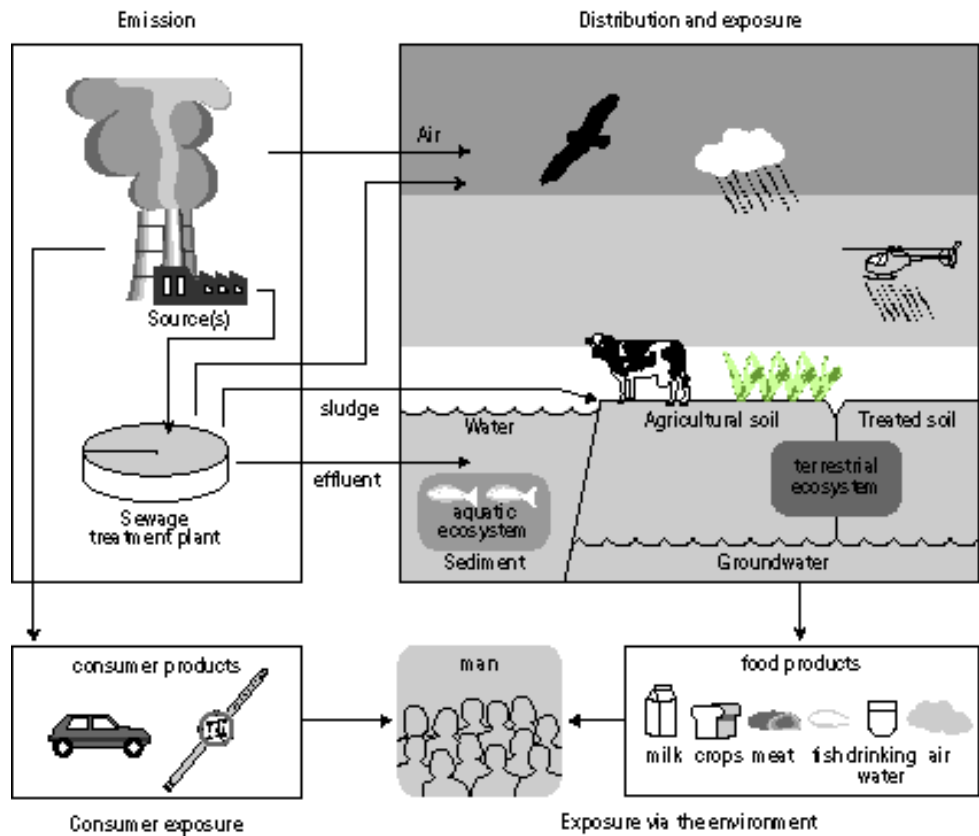
Figure 22   Modelling pathways in the USES software for toxic releases.

5.3.1 Weighting in CML'01 across damage categories

There are no suggested default weighting factors in CML'01 to aggregate the various damages into one single 'eco-value'. Weighting factors could be achieved, however, from a panel or ad hoc. For the present study, no weighting was performed.

5.4 Critical-Surface-Time '95

Olivier Jolliet and Pierre Crettaz of EPF Lausanne suggest a method for the characterisation of humantoxicological and ecotoxicological effects within the Critical Surface-Time 95 or CST'95 valuation method (Jolliet et al. 1997). The toxicity potentials in this approach are based on the assumption that two emissions are equivalent if they generate their respective no effect concentration (NEC) during one year in the entire ecosystem considered. The effect is assumed to be linear both with concentration and polluted volume. Toxicological damages to humans, to aquatic and terrestrial ecosystems are heeded.

The toxicological damage classes are completed by other damage classes like global warming, ozone depletion, land use and resources. Even if global warming and land use ultimately affect human health and ecosystem health, the relationship is indirect. Therefore, these damages were grouped into a separate class. The damage effects heeded in CST'95 are listed in Table 21.

Class of Effect	Environmental Effect	Class of Effect	Environmental Effect
A. Human Health	**Human toxicity** **Photochemical oxidant formation**	C. Aquatic Ecosystem	**Aquatic ecotoxicity** **Eutrophication**
B. Terrestrial Ecosystem	**Photochemical oxidant formation** **Terrestrial ecotoxicity** **Acidification**	D. Indirect effects	**Global warming** **Ozone depletion** **Land use** **Energy & non-energy resources**

Table 21   Damage effects heeded in CST'95 (Jolliet et al. 1997).

For every effect the damages are expressed in an equivalent polluted or used area (m^2) during one year (a), thus the name "critical surface-time" with the damage units in squaremeter-years (m^2a). The resource use is expressed in the energy required to convert metals at an average earth concentration into ore grade[41]. All energy consumptions are converted to wood energy equivalents and the area necessary to grow this wood is calculated.

In CST'95 the damages are expressed in damage units defined by a reference damage. The reference damage equals the pollution of the whole planet surface during one year with a certain damage. E.g. for emissions the acceptable damage is defined by a pollution concentration level which is equal to the No Effect Concentration NEC. For global warming and ozone depletion a distance-to target approach is used to calculate a reference damage: it is assumed that reductions in the total global present emissions of greenhouse gases and ozone depleters by a factor of 2.5 and 10 lead to acceptable damage levels. For land use, the reference damage corresponds to the agricultural use of the total land area available for one year, that is one third of the whole earth area. For energy use the reference damage corresponds to the generation of fuel wood on the total land area available for one year.

5.4.1 Weighting in CST'95 across damage categories

(Jolliet et al. 1997) give no default set to weigh the different effects – expressed in surface-time units – into one single score. Nor any panel survey was conducted in the present study to set weights for the different effects. For the present study weights are therefore set *ad hoc* by the author, based on a discussion of the reference damages for different effects (cf. below). This weighting set should be regarded as preliminary.

The reference damages for human toxicity, aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidant formation, acidification, eutrophication, global warming, and ozone depletion were all based on *no-effect* or *acceptable* damages, i.e. the reference damage is determined as the level of pollution causing a no-effect or acceptable damage. Therefore, it is reasonable to set equal weights for all these effects as a first guess. This weight is set to 1 (expressing a global NEC concentration for one year).

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[41] However presently only iron ores and bauxite ores (aluminium) are modelled in this damage category.

For the remaining two effects – land use and resource use – the reference damages are far from any acceptable level. For land use the reference damage would result in the *complete* – and hypothetical – conversion of all land area to agricultural areas. Energy and resources are converted into surface-time units by way of biomass fuel production from forest areas. For resource use the reference damage would result in the *complete* – and again hypothetical – conversion of all land area to forest areas.

According to [WRI 1999, p. 298] the crop and pasture land occupied 37% of all land area and 11% of the global surface in 1994. It is reasonable to believe that this anthropogenic land occupation already represents a non-negligible threat to ecosystems. However, it is difficult to define ad hoc a no-effect or acceptable agricultural area. It is assumed here that the occupation in 1994 of 11% of the global surface is close enough to the acceptable occupation to be used as first guess. This is a conservative estimate as the value is likely to be lower, and the resulting weighting factor higher. The reference damage from the land use effects assumes that *all* land areas or 30% of the global surface are converted to agriculture areas. The weighting factor for the land use reference damage compared to the acceptable (current) occupation damage is therefore 30%/11% = 2.7.

Forest and woodland areas covered 32% of all land area and 8% of the global surface in [WIR 1999, p. 298]. However not all forest areas are used for biomass fuel production. Again it is assumed that the present share of forest area devoted to fuel production is close to the acceptable fuel wood forest area.

Annual wood production is around 3500 million m^3/a [ESU 1996b, p.IX.8]. Wood uses are 47.8% fuel wood, 29.1% timber, 12.5% fiber wood and 3.7% char coal. Only fuel wood and char coal, 51.6% of the annual wood production or 1'786 million m^3/a, are used for energy purposes. The rest fulfills other primary needs and is not available for energy production.

Using a lower heating value of 12 MJ/kg and a wood density of 600 kg/m^3, the 1'786 million m^3/a of energy wood represent 1.29·1013 MJ/a of energy. Using the area occupation necessary to produce energy – 0.216 m^2a/MJ, the value used by (Jolliet et al. 1997) – the area devoted to produce this energy is 2.78·10^{12} m^2, or 0.544% of the total global surface. The reference damage for resource use assumes that *all* land areas or 30% of the global surface are used as biomass fuel land. Therefore the weighting factor for the energetic and mineral resources use score is 30%/0.544% = 55.1.

The weighting factors for the different effects are summarised in Table 22.

Effect	Reference annual damage	Weighting factor
Human toxicity	Pb NEC over the earth for one year	1
Humantoxicological oxidant formation	O_3 NEC over the earth for one year	1
Ecotoxicological oxidant formation	O_3 NEC over the earth for one year	1
Terrestrial ecotoxicity	Zn NEC in the whole soil area for one year	1
Acidification	Critical load deposed over whole earth for one year	1
Aquatic ecotoxicity	Zn NEC in the whole freshwater for one year	1
Eutrophication	P"NEC" in the whole freshwater for one year	1
Global warming	Present emissions divided by 2.5	1
Ozone depletion	Present emissions divided by 10	1
Land use	Total land available occupied for agriculture	2.727
Energy & resources	Total land available occupied for fuel wood production	55.10

Table 22   Ad hoc and preliminary weighting factors for the full aggregation of damage effects in CST'95 used in this study.

6 Results

6.1 What is shown in the result diagrams?

The results from the *relative comparison of PECK vs. MSWI* are shown for several environmental damage categories using three different LCIA methods:

- The left group shows the scores for Eco-indicator'99 (cf. chapter 5.2 on page 50)

- The groups in the middle show scores for some of the categories from the CML'01 method (cf. chapter 5.3 on page 52)

- The single column on the right is the aggregated score for Critcal-Surface-Time'95 (cf. chapter 5.4 on page 54)

The horizontal line at 100% represents the score of the MSWI; the columns representing the score of PECK is drawn in relation to that 100% line (i.e. PECK score divided by MSWI score). So the displayed damage score is always a *relative* score. Both scores always relate to the defined functional unit, which is the cluster of services defined in chapter 2.2 on page 4.

LCIA method	Label in diagram	Damage category
Eco-indicator'99 categories	EI'99 Recs., Egal.	EI'99 Resources Surplus Energy, Egalitarian
	EI'99 Recs., Hier.	EI'99 Resources Surplus Energy, Hierarchist
	EI'99 Recs., Indiv.	EI'99 Resources Surplus Energy, Individualist
	EI'99 HumH, Egal.	EI'99 Human Health, Egalitarian
	EI'99 HumH, Hier.	EI'99 Human Health, Hierarchist
	EI'99 HumH, Indiv.	EI'99 Human Health, Individualist
	EI'99 EcoH, Egal.	EI'99 Ecosystem Health, Egalitarian
	EI'99 EcoH, Hier.	EI'99 Ecosystem Health, Hierarchist
	EI'99 EcoH, Indiv.	EI'99 Ecosystem Health, Individualist
	EI'99 Egal., default sum	EI'99 Egalitarian, aggregated score weighted by default
	EI'99 Hier., default sum	EI'99 Hierarchist, aggregated score weighted by default
	EI'99 Indiv., default sum	EI'99 Individualist, aggregated score weighted by default
CML'01 categories (Guinee et al. 2001)	Abiotic Depletion Guinee	Abiotic Depletion Potential
	Global Warming GWP 500a	Global Warming Potential, 500 years timescale
	Ozone Depl. ODP steady state	Ozone Depletion Potential steady state
	Human Tox HTP inf.	Human Toxicity Potential, infinite timescale
	Freshwater Aqu.Tox. FAETP inf.	Freshwater Aquatic Ecotoxicity Potential, infinite timescale
	Marine Aqu.Tox. MAETP inf.	Marine Aquatic Ecotoxicity Potential, infinite timescale)
	Freshwater Sedim.Tox. FSETP inf.	Freshwater Sedimentary Ecotoxicity Potential, infinite timescale
	Marine Sedim.Tox. MSETP inf.	Marine Sedimentary Ecotoxicity Potential, infinite timescale)
	Terrest. Ecotox. TETP inf.	Terrest. Ecotoxicity Potential, infinite timescale)
	Human Tox HTP 20a	Human Toxicity Potential, 20 years timescale
	Freshwater Aqu.Tox. FAETP 20a	Freshwater Aquatic Ecotoxicity Potential, 20 years timescale
	Marine Aqu.Tox. MAETP 20a	Marine Aquatic Toxicity Ecotoxicity, 20 years timescale
	Freshwater Sedim.Tox. FSETP 20a	Freshwater Sedimentary Ecotoxicity Potential, 20 years timescale)
	Marine Sedim.Tox. MSETP 20a	Marine Sedimentary Ecotoxicity Potential, 20 years timescale
	Terrest. Ecotox. TETP 20a	Terrest. Ecotoxicity Potential, 20 years timescale
	Summersmog POCP high NOX	Photochemical Oxidant Creation Potential, high-NOx (Jenkin & Hayman, 1999; Derwent et al. 1998; high Nox)
	Acidification Potential (media-blind)	Acidification Potential (Hauschild & Wenzel (1998).
	Eutrophication Potential (4 air poll.)	Eutrophication Potential (Huijbregts, 1999; average Europe total, A&B)
Critical-Surface-Time'95	CST'95 tot.	Critical-Surface-Time'95, aggregated score

Table 23   Damage categories displayed in the result diagrams.

The contributions to the total score are displayed within the composite columns. These contributions are:

- **Heat energy complements**
- **Electric energy complements**
- **Mineral complement**
- **Copper processes** (recycling process of PECK secondary metal + complement)
- **Zinc processes** (recycling process of PECK secondary metal + complement)
- **Lead processes** (recycling process of PECK secondary metal + complement)
- **Iron processes** (recycling process of PECK secondary metal + complement)
- **Subsurface deposit**
- Rest: **PECK Incinerator processes** (mainly air emissions, auxiliary materials, waste collection) & **landfill processes** (mainly leachate emissions) & sewage sludge MWWTS complement.

> ### *Reminder*
> *During result discussion, it should be kept in mind that LCAs usually feature large uncertainties, which are usually not quantified due to lack of data. Hence, small* relative *differences in results in the order of <10% must be seen as insignificant. LCAs help to understand major environmental characteristics of systems, but they are not precision tools.*

6.2 Case Lab vs. Case Max

Two base scenarios were assessed: 'Case Lab', based on encountered performance and 'Case Max', which includes improvements anticipated by ARGE PECK.

Features	PECK Case Lab	Consequence	PECK Case Max	Consequence
Output products	Output product composition is determined by transfer coefficients derived from measurements		The transfer coefficients are augmented according to ARGE PECKS expectations	Output products show higher contents of the desired metals
Flue gas	Nitrogen oxide emissions are assumed to be the same as in a modern MSWI		Nitrogen oxide emissions are expected to be halved by staging of combustion air	Only 50% NOx air emissions and reduced DeNOx expenditures

6.3 Results for Case Lab

In the following diagram the results for the Case Lab are shown. The assessed performance is based on laboratory measurements and component trial runs. It assumes a non-hydraulic mineral product, which is recyclable e.g. as cement filler, gas

furnaces as heat energy complements, European grid power as electric energy complements, and 2% of Cr-VI in the PECK air emissions.
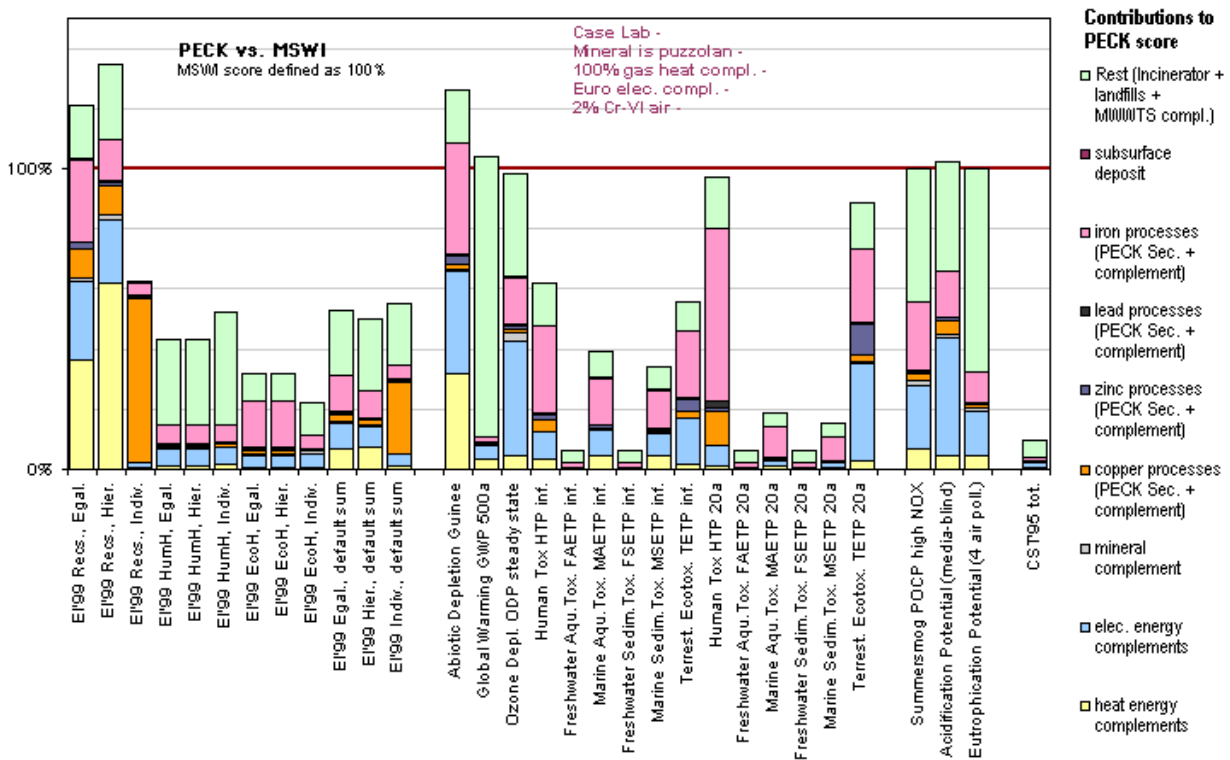

Figure 23   Results of the comparison of PECK vs. MSWI for the Case Lab

The CML'01 toxicity potentials by Huijbregts are all below 100%, i.e. PECK scores better than MSWI regarding toxicity. This is the direct result of PECK's aim to deplete metals from slags and ashes and convert them to metal recyclates. Also the Human Health and Ecosystem Health categories of Eco-indicator'99 show that effect.

The aim of PECK is to preserve mineral and metal resources. However, looking at the categories expressing damage to resources (EI'99 Resources Surplus Energy, CML'01 Abiotic Depletion Potential) one sees that these are exactly the categories in which PECK scores *inferior* to the MSWI. What has happened? PECK indeed *does* preserve mineral and metal resources, but the *energy demand* is somewhat higher for the PECK technology than for the MSWI. Most of the damage categories for resource use happen to weigh energy resources *higher* than mineral and metal resources[42].

So what is more important: avoiding toxic emissions or preservation of energy resources? What is the trade-off or the net effect?

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[42] The exception is the EI'99 Resources Surplus Energy of the individualist who perceives the damage to energy resources as being rather unimportant compared to metal resources: The individualist resources score is dominated by copper ore extractions. And indeed, in this category PECK scores better than the MSWI.

6.3.1 Discussion of trade-offs toxicity vs. energy

Comparative weighting and valuation of toxic emissions versus damage to resources is needed to answer the above question of trade-off. The subject of valuation was introduced above (cf. chapter 5.1 'Subjectivity in valuation' on page 48).

Eco-indicator'99 is an LCIA method that allows full aggregation of all the three main damage classes ecosystem health, human health and resources into one single 'Eco-damage' value. This carries the problem of relative weighting of emissions vs. resources. Eco-indicator'99 also provides a *default* weighting set to weigh the three damages classes[43]. These results are shown in the charts as the category *'...default sum'*. However, [Mettier 2000] finds that the expert panel that assigned the weights had a tendency to treat all damages equally and to distribute weights even-handedly. This resulted in exaggerated weights given to resource damages[44]. I.e. if the Eco-indicator'99 scores are weighted *by default*, they tend to *overestimate* damages to resources. *Nevertheless*, even the default sum displayed in the Figure 23 is in clear favour of PECK. So it is reasonable to conclude that PECK's advantage in reduced toxic emissions compensates by far the drawback of a slightly increased energy demand.

6.3.1.1 Displaying trade-offs in a mixing triangle chart

The 'mixing triangle' is a method to display the trade-offs that result from different weightings of the three damage classes in Eco-indicator'99 results. The mixing triangle can be used to graphically depict the outcome of product comparisons for *all possible weighting sets*. Each point within the triangle represents a combination of three weights (triplet) that add up to 100%, cf. Figure 24.

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[43] The default weighting sets for Ecosystem Quality, Human Health and Resources are 40%, 40%, 20% for the Hierarchist, 25%, 55%, 20% for the Individualist, and 50%, 30%, 20% for the Egalitarian.

[44] This is an effect of surveys that is often encountered: When confronted with a list of 'problems' that should be rated, most people hesitate to attribute small or zero weights to certain problems. Everything seems to be important on some scale of experience.
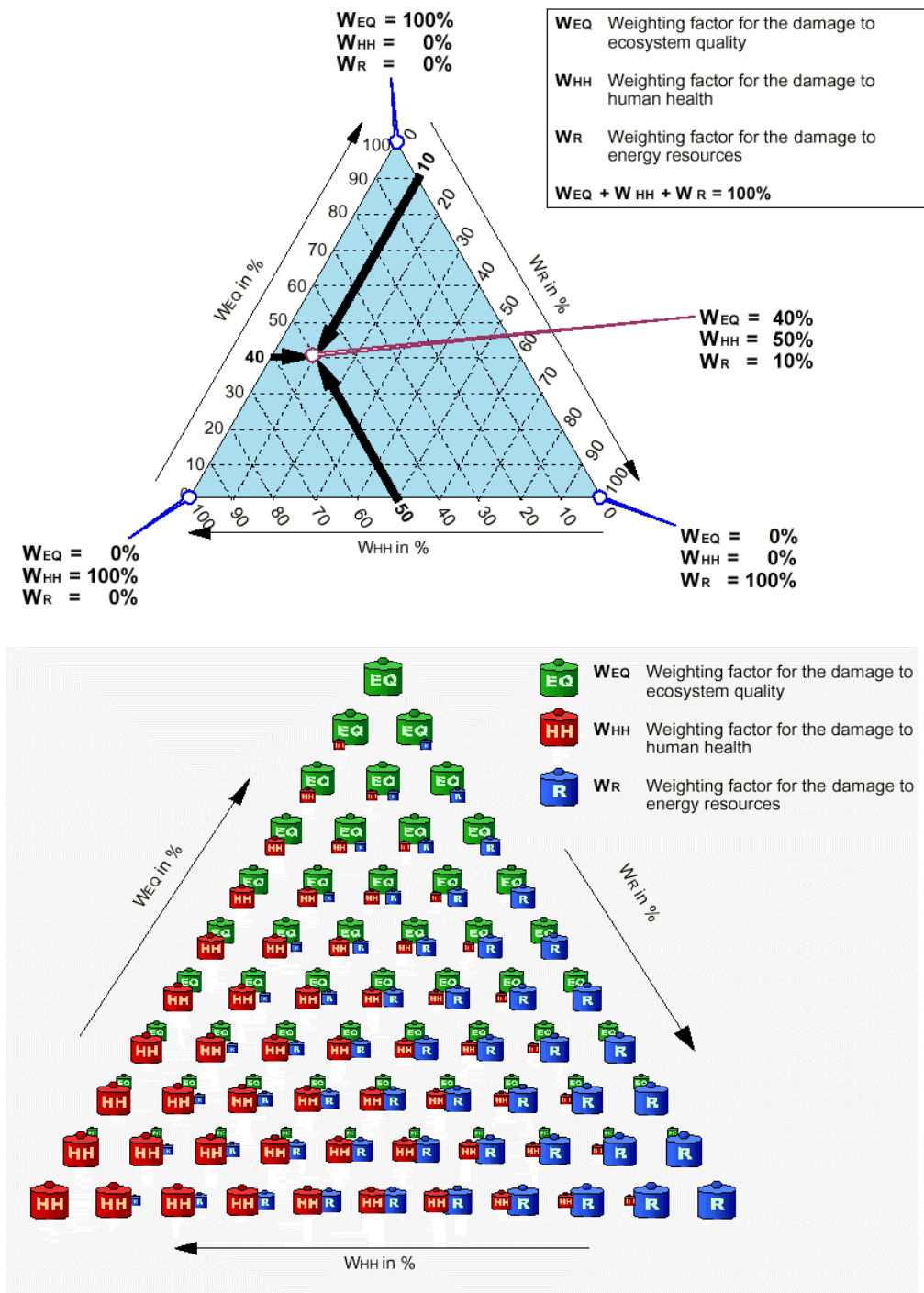
Figure 24   *How to read weighting triplets from mixing triangles.*

A mixing triangle showing the trade-off between PECK and MSWI for all possible weightings of the three damage categories from EI'99 results for the cultural archetype 'Hierarchist' is shown in Figure 25. The picture for the cultural archetype 'Egalitarian' is similar. In the Individualist's perspective PECK scores better in *all* of the three damage

categories. So for the Individualist there is no trade-off problem[45] and *any* weighting would result in the superiority of PECK over MSWI.
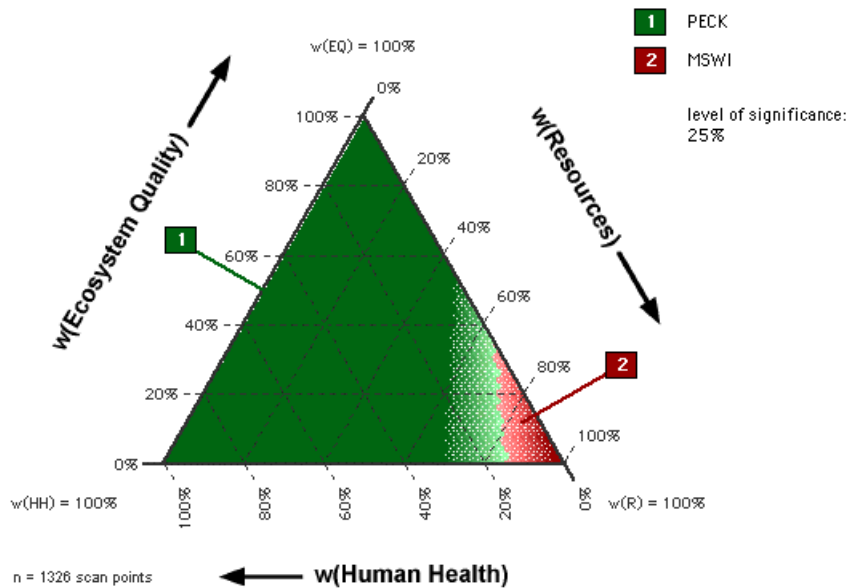
Figure 25 *Mixing triangle[46] for the two options PECK (1) and MSWI (2) for the cultural archetype 'Hierarchist'. Cf. text.*

The mixing triangle indicates the option that produces less environmental burden for every possible weighing triplet. For the larger part of the mixing triangle in Figure 25 the option 1 (PECK, green) scores better than the potion 2 (MSWI, red). The MSWI is only better than PECK for extremely high weights on (energy) resource damages (bottom right corner).

There is a straight line from the weighting point (30%, 0%, 70%) to the point (0%, 15%, 85%)[47]. Along this line *both* options, PECK as well as MSWI, *score the same*. This line is called 'line of indifference'. The hatched, faded-to-white area in the vicinity of the 'line of indifference' shows weighting sets that would lead to an advantage of the better option of *less than 25%*. Due to the large uncertainties involved in LCA calculations a difference of 25% is not very significant. The hatched area therefore shows weighting sets for which the LCA result is not very clear in favour of one of the options.

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[45] The individualist 'solved' that problem by having a weak perception of energy-resource related problems. So the disadvantage of PECK – the slightly increased energy demand – is not an important problem to him.

[46] The chart is generated with the MIXTRI tool by the author, available at http://www.unite.ch/doka/EI99/mixtri.htm.

[47] All weighing triplets are given in the order 'Weighting factor for Ecosystem Damage', 'Weighting factor for Human Health', 'Weighting factor for Resources': (w_{EQ}, w_{HH}, w_R).
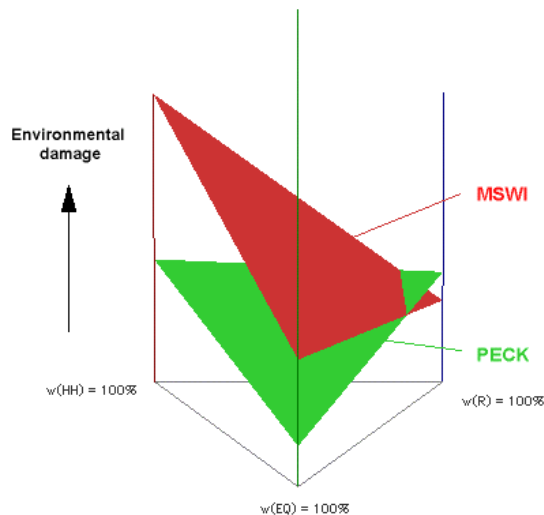
Figure 26   *3D-view of the mixing triangle for the two options PECK and MSWI (= KVA) for the cultural archetype 'Hierarchist'. Cf. text.*

A 3D-view of the same trade-off in the perception of the Hierarchist is shown in Figure 26. A z-axis in upward direction is added perpendicular to the mixing triangle plane (triangle outline at bottom). Along the z-Axis the weighted and aggregated environmental damages are drawn.

Since the weighting triangle makes *linear* mixtures of the three damage scores (Ecosystem damage, Human Health, Resources) the resulting scores are defined by a *flat*, but slanted triangle hovering in 3D-space above the mixing triangle plane. The green triangle represents the PECK option; the red triangle represents the MSWI option. The intersection of these two triangles is a straight line, which is the location where both options score the same, i.e. this line is the 'line of indifference' also observed in Figure 25.

The vertical, blue line on the right represents the result if *all weight (100%)* is given to resources alone. In that case, the results for the other damages (to human and ecosystem health) receive *no attention at all*. Only in the vicinity of this *extreme* case is the MSWI *slightly* better than PECK (i.e. the plane of PECK's green triangle is above MSWI's red triangle). However, as mentioned above, this extreme weighting is barely justifiable.

6.3.1.2   Trade-off in Critical-surface-time'95

Critical-surface-time'95 categories can also be fully aggregated and the sum result is displayed in Figure 23. CST'95 contains a valuation of metals toxicity and of energy resources, but based on heating value. Also CST'95 concludes that PECK is favourable over MSWI.

6.3.1.3   Conclusion

It can be concluded that the advantage of the PECK option of reducing toxicity of residues by recycling compared to the MSWI option outweighs by far the disadvantage of using more energy than the MSWI option.

6.4 Results for Case Max

The results for the Case Max are largely similar to in the Case Lab. Toxicity potentials are further reduced mainly by increased recycling rates of copper, zinc and cadmium. Eutrophication and Acidification are reduced due to reductions in NO_x air emissions from staged incineration. Energy demand was not altered in this case and remains above the MSWI option.
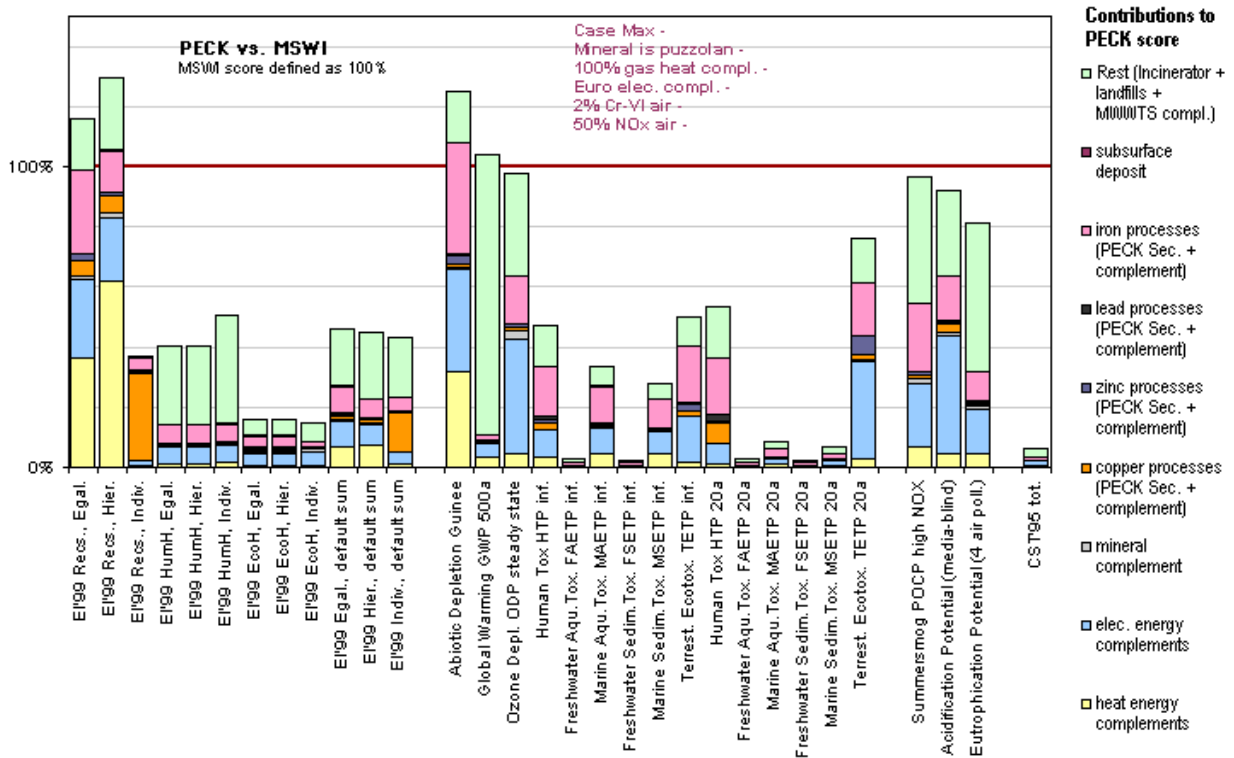

Figure 27   Results of the comparison of PECK vs. MSWI for the Case Max

The CST'95 score is smaller in the Case Max compared to the Case Lab. The reason for this is the increased transferral of cadmium to the zinc product instead of incineration residues, which have to be landfilled and emit metals by leaching. The lion share of the CST'95 score in Case Lab consists of Cadmium leachate emissions.

From the small differences in the comparison of Case Lab vs. Case Max it can be concluded, that the estimated and observed PECK performance (i.e. Case Lab) is already quite close to the expected PECK performance (i.e. Case Max). Further strategies for optimisation are discussed in chapter 6.5.4 'Are PECK recyclates better than average industrial sources?' on page 68.

6.5 Additional information

6.5.1 Landfilled or deposited masses

If the mineral product from PECK is recyclable (either as cement filler or residue landfill stabiliser 'Reststoffdeponieverfestigung') only very small masses are actually landfilled as waste from the PECK technology. The following numbers are all from the functional unit of one kilogram MSW incinerated and the Case Lab:

- Approximately 23 g sludge from the wet scrubber are landfilled in residue landfills.
- Approximately 0.7 g hazardous waste from the mercury trap are deposited in subsurface deposits

The recycling of the mineral product (approximately 180 g) is challenged by a composition that varies considerably, and by metal contents (esp. copper and zinc) unsuitable for either building materials or inert landfills.

In the iron blast furnace approx. 25 grams of slag are produced, which are used as a co-product in road construction. Approximately 0.3 g of hazardous dust from the blast furnace need to be deposited in subsurface deposits.

In the zinc furnace approximately 1 gram of slag is produced which is either used in road construction or needs to be landfilled.

6.5.2 Energy demands

A PECK incinerator needs more energy than a conventional MSWI. Still, per kg incinerated MSW PECK produces 1.7 MJ_{el} and 3.8 MJ_{th} or roughly 9 MJ of primary energy worth. The MSWI produces 1.8 MJ_{el} and 4.2 MJ_{th}, roughly 9.6 MJ of primary energy worth. No difference in energy demand was assumed between Case Lab and Case Max.

The energy demand of the Fluapur process is considerable. Especially the heat demand for distillation of the excess hydrochloric acid from the waste gas treatment system is considerable; it doubles the heat demand of incineration.

It might be interesting to note, that the recycling processes for the metals produced by PECK consume about 0.013 MJ_{el} and 3 MJ_{th} or roughly 3 MJ of primary energy worth, i.e. about a third of the energy production of PECK. This energy demand is heeded in the assessment as a burden of recycling, and not as a reduction of the net energy production of the PECK facility.

6.5.3 Zinc hydroxide product

The zinc product from PECK is expected to be processed by Wälz kilns, e.g. by the Berzelius Freiberg zinc recycling plant. The Freiberg plant only accepts materials meeting certain criteria [BZF 2000]. The materials should contain at least 5% zinc. Other constituents need to be below certain thresholds, reproduced in Table 24. The extrapolated zinc hydroxide product of PECK meets all those criteria in both cases 'Lab' and 'Max'. The most critical parameter is the tin concentration which is just below the threshold of 1%.

Constituent	Acceptance criteria of Berzelius Freiberg zinc recycling		Composition of PECK zinc product Case Lab	Factor below threshold	Composition of PECK zinc product Case Max	Factor below threshold
	w-%		w-%	-	w-%	-
Zinc	minimal	5%	36.6%	7.3	41.9%	8.4
Sulfur	maximal	5%	-		-	
Chlorine	maximal	7%	1.03%	6.8	0.99%	7.1
Fluor	maximal	5%	-		-	
Arsenic	maximal	0.10%	0.0079%	12.6	0.0076%	13.1
Cadmium	maximal	1%	0.469%	2.1	0.463%	2.2
Sum Ni, Co, Cr	maximal	3%	1.50%	2.0	1.45%	2.1
Mercury	maximal	0.002%	0.000061%	33.0	0.000058%	34.2
Tin	maximal	1%	0.909%	1.1	0.878%	1.1

Table 24   Acceptance criteria of the Berzelius Freiberg zinc recycling plant [BZF 2000] and compositions of the PECK zinc product.

Dioxins

Dioxins play only a small role in the total environmental burden. I.e. other pollutants must be regarded as more severe in terms of threats to human health or ecological integrity. This is however just a rough estimate of the overall potential from normal operation of the dioxin releasing plants. The major contribution to the total dioxin burden comes from the waste incineration process itself[48]. An emission factor of 3 nanograms TCDD equivalents per kg MWS was used.

During incineration or metal recycling, dioxins are formed from organic precursor components and chlorine in suitable temperature ranges. Copper is the most efficient metal to catalyse the formation of dioxins and furans[49] [UNEP 2001]. So increases in copper and chlorine in the recycled products need to be observed carefully.

The zinc product from PECK is expected to be processed by Wälz kilns. Wälz kilns are normally fed with EAF dust. EAF dust usually contains 0.5 – 2% chlorine and 0.1 – 0.3% copper. The zinc product from PECK (Case Lab) contains an expected 1% of chlorine and 6% copper. The chlorine concentrations in the zinc product are probably similar to the EAF dust and should not pose any problems.

But it is imaginable that the 20 – 60 times increased copper content in the zinc product will lead to higher dioxin emissions in the Wälz kiln, though this cannot be quantified here. However, the effect is bound to be small. B.U.S. Zinkrecycling Freiberg processed 60'000 tons of zinc bearing material per year in 1999. A 150'000 ton MSW/year incinerator will produce about 375 tons of zinc product. This would increase the *copper* input to the Freiberg Wälz kiln in the range of 12 to 37%.

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[48] For dioxin emisisons from PECK the average values from a modern MSWI were adopted, since no measurements were available.

[49] polychlorinated dibenzo-p-dioxins PCDD and polychlorinated dibenzofurans PCDF

The contribution from dioxin emissions from zinc smeltering to the total environmental burden is lower than 0.01% and – compared to other burdens in the service cluster – of unperceptible importance even with an increase of e.g. 50%.

6.5.4 Are PECK recyclates better than average industrial sources?

How can the PECK recyclates be characterised compared to average industrial sources of corresponding secondary or primary metals? The burdens per kilogram of metal expressed in Human Toxicity Potential damage scores are shown in Figure 28.
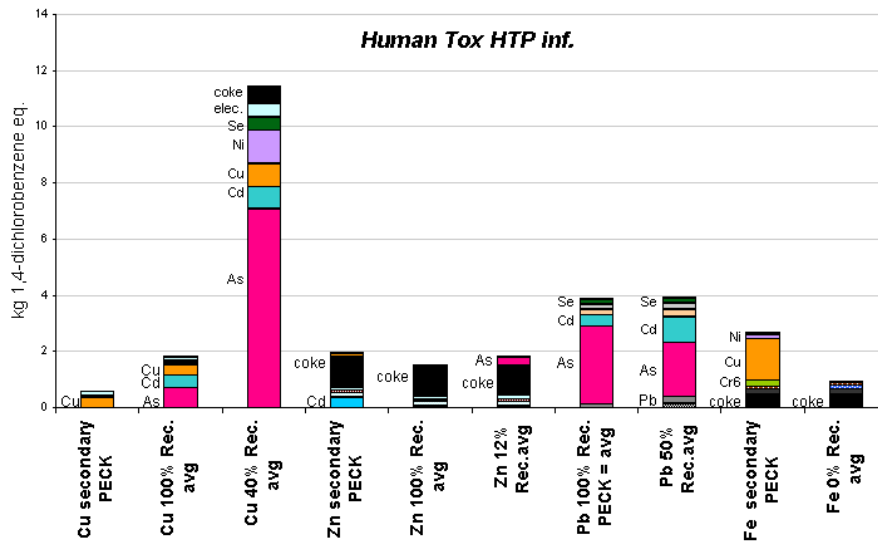
Figure 28   *Human Toxicity Potential damage scores for one kilogram of metal for copper, zinc, lead and iron from various sources: recyclate from PECK Case , average industrial recyclate and typical mixture of secondary and primary sources (average industrial). Element labels indicate contributions from air emisisons, 'coke' indicates burdens from furnace coke, 'elec' indicates burdens from electricity demand.*

Copper favourable: The copper product seems remarkably clean esp. from arsenic and cadmium. However the copper scrap composition was not measured directly, but was extrapolated from measurements of metal particles in the Küpat slag.

Iron poor, could be better: The iron scrap is contaminated with copper, nickel, chromium and zinc. Especially the copper contamination leads to higher burdens than iron from primary sources. The extrapolated levels of copper in iron scrap were confirmed by measurements of MSWI scrap [Zeltner 2001]. MSWI iron scrap is usually contaminated with copper and tin (Sn) and is diluted with cleaner scrap in Switzerland to be recyclable [Zeltner 2001]. It should be tried to transfer the copper and zinc traces to their target PECK outputs, i.e. the copper scrap and zinc product, which is the case in the Case Max.

Zinc somewhat poor, *can't* be better: The zinc product is quite burdened with cadmium and lead and, to a smaller extent, arsenic. However, the zinc product is the target product for cadmium and lead in the Fluapur process. This means that PECK

zinc product is a somewhat burdened recyclate, and not especially cleaner than primary zinc or even secondary zinc from EAF dust.

Lead: no information: no PECK-specific information on the lead composition could be generated. Figure 28 shows the scores of average industrial lead recyclate (used as approximation for PECK lead) and average industrial lead as a typical mixture of 50% secondary and 50% primary lead.

Mineral poor, could be better: The mineral product is contaminated and can't satisfy the composition threshold limits set for inert landfill materials regarding zinc and copper, c.f. Table 25. It should be tried to transfer both copper and zinc traces to their target PECK outputs, i.e. the copper scrap and zinc product.

	Mineral product PECK Case Lab mg/kg	*Current Swiss composition threshold value for inert landfills* mg/kg	
Cd	0.16	100	within limits
Cu	1'085.91	500	threshold exceeded by 117%
Ni		500	within limits
Pb	219.73	500	within limits
Zn	1'274.37	1000	threshold exceeded by 27%

Table 25   Comparison of the PECK mineral product composition (Case Lab) and the current Swiss threshold values for inert landfills for some metals. Copper and zinc thresholds are also exceeded in the Case Max.

6.6 Sensitivity analyses

Starting out from the base scenario 'Case Lab', various additional sensitivities can be calculated. A sensitivity analyses is a reliability test in which parameters of the assessment are modified and the effect on the result is observed.

The following table lists the base situation used in the 'Case Lab' assessment *on the left* and the changes for the sensitivity case *on the right*. The consequences of either choice is indicated. The sensitivity changes influence both technologies, MSWI and PECK.

All combinations of the sensitivities are possible[50].

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[50]   Though not all combinations are reasonable. E.g. it makes little sense to combine maxLT and omLT.

	Base Case	Consequence	Sensitivity Case	Consequence
Sensitivities on mineral material	Mineral product is recyclable, but has <u>no hydraulic properties</u>	The primary mineral material produced by the complement process is <u>inert sand</u>	**MHv** Mineral product is recyclable, and has <u>hydraulic properties</u>	The primary mineral material produced by the complement process is <u>hydraulic, burnt lime (CaO)</u>
	Mineral product is <u>recyclable</u>	Mineral product does not need to be landfilled	**MIL** Mineral product is not recyclable and is <u>landfilled</u>	Mineral product is landfilled on an inert landfill.
Sensitivities on complement energy sources	Complement heat energy is from gas furnace		**Oil** Complement heat energy is from oil furnace	Since oil energy is more burdening than gas energy a high heat energy demand of the incinerator technology is 'punished' more severely.
	Complement electric energy is from average European grid production		**eCH** Complement electric energy is from average Swiss national grid production	Since Swiss grid power is less burdening than European grid power a high electric energy demand of the incinerator technology is 'punished' less severely.
Sensitivities on landfill performance	Long-term leachate emissions are determined by generic <u>availability test</u>	<u>Only part</u> of the landfilled metals are emitted as leachate emissions	**maxLT** Long-term leachate emissions <u>set to maximum</u> (TK =100%)	<u>All</u> of the landfilled metals are emitted as long-term leachate emissions.
	Long-term leachate emissions are <u>included</u> in the assessment	Even <u>burdens in the far future</u> are included in the assessment	**omLT** Long-term leachate emissions are <u>omitted</u> from the assessment	Only <u>burdens in the first few decades</u> are included in the assessment.

6.6.1 Sensitivity on mineral material

It is currently unknown, if and how the PECK mineral material can be used. It makes sense to look at the performance of PECK, when different possibilities are achieved.

One unknown factor is, whether the mineral product has hydraulic properties or not. In the standard case it is assumed, that the mineral product has no hydraulic properties, i.e. is inert. But it is assumed that the mineral product can be recycled is some form and can compete with e.g. sand for building purposes. The MSWI, where no mineral product is produced, must be complemented with construction sand from conventional sources. This is the base case as displayed in Figure 23.

For the purposes of a sensitivity analysis it can be supposed that the mineral product has hydraulic properties. This influences the cluster of delivered services. It is assumed that in this case the mineral product can replace not inert sand but hydraulic burnt lime e.g. in cement production. The MSWI, where no mineral product is produced, must be complemented with burnt lime from conventional sources. The result of the comparison of PECK vs. MSWI in this sensitivity case MHy is displayed in Figure 29.

The mineral product might also have pozzolanic properties, i.e. contain amorphous, non-crystalline, reactive silica. The definition of pozzolans requires presence of reactive silica *and* a calcium content under 10 w–%. The PECK mineral product contains approx. 8 w–% calcium, so it might qualify as pozzolanic, *if* reactive silica were present. A sensitivity case with the mineral product having pozzolanic properties and the complement system consequently supplying a conventional pozzolanic material was, however, not considered here.
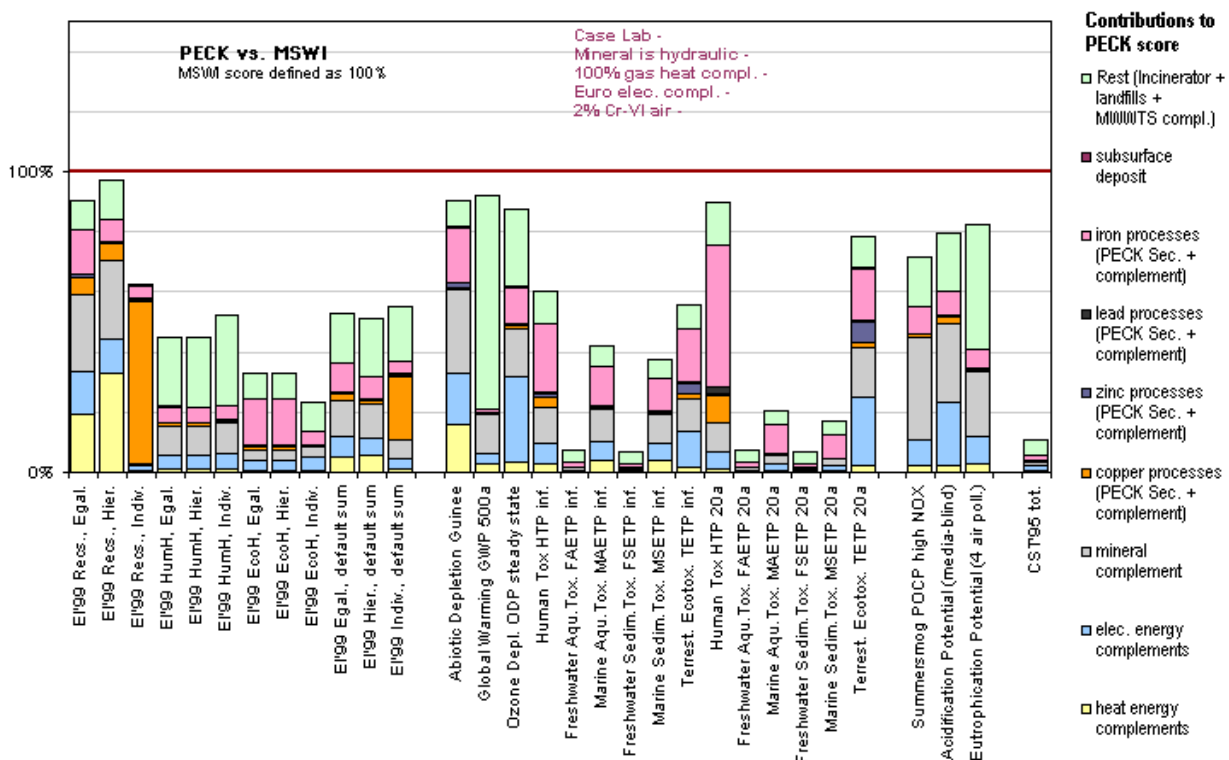
Figure 29   Sensitivity Case MHy with a hydraulic PECK mineral product. Results of the comparison of PECK vs. MSWI.

Assuming that the mineral product produced by the PECK process is hydraulic has two effects compared to the base case:

First, the MSWI option performs worse compared to PECK since it needs to be complemented with a more burdened product (i.e. burnt lime instead of sand). In this case PECK outranks the MSWI option in *all* of the displayed damage categories.

Second, the burdens from the mineral complement become more important. PECK produces in the Case Lab 161 grams of mineral product. The service cluster calls for an amount of 354 grams of mineral product. So the PECK option needs to be complemented with 192 grams of mineral product from an complementary source. In

the sensitivity case MHy this complemented material is burnt lime. The MSWI option needs to be complemented with the full amount of 354 grams of burnt lime. Since burnt lime is more burdensome per kilogram than sand, the contribution to the total damage score increases even in the PECK option as compared to the base case with sand as a complementary material.

Another uncertainty is whether the mineral product can be recycled at all. It might have unfavourable properties such as fluctuating composition or heavy metal contaminations prohibiting recycling. In the base case it is assumed that the mineral product can be recycled in some form. If the mineral product cannot be recycled it probably has to be disposed in a landfill as waste. ARGE PECK assumes that if the latter were the case, that the mineral product would be compliant with the demands of a future landfill for inorganic and largely inert materials. As with other landfills, the emissions from this speculative landfill are derived from the waste composition of the material and elemental transfer coefficients. The transfer coefficients used are *a tenth* of the elemental transfer coefficients of a conventional slag landfill. In this sensitivity case MIL, however, *all* mineral material for the cluster of services must be provided from a complementary source for either option PECK or MSWI. The complemetary material is inert sand (base case condition).
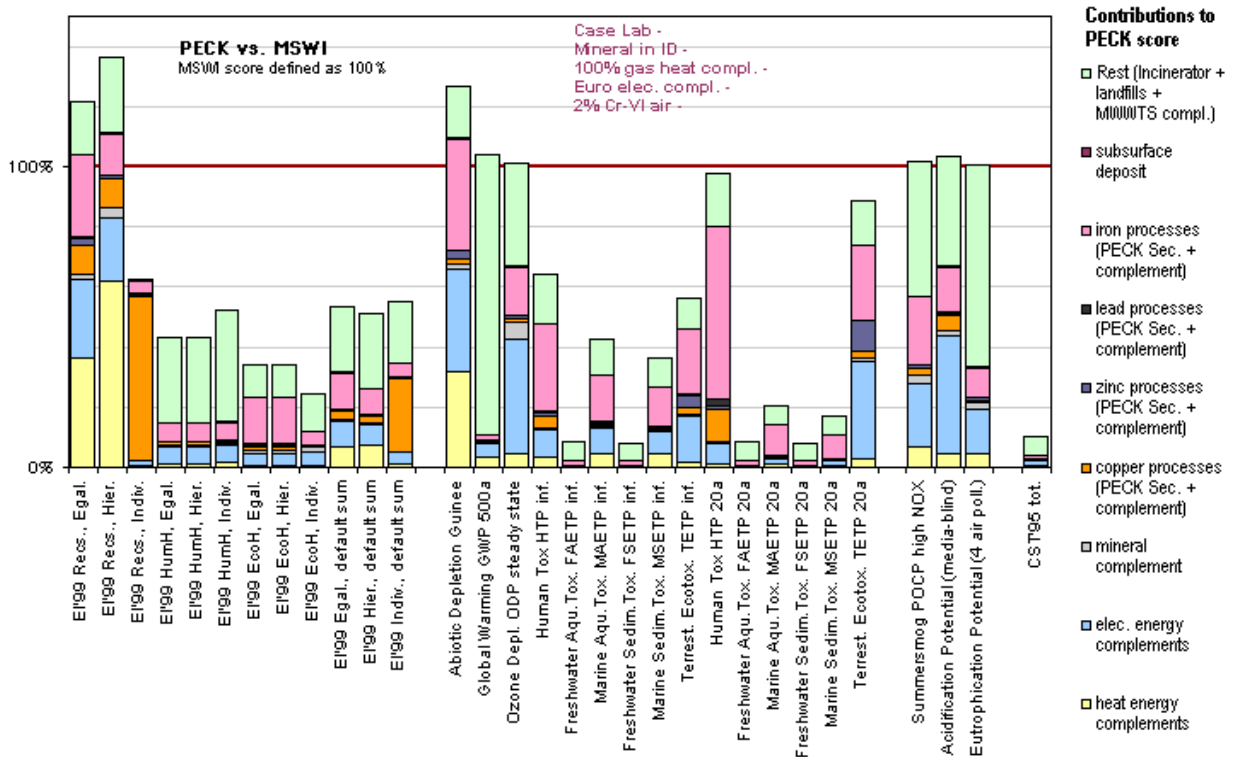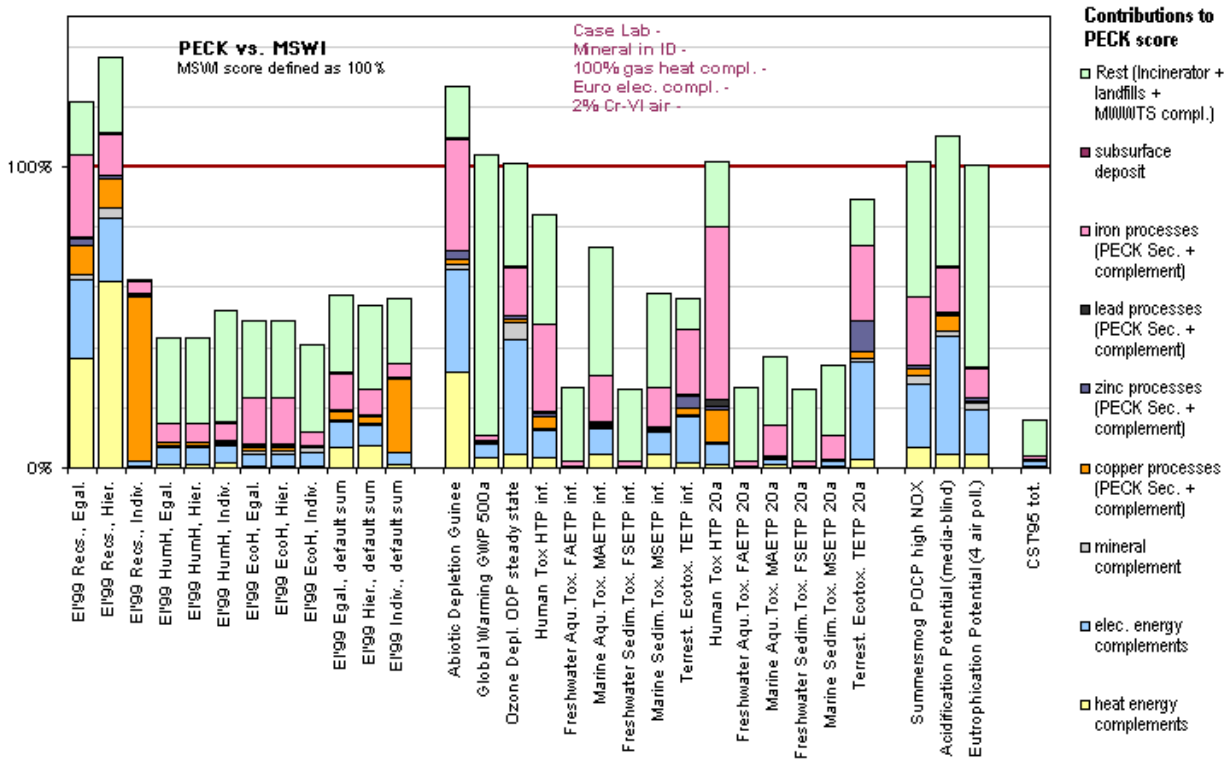

Figure 30   *Sensitivity Case MIL if the PECK mineral product has to be landfilled. The landfill transfer coefficients are set to 10% of those from a slag landfill. Results of the comparison of PECK vs. MSWI.*

The result for this sensitivity case MIL with landfilled mineral product is very similar to the base Case Lab in Figure 23. This is not surprising, as the mineral product complement is only a minor contribution to the total score in the Case Lab. This

contribution is roughly doubled in this sensitivity case MIL. On the other hand the assumed additional emissions from the landfilling of the mineral material are small. Most notable are increases in copper leachate emissions. However these small increases are based on the assumption that the transfer coefficients of the inert material landfill are *a tenth* of the elemental transfer coefficients of a conventional slag landfill. In Figure 31 these transfer coefficients are set *equal* to transfer coefficients a slag landfill. Here, PECK still scores similar to the Case Lab, but with significantly increased toxicity damage scores. But still, an overall favourable result for PECK prevails.

Figure 31   *Sensitivity case MIL if the PECK mineral product has to be landfilled. The landfill transfer coefficients are set equal to those from a slag landfill. Results of the comparison of PECK vs. MSWI.*

6.6.2 Sensitivity on complement energy sources

In the cluster of services it is requested that 37% and 18% of the lower heating value in feed waste are converted to useful heat and electricity, respectively. The PECK option meets 86.1% and 79.2% of this request for useful heat and electricity, respectively. I.e. PECK converts 31.8% and 14.2% of the lower heating value in feed waste to useful heat and electricity, respectively. No difference in energy demand was assumed between Case Lab and Case Max. The energy source to complement the energy part in the cluster of services is *heat from natural gas* and *electricity from the European grid* (UCTE). These choices are debatable, as other alternatives are imaginable.

The sensitivity case 'Oil' chooses *heat from light fuel oil* as a complementary heat source, cf. Figure 32. Heat from oil is environmentally more burdening than heat from natural gas. Since the PECK option has a relative disadvantage concerning energy

production, choosing a more burdening complementary heat source increases the burdens from the PECK option in some of the damage scores, e.g. Ozone Depletion, Summersmog and Acidification. Regarding Ozone Depletion PECK scores 50% worse than the MSWI in this case. Since Ozone Depletion receives only a moderate weight in single score indicators like EI'99, the overall favourable judgement for the PECK option remains.
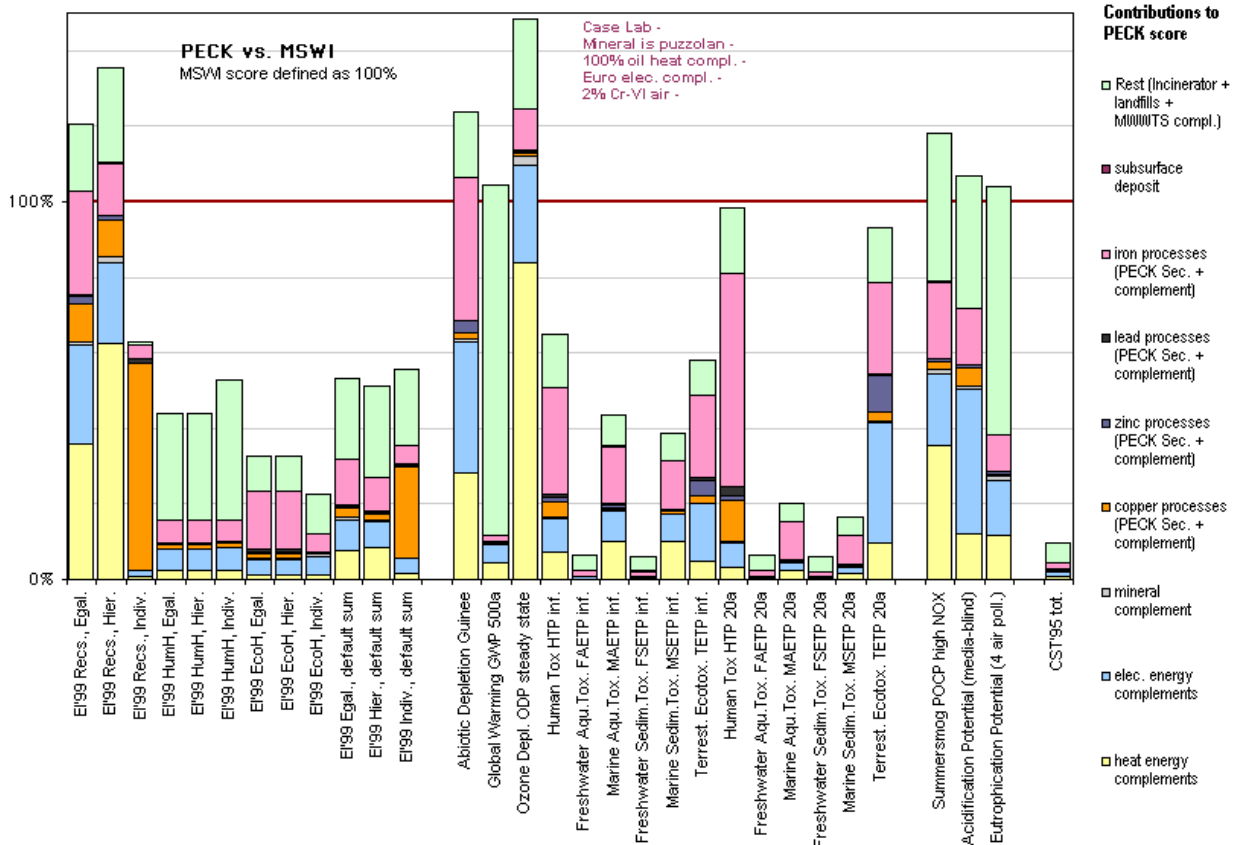

Figure 32   *Sensitivity case 'Oil' if a heat energy complement from fuel oil instead of natural gas is chosen. Results of the comparison of PECK vs. MSWI.*

The sensitivity case 'eCH' chooses electricity from the Swiss National grid[51] as a complementary electricity source instead of the European grid as in the base case, cf. Figure 33. Electricity from the Swiss National grid is less burdening than electricity from the European grid regarding pollutants.

The disadvantage of PECK regarding energy production is therefore less pronounced in this sensitivity case. This increases the advantage of PECK very slightly, but the overall

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[51] Contributions to the inland mix from imports of electricity are heeded in this mix. The calculation with pure Swiss national production – mainly hydro and nuclear power – does not change the conclusions from this sensitivity scenario.

picture remains the same[52]. The contributions to the total damage of PECK from the electricity complement decrease significantly.
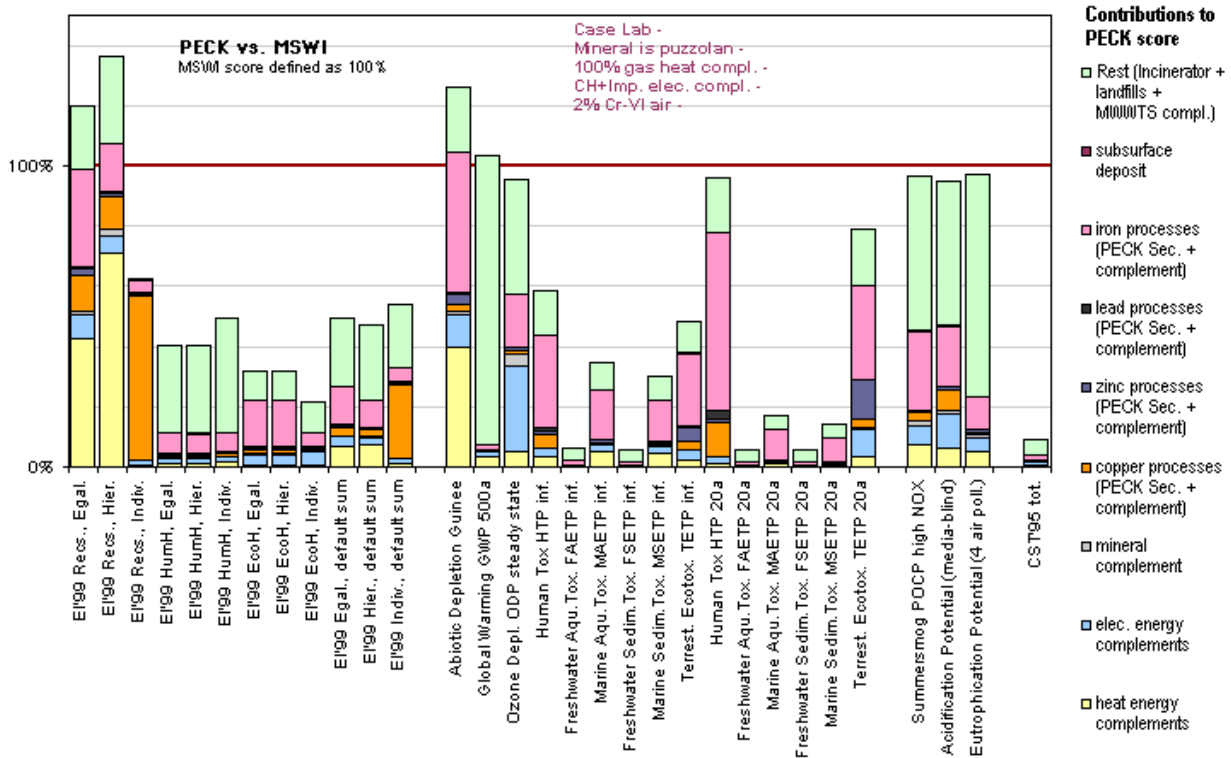

Figure 33 *Sensitivity case 'eCH' if a electric energy complement from the Swiss grid instead of the European grid is chosen. Results of the comparison of PECK vs. MSWI.*

6.6.3 Sensitivities on landfill performance

Long-term emissions from landfills play an important role in the environmental performance of incinerators. Most of the metals in the landfilled incineration residues are released through long-term leachate emissions. In the base case these potential leachabilities are estimated from availability tests. As a sensitivity, the calculation can be performed with maximal leachability, i.e. the long-term transfer coefficients for all chemical elements is set to 100%. This means that it is assumed that within a very-long time period – e.g. 100'000 years – all elements in the landfilled materials are completely transferred to the environment as water emissions. Most landfill experts agree that, given enough time, this scenario is likely (e.g., Bäverman et al 1999, Bjoerklund 1998,

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[52] The reason for this is that the MSWI uses just little less electricity than PECK, approx. 13%. The advantage of choosing a less burdening electricity complement *influences also the damage score of the MSWI option.* But since the relative difference is small, the influence of the electricity mixture is small, *although* the contribution to the total score from the electricity complement is important.

Finnveden 1999, Sabbas et al 1998, Sundqvist et al. 1997, Leuenberger 1999)[53]. These emissions are then – in accordance with the current paradigm in LCA – valued like they would occur today [Hellweg et al. forthcoming, Doka 2002].

The result in the sensitivity case 'maxLT' is calculated assuming complete leaching from all landfilled materials. In this case the burden from both technologies is increased. In Figure 34, which displays the burdens of PECK *in relation* to the MSWI, the advantage of PECK in all the toxicological categories increases, while there is no change in the resource consumption categories, which are not affected by any long-term emissions. The decrease in toxic impact is a result of the deceased metal content in PECK residues. No information on possible differences in speciation and binding form of chemical elements in the landfilled incineration residues of PECK and MSWI was included in the assessment.
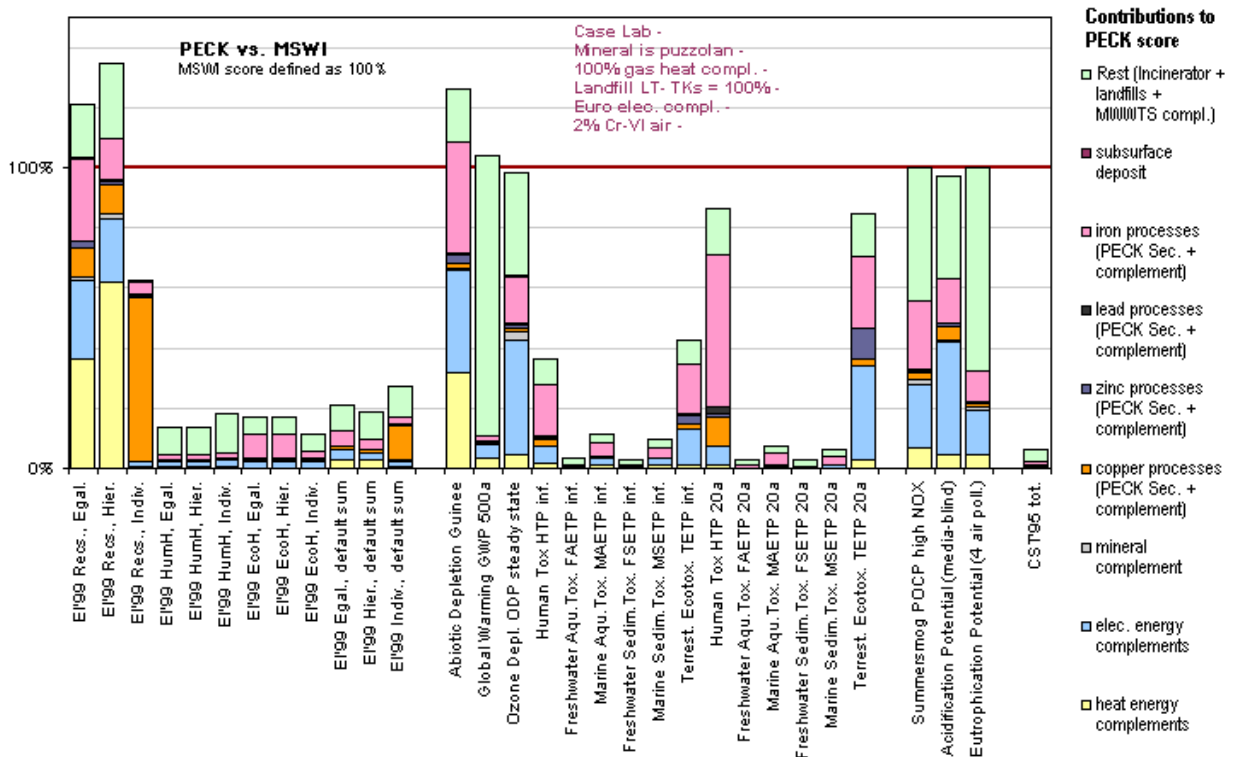

Figure 34   *Sensitivity case 'maxLT' if a complete long-term leaching from the landfills is assumed. Results of the comparison of PECK vs. MSWI.*

Long-term emissions can occur in the far future and can have different effects than today. Moreover, there is considerable difficulty in predicting the precise dynamics of leaching from landfills. These can be reasons to weigh long-term emissions differently than short-term emissions [Hellweg et al. forthcoming].

In the sensitivity case 'noLT' all long-term emissions were completely excluded from the assessment. The temporal cut-off occurs after the controlled and surveyed phase of

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[53] In contrast to regular slag and filter ash landfill, it is assumed here that *underground deposits* remain safe for a very long time and do not emit any of the stored materials. However, Leuenberger (1999) argues that long-term stability of excavated salt mines might be endangered due to mechanical inbalances created by salt extraction during human mine use.

the landfill, which is approx. 40 years for a residual material landfill and approx. 75 years for a slag landfill. This sensitivity shows the magnitude of mistake one can make by forgetting to include or deliberately neglecting long-term emissions. It proves to be the most influential one. The results are changed to a degree where PECK has no real advantage over the conventional MSWI. There is only some moderate advantage for the Individualist perspective of Eco-indicator'99, who pays no heed to energy resources – the disadvantage of PECK. Therefore, the main advantage of PECK is, as already stated above, avoiding toxic landfill emissions by concentrating metals in recyclable materials, while for the MSWI a large fraction of heavy metals ends up in landfills. If this disadvantage of MSWI is disregarded by ignoring long-term leachate emissions, the additional advantage of PECK, mineral resource preservation, is not large enough in its effect to differentiate PECK from MSWI.

> *It can be confirmed that the long-term emissions play a vital role in the assessment and they should not be excluded. Without them, PECK has no real advantage over MSWI.*
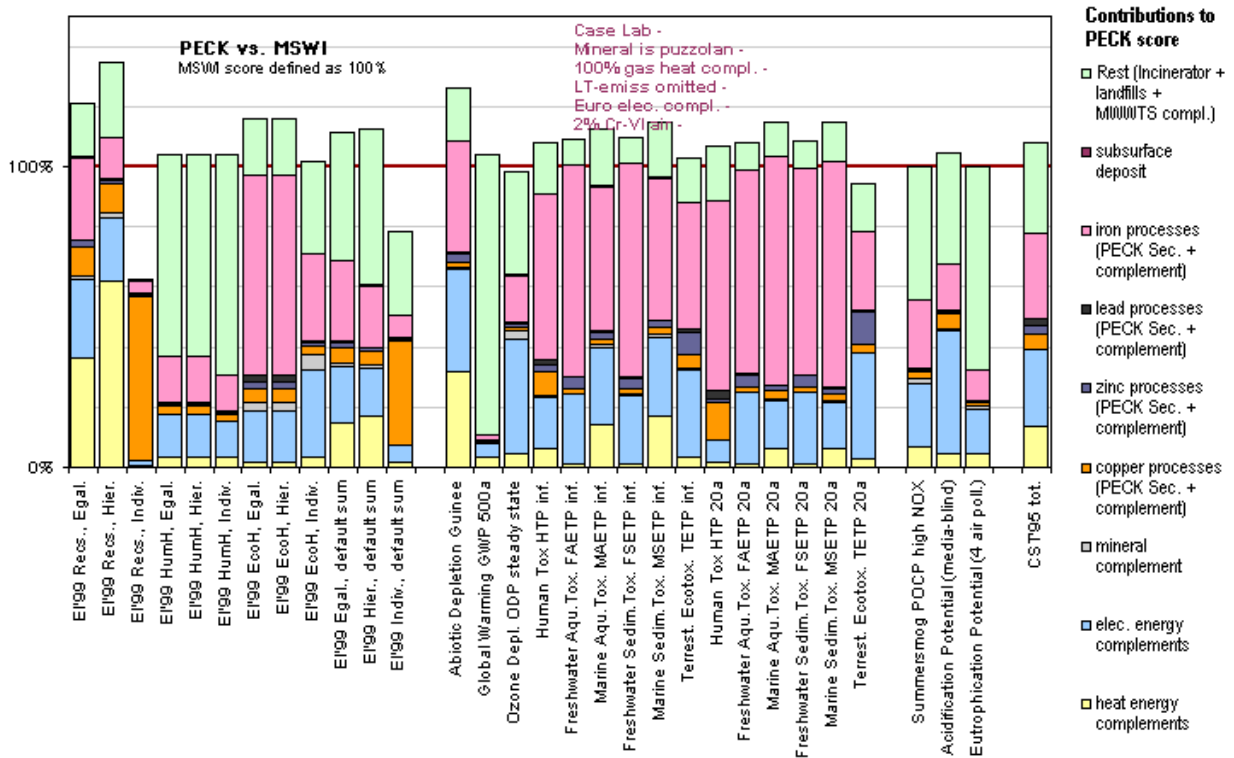

Figure 35   *Sensitivity case 'noLT' if all long-term emissions from the landfills are omitted. Results of the comparison of PECK vs. MSWI.*

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