LCA Case Studies

Environmental Assessment of End-of-Life Treatment Options for a GSM 900 Antenna Rack

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DOI: http://dx.doi.org/10.1065/lca2005.08.216

Abstract

Goal, Scope and Background. Telephony as well as remote data transfer is increasingly performed via mobile phone networks. However, the environmental consequences, in particular of the End-of-Life (EOL) treatment, of such network infrastructures have been investigated insufficiently to date. In the present report the environmental implications of the EOL treatment of a single GSM 900 antenna rack have been analysed.

Methods. Based on comprehensive inventories of a GSM 900 antenna station rack and currently applied EOL treatment, the environmental impacts related to the EOL treatment of the rack are investigated. Six different EOL treatment scenarios are developed to find an environmentally safe treatment alternative. System expansion, i.e. inclusion of the production phase, is applied to all scenarios in order to consider different amounts of regained materials.

Results and Discussion. The production of primary rack materials, especially that of palladium (accounts for almost 40% of the ecotoxicity impact category), to substitute lost materials dominates the overall environmental impact. Releases of heavy metals from landfilled rack components / materials and of by-products to the environment greatly influence the overall impacts on human health and ecosystem quality. The final disposal of rack components contributes to about 70% of the non-carcinogenic effects. Landfilled dust from steel production contributes to nearly 11% of this impact category.

Conclusions. The results suggest that all precious metals containing electronic scrap should be treated in specially equipped metal recovery plants. A complete rack disassembly before processing in high-standard metal recovery plants is not necessary. An elaborated pre-treatment and fractionation of the scrap prior to precious material recovery does not lower the environmental impacts and is not mandatory and would only become environmentally interesting if high recovery of heavy metals is achieved. To avoid the formation and release of volatile and toxic heavy metal, incineration of electronic scrap as of by-products prior to landfilling should be avoided. To reduce the overall environmental load, a standardisation of the sizes of rack components, facilitating their re-use, is recommended.

Keywords: Antenna rack; end-of-life scenarios; end-of-life treatment; GSM 900; impact assessment

Introduction

Since the implementation of the innovative Global System for Mobile communication (GSM) in the early 1990s, cellular mobile phone technology represents a steadily increasing and rapidly evolving mobile communication technology. Initially, only a few GSM networks in few countries were operated covering main roads, main places and other 'hot spots' of mobile communication traffic. Today the number of GSM networks exceeds 500 in more than 180 countries worldwide (GSMAssociation 2004). Linked to the increasing numbers of networks is a substantial rise in network components. For example more than 6350 GSM antenna stations were operated in Switzerland in 2002 (Rothus 2002) and the tendency is growing. The highest rates of growth, in numbers of subscribers as well as in numbers of networks launched, are expected for the Latin American and the Asian-Pacific regions (GSMAssociation 2004). Prognoses on the evolution of the forthcoming Universal Mobile Telecommunication Systems mobile phone standard (UMTS) predict network and subscriber growing rates similar to the GSM standard, which would lead to a total number of mobile phone users in 2010 of about 500 million in China alone (Friedl&Partners 2001). Tightly associated with the above outlined trends is a growth in network as well as subscriber devices that need to be replaced. This is due to the fact that they either don't meet the technical requirements any more or because they have reached their End-of-Life (EOL). The increased amount of such electronic scrap is fortified by the ongoing change-over from GSM to UMTS in numerous countries world wide. During the past years, adverse environmental implications caused by treated network component materials as well as insufficient End-of-Life (EOL) treatment were increasingly recognised by national governmental authorities, manufacturers and recyclers. Restrictive regulations seek to prevent the dumping of valuable electronic scrap and aim to ensure increased recycling rates of electronic devices (CEC, 2003b). Supporting regulations prohibit the usage of numerous materials assessed to be environmentally toxic (CEC 2003a,CEC 2003b). To meet the requirements of the regulations, the manufacturers have endeavoured to replace environmentally critical materials and EOL treatment methods were constantly updated. However, several problems remain:

a) Regulations on environmental save EOL treatment methods are not consistent world wide.
b) To date, environmental impacts related to the EOL treatment of mobile phone network scrap have not been quantified in a life cycle perspective.
c) Likewise, impacts of EOL treatment scenarios for single network components have not been quantified in detail.
d) Consequences of the increased amount of network scrap to be treated due to the change-over from GSM to UMTS have not been studied.

A few studies were carried out on the life cycle of mobile phones (RANDA-GROUP 2000) and networks (Faist-Emmenegger et al. 2003, Weidman et al. 2001). For single network components, e.g. transceiver units built in antenna racks, some EOL scenarios were investigated (Furuhjelm et al. 2000, Grunewald et al. 1999). Numerous studies demonstrate the importance of the EOL phase of a network component compared with other life cycle stages (Tanskanen et al. 2001). However, most studies lack a sound examination of the EOL phase analysing emissions, emission paths and emission sources in detail.

Current and forthcoming governmental regulations require a sound understanding of the environmental performance of mobile phone network components during their EOL phases.

In the study presented here, the environmental impacts caused by the EOL treatment of a typical GSM 900 BTS (Base Transceiver Station) antenna rack were investigated. Treatment scenarios varying from direct disposal excluding any kind of EOL treatment to current state-of-the-art EOL treatment methodology were developed. To assess the environmental impacts, the IMPACT2002+ method (Jolliet et al. 2003) was applied.

This paper compiles the results for a typical antenna rack and compares the different EOL scenarios. In particular, it aims at addressing the following questions:

- Which of the EOL scenarios represents the preferable alternative?
- Which stage within the EOL phase contributes dominantly to the overall environmental impact of the entire EOL phase, and why?
- Does the rack contain materials posing a distinguished environmental risk during the EOL phase?

The paper is structured according to the ISO14040 series (ISO 1998) into goal and scope definition, inventory, impact assessment and interpretation and is concluded by a discussion and recommendations to concerned actors.

1 Goal and Scope

1.1 Study objective

The goal of the study reported here is the

- identification of an environmentally preferable combination of currently used EOL treatment processes for a generic antenna rack, and the
- determination of environmentally critical EOL treatment processes and materials causing critical impacts in these processes.

The study was carried out applying the Process Life Cycle Assessment (PLCA) method. The results are intended to provide knowledge on the environmental consequences related to the processing of mobile phone network scrap. The outcome is also meant to support the decision-making of network operators, network component manufacturers as well as recyclers.

Functional Unit and Reference Flow. The treatment of one representative GSM 900 antenna rack in the EOL phase was selected as a functional unit. One treated antenna rack represents the reference flow. In further studies, these results could also be integrated in the overall assessment of a network, defining the required number of racks per network functional unit (e.g. per served customer or per transferred Mb).

Data Requirements. The data for the background system (infrastructure data, primary material production data, etc.) comply with the requirements documented for the ecoinvent-database (Frischknecht et al. 2004). For the collection of the data intended for the foreground system (EOL processing data, technical rack specifications), the following requirements are set:

- representative for Switzerland and Western-Europe and
- representative for the last ten years (in the case of EOL process data) and for the period between 1999 through 2004 (in the case of rack specific data), respectively.

For validation purposes, EOL treatment data of similar processing steps are compared with each other. Likewise, the technical data compiled for the investigated antenna rack are compared with existing rack types. If EOL treatment data are missing, approximations based on closely related process data are used.

System boundaries and System Expansion. The investigated system comprises all EOL treatment stages applied to a representative antenna rack. The EOL phase of a rack begins with the dismounting of the rack and ends with the production of secondary materials and the final disposal (incineration and landfilling) of waste products (**Fig. 1**). Not included are the rack assembly and the use phase of the rack. In conformity with ongoing ISO practices, the use phase was assumed to be equal in each of the EOL treatment scenarios and, thus, was not modelled.

System expansion, i.e. the inclusion of the production phase for all antenna rack materials in the EOL scenarios, was applied to all scenarios so that each scenario generated comparable outputs (see Fig. 1). Scenarios 0–2 do not contain material recovery (recovery rate = 0%) and 100% of the materials are substituted by primary materials. In scenarios 3–5, where materiel recovery is included, the yield of the recovery process is assumed to be 75% for aluminium and steel, respectively (BDSV 2001, BUWAL 2004, VSSV 2005). Potentially 90–95% of the steel scrap can be processed such that secondary steel is produced. Approximately 5% remain as waste (VSSV 2005). According to Swiss waste and recycling statistics, about 75% of domestic tin and steel sheet waste are recycled (BUWAL 2004). The recovered materials substitute the primary materials. The remaining 25% of the processed steel and aluminium are lost in the EOL treat-

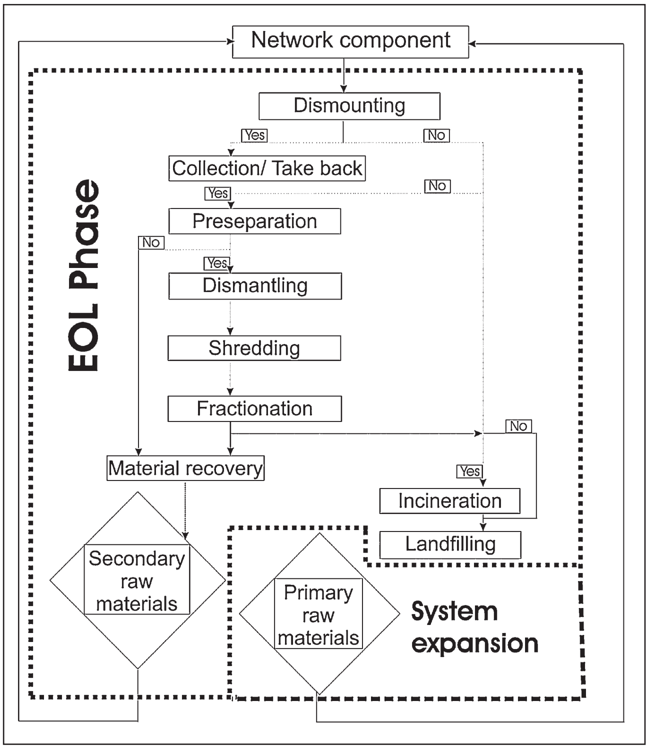

Fig. 1: Flow chart and system boundaries of the EOL phase of the antenna rack (dotted line) and system expansion (dashed line)

ment processes or are not realisable due to low quality. In scenarios 4–5, where precious metal recovery partially takes place in ordinary copper smelters, only 25% of the precious metals processed are assumed to be recovered and 75% are assumed to be lost. In scenario 3, where all precious metals are processed in a specialised metal recovery plant, the respective recovery rate is increased to 35% (the recovery rate chosen bases on (HELCOM 2002) and (Lehner 2001)). The remaining 65% of the processed metals are assumed to be lost.

Cut-off. The cut-off rules as applied in ecoinvent are adopted for the background system. Thermal energy, generated in the incineration processes, was not considered to substitute primary energy generation consumed in the base material production phase. Minor material losses occurring in the EOL treatment of the rack (the foreground system) are inventoried, but no subsequent processing was carried out.

Allocation. Allocation procedures according to ecoinvent are applied to the background system. Allocation based on physical properties (Ekvall et al. 2001) is applied to the foreground system infrastructure (for example, shredder use is allocated to mass of treated scrap).

Impact Assessment. The IMPACT2002+ method (Jolliet et al. 2003) is used to determine the environmental impacts related to the emissions released and resources consumed in the studied system. This method links emissions and resource consumptions compiled in the life cycle inventory to so-called midpoint categories representing the environmental impacts as effect scores of various reference substances. These scores are linked to damage categories representing the impacts on human health, ecosystem quality, climate change and resources, respectively (Humbert et al. 2004). To discuss the individual environmental impact categories in detail, and to cross-compare the shares of the individual impact categories with reference to the damage categories, the impact assessment was finalised at the normalised endpoint level. In addition, robustness of results is tested using CML2001 (Guinée et al. 2001) and the Ecoindicator 99 (H,A) methodology (Goedkoop et al. 2000).

Interpretation and Weighting. The results of the impact assessment are interpreted impact category by impact category. No weighting is applied.

Review Process. The collection of the data and the modelling of the EOL phase were subject to internal critical review.

1.2 Study objects

1.2.1 Antenna rack

The investigated rack is representative for antenna racks (denoted by number 3 in **Fig. 2**) used in GSM 900 networks presently in operation. In that kind of network the communication between the participants, i.e. the transmission of speech, text messages and other data streams, is transmitted using frequencies located in the 900 MHz band, thus the name GSM 900. The antenna racks form the key electronic unit of the individual antenna sites, which transmit data streams arriving at the sites from the antenna controller units (denoted by number 4 in Fig. 2) to the mobile units (subscriber devices; denoted by number 1 in Fig. 2) and vice versa via the air interface. A group of three to four racks, housed in appropriate shells, and a single antenna mast, bearing the radiating element(s), typically form such a BTS (number 2 in Fig. 2). In the mobile phone network, several BTS belong to the Base Station Subsystem (BSS) and form the outer most part of the wired network part.

The handling of the radio channels and the transmission of data to both the subscriber and the network belong to the key functions that an antenna rack fulfils. To perform these functionalities, antenna racks can be operated in different modes which determine the hardware configuration of the

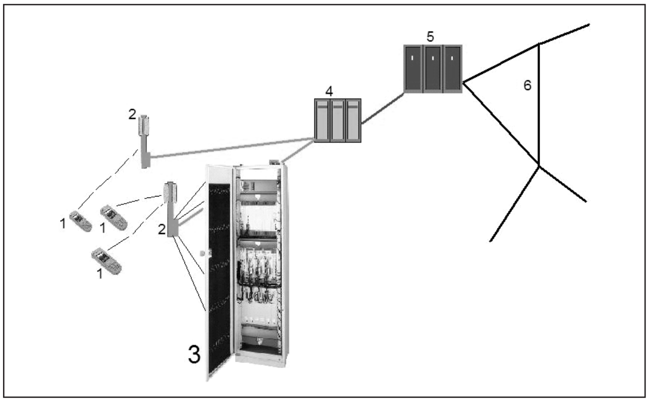

Fig. 2: Example and location of an antenna rack (ERICSSON RBS 3202) in a mobile phone network (1 = Mobile phone, 2 = Antenna site, 3 = Antenna rack, 4 = Radio network controller, 5 = Mobile Switching Centre, 6 = Public Switched Telephone Network (PSTN))

Table 1: Operation mode for which the investigated BTS rack is designed

Operation parameter	Specification
FDD	Yes
FDMA/TDMA	Yes
Speech coding	9.6 kbit/s
Normal circuit switched mode	Yes
GPRS	No
HSCSD	No
Transceiving units	12
Channels/transceiving unit	8
Max no. of subscribers	96 (Scharnhorst 2003)

racks. The operation mode given in (**Table 1**) was assumed to be applied in practice to the investigated rack. Further information on technical aspects of mobile telephony can be found in (Bekkers et al. 1997, Eberspächer et al. 2001).

The interior of the investigated rack consisted of transceiving units, antenna connectors, etc.; corresponding to the defined operation mode. Detailed information on the rack inventory is compiled in the **Supporting Information** (Appendix A, online only at <http://dx.doi.org/10.1065/lca2005.08.216>). Antenna racks can be configured for both outdoor and indoor use. For the different environments, the racks are exposed to require different rack assemblies, e.g. different shells, air conditioners, etc. The investigated rack was assumed to be designed for indoor conditions.

1.2.2 EOL treatment system and stages

An antenna rack is replaced by another one for different reasons. The replaced rack is then processed in appropriate EOL treatment facilities. Per definition in the study presented here, the EOL phase of an antenna rack begins when this network component no longer provides its service(s) properly:

- due to damage,
- because other functionalities or services being required, the device cannot provide or
- due to changes in network technology, requiring the replacement of the device.

The EOL treatment of antenna scrap has two major intentions, namely: i.) to eliminate of the electronic scrap, ii.) to recover (precious) materials, thus avoiding environmental burdens due to primary production or disposal of materials.

When processing the antenna rack in the individual EOL treatment facilities, the following major material streams can be identified:

- electronic scrap / materials (already extracted from scrap) that presently cannot be treated,
- scrap / materials that can be treated and
- by-products generated while processing the electronic scrap

At a certain moment, any further processing of scrap and / or materials extracted so far is ecologically and / or economically worthless. At that stage, the above defined major flows either leave the EOL system as output(s) to be processed elsewhere or the flows end as the EOL phase ends and no output(s) to technosphere are generated. In the study, the EOL phase was closed as soon as:

- un-recyclable material mixtures are landfilled,
- materials recovered have a purity which allows processing in the production phase and
- by-products are landfilled.

A complete and ideal EOL treatment of electronic scrap, typical for Western-European conditions, can be distinguished into eight EOL stages:

i. Dismounting: The antenna site is visited by service staff dismounting the rack and installing the new antenna rack, using electric tools. The old rack is transported to a depot where it is stored before further processing can take place.
ii. Service (Storage): The racks are in a depot during a few days to several months. Depending on the rack's state, it is then either re-used or it is supplied for further recycling.
iii. Pre-separation: The rack is transported from the depot to a pre-separation facility. There the rack is disassembled, i.e. the individual sub-components such as air conditioners, cables and diverse electronic cards are removed and the rack shell is deconstructed. Diverse electric tools are used in the disassembly and deconstruction processes.
iv. Dismantling: The separated rack sub-components are further decomposed into parts like housing, cables and printed wiring boards. Subsequently, the collected parts are transferred to a fractionation facility.
v. Fractionation: The decomposed rack sub-components are shredded, separated, cut and sifted. The fractionation process is completed by a sedimentation process. The fractionation steps are performed using a number of different separation facilities. Iron, non-iron metals and plastic mixtures represent the major fractions which are efficiently extractable at the moment. Metal fractions high in iron or aluminium content are then transferred directly to steel works and aluminium plants, respectively. To recover precious materials, heavy metal fractions are transferred to appropriate smelter plants. The plastic elements are commonly incinerated and the residuals are landfilled.
vi. Material recovery: Precious materials contained in the heavy metal fraction are extracted by processing the fraction stepwise in diverse units such as kilns, converters, anode casting units, electrolytic refinement facilities and metal smelters. Presently, materials being efficiently extractable among others are copper, gold, silver, palladium, platinum, and selenium. The recovered metals mostly have a pureness which allows direct processing in downstream production processes. Depending on toxicity and other aspects, the by-products generated during the recovery process are either incinerated and then landfilled or directly landfilled.
vii. Incineration: Materials such as plastics or other materials, which currently cannot be efficiently recycled as such, but possess an energetic value or need to be incinerated due to environmental safety issues, are incinerated in suitably equipped incineration plants. Ashes and slag are transferred to the final disposal stage.
viii. Final disposal: All materials being unrecoverable and by-products, which accrued during the numerous EOL treatment processes, are transported to and disposed of in qualified landfills.

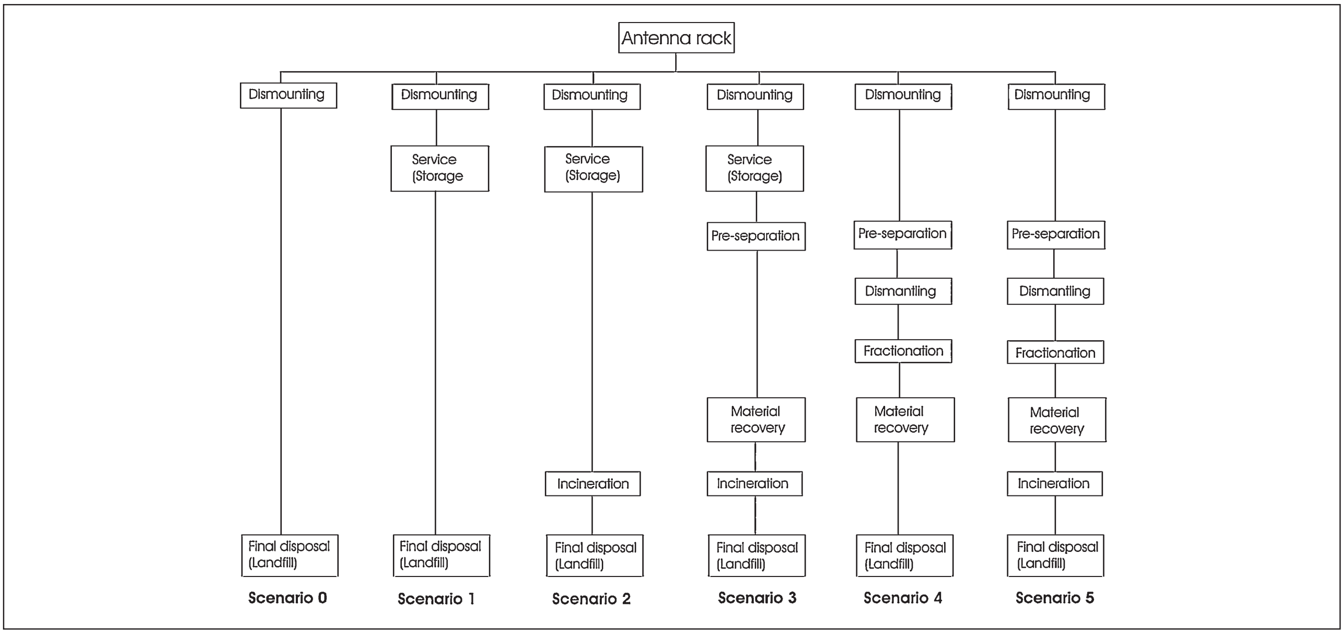

Fig. 3: Composition of the investigated EOL treatment scenarios

To analyse the environmental implications related to the EOL treatment of an antenna rack, the following six scenarios were developed based on the above outlined EOL treatment stages (**Fig. 3**).

Scenario 0: Landfill. The antenna racks dismounted are assumed to be landfilled directly without any kind of treatment, material recovery and incineration. The scenario includes the dismounting of the racks, transportation of the racks to the landfill site and the landfilling of the rack.

Scenario 1: Storage and Landfilling. Similar to scenario 0, the dismounted antenna racks are landfilled. Prior to landfilling the rack is stored for 20 days in a depot. The process is the same as in scenario 0, and a storage process is included.

Scenario 2: Incineration and Landfilling. The rack is incinerated before landfilling in this alternative. This scenario consists of the same processes as described in scenario 1 plus an incineration process.

Scenario 3: Material Recovery. After dismounting the rack, it is transported to a pre-treatment facility where the bigger housing parts such as the shelves and frames made of aluminium and steel are dismounted. These elements are directly processed in aluminium plants and steel works, respectively. The rack interior, i.e. the printed wiring boards, cables, etc., is transferred directly to precious metal plants. By-products generated during the precious metal recovery and materials unrecoverable with present EOL treatment technology are incinerated and finally landfilled. The scenario consists of a dismounting step, a service and pre-treatment step and a material recovery step, as well as of an incineration and a landfill step. Transportation processes connecting the aforementioned processes are considered as well.

Scenario 4: Advanced Dismantling and Recovery. The dismounting step is followed by an elaborate decomposing and dismantling step wherein the rack is disassembled into cables, printed wiring boards and device housings. 75% of the printed wiring boards are sorted out and transferred directly to an ordinary copper smelter where only copper is recovered. All other elements are transferred to a fractionation facility where they are shredded, separated, cut and sifted. Outputs are iron-metal fractions, non-iron metals and plastic fractions. Whereas the plastic fraction is transferred to an incineration process, most of the metal fractions are transferred to either steel works or aluminium plants. The heavy metal fraction is transported to and processed in a specialised precious metal recovery plant. By-products and materials being unrecoverable with the present technologies are directly landfilled. This scenario consists of the same steps as scenario 3 plus the pre-treatment process and the fractionation process.

Scenario 5: Advanced Dismantling, Recovery and By-product incineration. This scenario consists of the same steps as scenario 4, but includes the incineration of by-products and the materials being unrecoverable with present EOL technologies prior to landfilling.

2 Life Cycle Inventory

2.1 Study objects

The compilation of inventory data and the scenario assembly were carried out using the GaBi4 software (IKP&PE 2003). For background data, datasets provided by the Swiss national data base for life cycle inventories – ecoinvent (ecoinventCentre 2003) – and datasets provided by the database included in the GaBi4 software were adopted. Cumulated data sets including emissions and resource consumptions of upstream processes were adopted from the ecoinvent data base.

2.1.1 Antenna rack

Rack modelling. Based on general technical specifications of diverse antenna racks and their interior (LucentTechnologies 2000, LucentTechnologies 2001, SiemensAG 2000), an average GSM 900 antenna rack is composed. The rack interior, i.e. rack devices such as connectors, filters and transceiving units, etc., is modelled as an interface to the elementary flows. This means that for each of these rack devices a mass balance, specifying qualitatively and quantitatively the elementary input into the respective rack device, was created. The output is represented by the rack device itself, specified by its mass. To the entire rack, the functional unit defined earlier is applied. An overview on the rack specifications adopted for the study is given in the **Supporting Information** (**Appendix A**, online only at <http://dx.doi.org/10.1065/lca2005.08.216>).

Data collection: Rack specific data were compiled from literature, e.g. from original rack data sheets published by manufacturers, web-sites and books. Network infrastructure data as operation modes, transport distances, etc. were obtained from network operators. Specific technical data on rack devices, such as transceivers, for example, were collected from literature and from a few technical specifications sheets (SiemensAG 2002) which were empirically determined by the author. Mass balance data, i.e. qualitative and quantitative information on the specific materials the devices are made of, were partly adopted from literature and approximated.

Data quality, validity, assumptions and limitations. The rack data compiled for the investigation are valid for Western-Europe. The rack inventoried represents GSM 900 mobile communication technology typical for the period between 1999 through 2002 and refers to 2G specifications (ETSI 1996). The data are expected to differ from antenna racks operated in networks other than a GSM 900. The antenna rack was assumed to be configured for indoor use and is fully equipped, i.e. there is no room for rack expansion. Replacement of rack devices such as transceivers or any other unit was not envisaged during rack operation time. The rack analysed in the study represents a model rack and does not correspond to any existing antenna rack type.

2.1.2 EOL treatment system

EOL System Modelling. The EOL system consists of several EOL stages (e.g. dismounting of the rack, dismantling and fractionation stage, etc.). Those stages are modelled as EOL modules connected with each other. Each of the modules consists of numerous processes, e.g. electricity generated and consumed within a specific EOL stage.

Two different kinds of processes contributing to the EOL treatment were distinguished: *directly* and *indirectly contributing* processes. For example, all transports of the antenna rack to be treated, the facilities (e.g. tools, devices, smelters, etc.) needed to treat the antenna rack and the infrastructure, which houses the facilities, belong to the former. Indirect contributing processes are not modelled explicitly in the study, but are part of the directly contributing processes (ecoinventCentre 2003). For example, the infrastructure needed to produce the concrete plates needed to build a certain EOL treatment building was not modelled explicitly in the study, but is included in the respective ecoinvent concrete generation data set.

A detailed overview on the modules and the processes they comprise is given in the **Supporting Information** (**Appendix B**, online only at <http://dx.doi.org/10.1065/lca2005.08.216>).

Data collection. Information on dismounting and storage of antenna racks was gathered from manufacturers. Additional information was approximated based on manufacturer information. Transport related data were estimated based on the current regional distribution of the total Swiss GSM 900 network. Data on the rack processing during the pre-treatment, fractionation and material recovery stages were partly obtained from recyclers and mostly compiled from literature. To a minor extent those data were approximated. Inventories for the EOL facility infrastructure were created based on technical specifications found on the web.

Likewise, inventory data for generating materials needed such as concrete, steel and electricity were adopted from the ecoinvent database (v1.01) (ecoinventCentre 2003). Transport-related data were adopted from the GaBi4 database (IKP&PE 2003). A few data sets on the incineration and landfilling are adopted from the ecoinvent database. In many cases, however, inventory data related to those EOL processes did not exist and are approximated based on closely related ecoinvent data sets. The scenarios developed also consider direct rack incineration and / or landfilling and the corresponding processes were inventoried for those alternatives. Emissions to the environment from incineration and / or landfilling of racks were determined by transfer fractions and transfer coefficients. The fractions and coefficients were determined based on available literature or were approximated based on physical and chemical characteristics. A compilation of the values adopted is given in the **Supporting Information** (**Appendix C**, online only at <http://dx.doi.org/10.1065/lca2005.08.216>).

Detailed inventory information is given in the supporting information. Inventory results for energy carriers and CO_2 emissions are presented below in the impact assessment section (**Tables 2** and **3**).

Table 2: Selected resources consumed by the EOL treatment stages of the different scenarios while the antenna rack is treated and base materials are produced

Stages	Dismounting	Service	Pretreatment	Fractionation	Primary prod.	Secondary prod. 1)	Incineration	Landfill
Scenarios	**0–5**	**1–2**	**3–5**	**4–5**	**0–5**	**3–5**	**2–3 and 5**	**0–5**
Hard coal [MJ]	0	3	1	1	1485	611	4	0
Lignite [MJ]	0	3	1	1	716	490	1	1
Natural gas [MJ]	0	10	10	1	2329	6070	12	9
Crude oil [MJ]	0	64	95	1	2021	466	104	94
Uranium [MJ]	1	8	2	3	2240	1120	4	1120

1) Based on data on the annual resource consumptions published by the German 'Badische Stahlwerke' GmbH (BSW 2004)

Table 3: Carbon dioxide emitted by the EOL treatment stages of the different scenarios while the antenna racks is treated and base materials are produced

Stages	Dismounting	Service	Pretreatment	Fractionation	Primary prod.	Secondary prod.	Incineration	Landfill
Scenarios	**0–5**	**1–2**	**3–5**	**4–5**	**0–5**	**3–5**	**2–3 and 5**	**0–5**
CO_2 [kg]	0.14	5.63	7.1	0.32	459.42	176.71	8.41	8.42

Data quality, validity, assumptions and limitations: All data used in the analysis are applicable to Western-European conditions. The data represent the technical properties of the EOL treatment technology between 1999 through 2004. The pre-treatment, dismantling and fractionation data represent Swiss conditions. Specifications on the material recovery process apply to the Swedish BOLIDEN plant. The data on precious metal recovery rates are calculated based on information found in (HELCOM 2002) and in (Lehner 2001). The process assemblies as modelled represent approximations and may not always reflect the effectively occurring conditions at the different EOL treatment facilities. The ecoinvent data sets on landfilling include long-term emission data occurring during the next 60,000 years. It is assumed that in many cases all matter disposed of is leached out. This assumption was adopted for the landfill processes compiled for direct landfilling of the antenna rack.

3 Life Cycle Impact Assessment

3.1 Overall impact assessment results

Fig. 4 presents impact assessment results at midpoint level in the following impact categories: carcinogenic effects (CarcEff), non-carcinogenic effects (NoncarcEff), respiratory organic effects (RespOrg), respiratory inorganic effects (RespInorg), terrestrial ecotoxicity (TerrEcox), aquatic ecotoxicity (AquEcox), ionising radiation (IonRad), ozone layer depletion (Ozone), photochemical oxidation (PhotoOx), nonrenewable energy (NonReE), mineral extraction (MinEx), global warming potential (GlobWarm).

In a first step, the different scenario are compared both at midpoint and endpoint levels. In a second step, results are discussed in more details for the impact category contributing to human health, ecosystem quality, resources and climate change, also discussing normalized results at damage level.

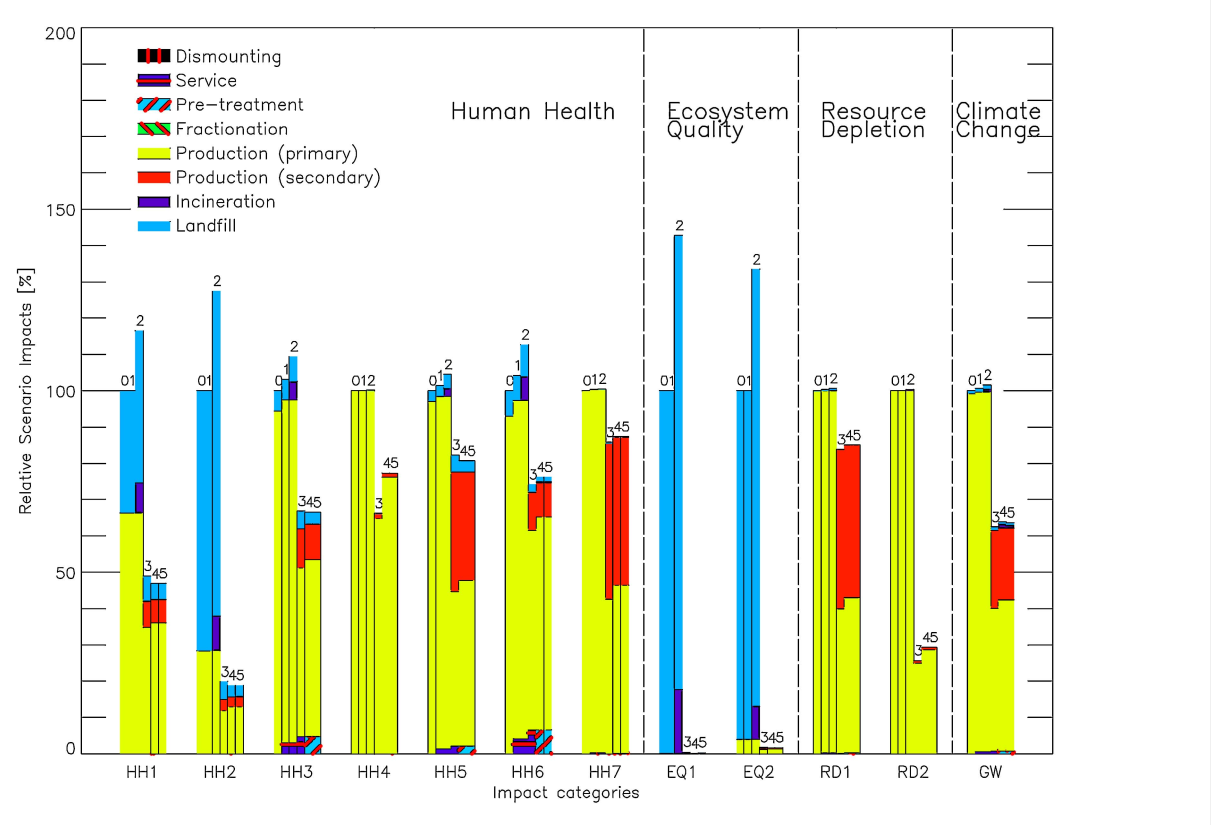

Fig. 4: General EOL treatment scenario comparison and contribution of the major EOL treatment stages to the overall impact of each scenario. In each impact category, scenario 0 was set to 100% and the other scenarios were related to it. If not otherwise stated, the following abbreviations were applied to the single EOL scenarios: 0 = scenario 0, 1 = scenario 1, 2 = scenario 2, etc.
Abbreviations of the x-axis: HH1: Carcinogenic effects – HH2: Non-carcinogenic effects – HH3: Respiratory organic effects – HH4: Respiratory inorganic effects – HH5: Ozone depletion potential – HH6: Photochemical oxidation – HH7: Ionising radiation – EQ1: errestrial ecotoxicity – EQ2: Aquatic ecotoxicity – RD1: Non-renewable energy – RD2: Mineral extraction – GW: Global warming

Two major EOL treatment groups can be identified based on the impact assessment results: i.) scenarios 0, 1 and 2 excluding material recovery / recycling and ii.) scenarios 3, 4, and 5 including material recovery / recycling (see Fig. 4). The differences between these groups are especially large with reference to terrestrial and aquatic ecotoxicity as well as to carcinogenic and non-carcinogenic effects.

Comparing the environmental impacts of the different EOL treatment scenarios category by category indicates that scenario 3 causes the fewest impact (see Fig. 4) and represents the environmentally preferable option. The results further indicate that all electronic scrap containing precious metals should be treated in specialised metal recovery plants facilitated to recover precious metals. The increased precious metal recovery rate of 10% between scenario 3 and scenarios 4 and 5 leads to a reduction of 15% in case of effects on human respiratory organs (see Fig. 4). Simple processing of precious metals containing electronic scrap in ordinary copper huts should be avoided (scenarios 4 and 5) as precious metals cannot be recovered as efficiently as in specialised metal recovery plants. Scenario 2 (immediate rack incineration and subsequent landfilling) causes large environmentally impairing emissions and should be avoided.

The production of primary materials to substitute lost materials causes major contributions to each impact category. Energy generated for and consumed in the production of primary materials as well as the different primary material production processes themselves, including the disposal of by-products, cause environmentally harmful emissions. Indirect emissions released from landfilled by-products, generated in the primary material production stage, contribute to the impacts on human respiratory organs and photochemical oxidation processes.

Long term emissions of arsenic, zinc, antimony and copper as well as of aluminium related to landfilling cause distinct toxic impacts on terrestrial and aquatic ecosystems (all scenarios), but are associated with large uncertainties. These emissions also cause significant carcinogenic and non-carcinogenic effects on human health. Comparatively less or no detectable impacts are observed for lead, cadmium and other heavy metals known to cause toxic impacts.

Compaction of electronic scrap and / or treatment residuals by means of thermal treatment prior to landfilling (scenarios 2 and 5) causes the release of highly volatile materials, e.g. arsenic and bromine, contributing to the terrestrial and aquatic ecotoxicity as well as to carcinogenic and non-carcinogenic effects. These materials increase the environmental impacts and thus thermal treatment prior to landfilling should be avoided, unless the ashes are well stabilised and enable to reduce long-term emissions and unless a significant heat recovery and electricity production can be achieved while incinerating by-products.

The results also prove that elaborated pre-treatment and fractionation of the scrap (scenarios 4 and 5) does not further reduce the environmental impacts related to the EOL treatment of the rack. Instead, material losses are associated with the pre-treatment and fractionation which then need to be substituted by primary materials. This may lead to slightly increased adverse effects on the environment worsening the overall environmental performance of the rack during the EOL phase.

Little impact is attributable to the service stage (scenario 3). Mainly radioactive emissions from the electricity generation cause ionising effects. The dismounting and the storage of the rack causes very little impacts being negligible compared to the impacts of the other EOL treatment stages.

In the following sub-sections, the respective contributions of the midpoint categories are discussed in more detail for each damage category.

3.2 Human health

Human health is primarily impaired by effects on human respiratory organs caused by inorganic emissions (impact category: respiratory inorganics; **Fig 5**), the ranking between scenarios at damage level remain the same as for midpoint results. In nearly all EOL treatment scenarios, Fig.4 shows that the substitution of lost materials by primary material production processes (system expansion) dominates the **respiratory inorganic** impact category. Key critical process is the production of primary palladium accounting for more than 85% of the total impact due to inorganic emissions. The roasting of the platinum group metal ores in Russia causes considerable sulphur dioxide emissions into air (Althaus et al. 2003). To a lower extent, SO_2 is released to air during the production of primary platinum, eventually leading to secondary particles. About 5% of the total impact is attributable to that production process. Material recovery processes exert lower effects. The contribution of all other EOL stages to the inorganic respiratory impact category is negligible.

Heavy metals (arsenic, zinc and antimony), leached out of the landfilled rack and transferred to the surrounding soil and water, wreak major **non-carcinogenic effects** (scenarios 0–2). In these alternatives, about 70% of the total impact is attributable to the final disposal and is linked to a high level of uncertainty. More than 23% is related to the primary

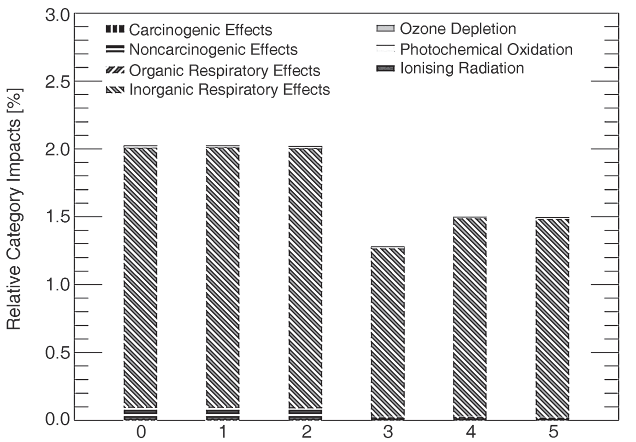

Fig. 5: Contributions of the individual impact categories at endpoint level to the impact on human health for all scenarios

material production stage. If the material recovery stage is included (scenarios 3–5), direct arsenic and zinc emissions to water released during the primary production of palladium, and partly of platinum to substitute lost metals, cause distinct non-carcinogenic effects. The direct emissions released from these two production processes account for more than 25% and 12% to the overall impact, respectively. The disposal of by-products, e.g. redmud in the production of aluminium and dust accrued during the production of primary steel to substitute lost metals, cause indirect arsenic and zinc emissions to water. The heavy metal emissions to water, stemming from landfilled by-products of the aluminium production, account for ~ 15% of the total impact. About 11% of the total impact is attributable to the landfilled dust from steel production.

Carcinogenic effects are caused by arsenic emissions to soil and water from the degradation of the rack in the landfill. Arsenic emissions to water and benzo(a)pyrene emissions to air are dominantly related to the production of primary materials to substitute lost materials. Mainly heavy metal releases of landfilled by-products to water from the primary aluminium, iron and steel production contribute to that category. Benzo(a)pyrene emissions to air occur while liquid aluminium is produced and while generating the energy consumed in the palladium production. NMVOC emissions to air exert impacts on respiratory organs (impact category: respiratory organics). Emissions of Halon 1211 released in gas transportation processes in Russia contribute to the ozone depletion category.

Emissions initialising **photochemical oxidation** reactions in the lower atmosphere are primarily released in the primary material production stage (causing more than 60% of the total impact) where materials to substitute lost materials are produced and partly in the pre-service / fractionation stage (causing nearly 10% of the total impact). In this context, NMVOC emissions due to energy generation processes and due to diesel consumed for scrap transports are critical.

3.3 Ecotoxicity

The overall ecosystem quality is dominantly affected by impacts on the terrestrial ecosystem (impact category: **terrestrial ecotoxicity**; **Fig. 6**), the ranking between scenarios at damage level remaining the same as for midpoint results. If only the final disposal of the rack (scenario 0–2) and the production of primary materials to substitute lost materials are considered while excluding material recovery processes, then emissions released to soil in the final disposal stage dominantly affect the terrestrial ecosystem. Copper emitted to soil during the degradation of the rack in the landfill accounts for nearly 96% of the total impact. If material recovery processes are included and residuals of all processes considered are landfilled without previous incineration (scenario 4), emissions released during the production of primary palladium and steel to substitute lost metals dominate that impact category. The production of primary palladium accounts for nearly 40% of the total impact. The production of primary steel accounts for 26%, respectively. Copper and partly zinc released to air represent the major toxic emissions. Copper is emitted directly in the production of palladium. Landfilled by-products of the primary steel production contribute to the copper and zinc emissions.

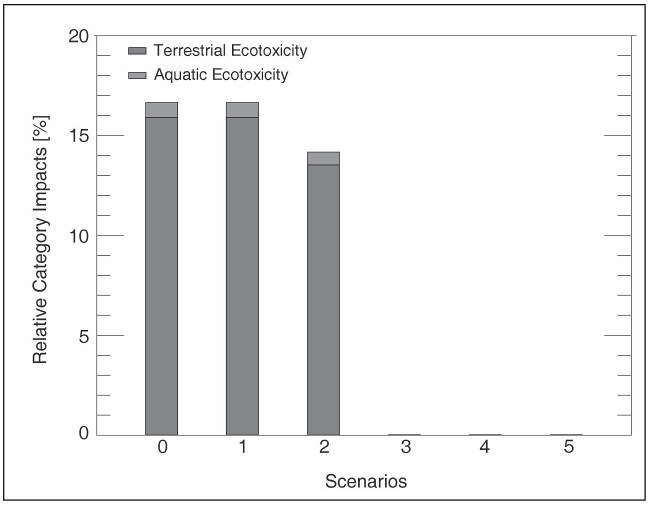

Fig. 6: Contributions of the individual impact categories at endpoint level to the impact on ecosystem quality for all scenarios

If no material recovery, but disposal is foreseen (scenario 0–2), the aquatic ecosystem is affected by both, heavy metal emissions to soil and water as well as by other inorganic emissions to water during the final disposal stage, i.e. during landfilling. Especially copper emitted to soil (~ 45% of the total impact) and water (~ 35% of the total impact) and aluminium emitted to water (~ 17% of the total impact) contribute dominantly to that impact category. If material recovery processes are included, but residual incineration prior to landfilling is excluded, emissions released during the production of primary aluminium (accounting for 51% of the total impact)and palladium (~ 16% of the total impact) to substitute the metals lost as well as the production of secondary steel contribute to the **aquatic ecotoxicity**. Indirect aluminium emissions to water (nearly 50% of the total impact) mainly stem from the deposition of redmud in landfills. Direct aluminium and nickel emissions occur during the processing of palladium in South Africa and to a lesser extent in Russia. Aluminium emissions from steel production primarily are attributable to the disposal of sludge from steel rolling. Zinc emissions in this context are detected for the disposal of dust from the production of unalloyed electric steel.

3.4 Resources

Depletion of **non-renewable energy resources** shows the largest contribution to the overall impact represented by this damage category (impact category: non-renewable energy; see Table 2 and **Fig.** 7). Mainly natural gas, crude oil, hard coal and uranium are consumed by the production of primary steel, aluminium and palladium.

Mineral resource depletion is significant while primary materials are produced. Disposing of all materials and producing new materials (system expansion, scenarios 0–2) leads to largest mineral resource depletion. Iron ore mined for primary steel production accounts for nearly 96% of the overall mineral resource depletion caused by the rack material production.

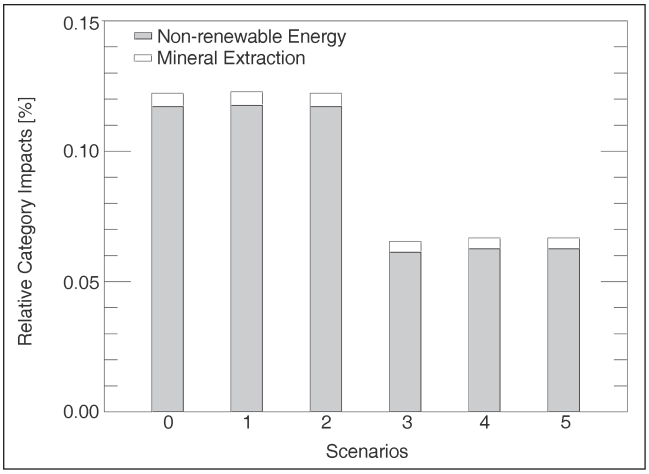

Fig. 7: Contributions of the individual impact categories at endpoint level to the impact on the resource depletion for all scenarios

3.5 Climate change

Direct and indirect CO_2 emissions during the production of primary materials in all scenarios and partly in the final disposal stage, cause large impacts on the global warming effect. In this context, scenarios 0–2 represent the environmentally most critical alternatives (**Fig, 8**; see Table 3).

Carbon dioxide emissions in the primary material production stage primarily are attributable to electricity generation processes needed for the production of primary aluminium, steel and palladium to substitute the lost metals (see Table 3). In the case of primary steel production, especially the sinter and conversion processes contribute to the overall CO_2 emissions released during that process.

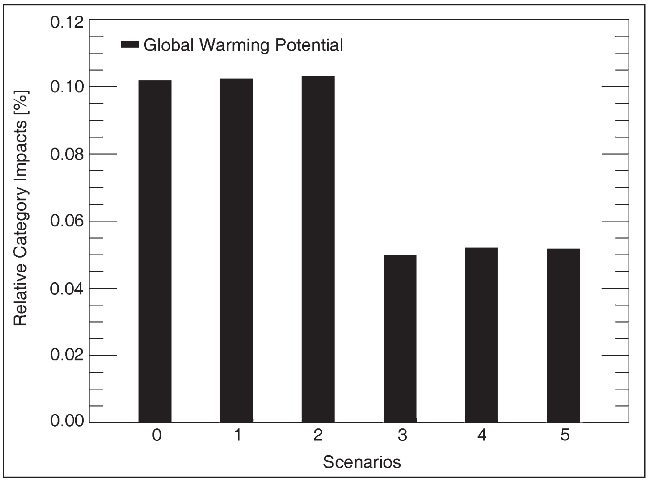

Fig. 8: Contributions of the individual impact categories at endpoint level to the impact on climate change for all scenarios

4 Discussion and Recommendations

4.1 General

Key impacts during the EOL treatment of the antenna rack and the production of the primary materials needed for the rack manufacturing are attributable to:

- direct emissions due to heavy metals leached while the rack is degraded in the landfill,
- indirect heavy metal emissions from landfilled by-products generated in primary material production and
- direct emissions of heavy metals in primary production of precious metals.

If the antenna rack is recycled and not disposed of directly, the environmental impacts related to the EOL phase are low compared with impacts related to the rack production phase. It also is shown that the final disposal without material recycling can pose significant ecotoxic impacts (see Fig. 5). However, it has to be mentioned, in particular, that the emissions inventoried and assessed for the landfill processes have to be interpreted carefully. Firstly, present LCA methodology consider overall integrated emissions, these emissions related to landfilling occur over long time periods (e.g. 60,000 years). Secondly, neither the ecoinvent data base nor the IMPACT2002+ method distinguishes explicitly the exact chemical state, especially the metal speciation in which the emissions are released to the environment.

It is found that a certain EOL treatment optimum exists and that recycling expenditures due to overly intensive pre-treatment can increase the environmental impact related to the EOL phase, mainly due to additional material losses in pre-treatment processes. The impact assessment results obtained using the IMPACT2002+ method are checked against results according to CML2001 (Guinée et al. 2001) and the Ecoindicator 99 (H,A) methodology (Goedkoop et al. 2000). Both methods, CML2001 and Ecoindicator 99 (H,A), yielded results comparable to those obtained using IMPACT2002+ (**Fig. 9**). In many cases the ranking of the dominating processes remains the same for the different impact assessment methods. Human toxicity of CML2001 is dominated by long-term antimony emissions to soil from landfilled antimony. The aquatic ecotoxicity category of the same method is dominated by vanadium emissions to soil from landfilled plastic incineration residuals.

Additionally, the robustness of the IMPACT2002+ method has been examined by excluding those emissions contributing less than 1/1000 to the overall environmental impact and then assessing the environmental impacts of the EOL treatment scenarios again. The results remained the same. Based on the results, the following recommendations to actors are formulated.

4.2 Recommendations to recyclers / operators

As an antenna rack reaches its EOL phase and cannot be used otherwise it should be dismounted and processed. A pre-treatment comprising of merely the disassembly of the rack housing and the removal of the rack sub-components (transceivers, etc.) is sufficient. All electronic scrap containing precious metals should be treated in specialised metal recovery plants to effectively recover precious metals. After pre-processing the steel and aluminium fractions extracted, they should be processed in steel works or aluminium plants, respectively. Precious metals should be recovered in high-standard material recovery facilities.

According to the results, incineration of the electronic scrap, as e.g. printed wiring board assemblies, prior to landfilling should be avoided unless ashes are stabilized long-term and

		Assessment method			IMPACT2002+	EI99 (H,A)	CML2001
	Life cycle process	Ranking					
Impact category		IMPACT2002+	EI99 (H,A)	CML 2001			
					kg Triethylene glycol	DALY	kg DCB-equiv.
Human toxicity	Pre-treatment	1	1	6	2.32E-02	3.58E-08	0.617
	Thermal treatment	2	2	2	1.08E-02	1.68E-08	19.587
	Steel secondary	3	3	3	6.76E-03	1.05E-08	9.792
					kg Triethylene glycol	PDF*m^2*year	kg DCB-equiv.
Aquatic ecotoxicity	Thermal treatment	1	1	2	2.41E+05	3.158	5.982
	Aluminium secondary	3	2	4	2.35E+04	2.266	1.840
	Steel secondary	2	3	3	1.71E+05	0.839	4.625
					kg Triethylene glycol		kg DCB-equiv.
Terrestrial ecotoxicity	Thermal treatment	1	-	1	3.70E+03	-	0.627
	Aluminium secondary	2	-	2	354.98	-	0.221
	Steel secondary	3	-	3	166.14	-	0.170
					kg Ethene-equiv.		kg Ethen-equiv.
Photochemical oxidation	Thermal treatment	1	-	1	0.914	-	0.0185
	Pre-treatment	2	-	2	0.229	-	0.0183
	Steel secondary	3	-	3	0.048	-	0.0154
					kg CO_2-equiv.	DALY	kg CO_2-equiv.
Global warming potential	Thermal treatment	1	1	1	45.555	9.56E-06	45.560
	Steel secondary	2	2	2	45.455	9.53E-06	45.383
	Aluminium secondary	3	3	3	15.551	3.25E-06	15.498
					C14 in air equiv.	DALY	DALY
Ionising radiation	Steel secondary	1	1	1	4.39	9.24E-10	9.24E-10
	Thermal treatment	2	2	2	2.86	6.01E-10	6.01E-10
	Aluminium secondary	3	3	3	0.39	8.26E-11	8.26E-11

Fig. 9: Comparison and ranking of the impact assessment results (given for EOL scenario 5) for the EOL phase of the antenna rack using the different impact assessment methods

recoverable energy is significant. Such additional incineration can lead to emissions of diverse heavy metals, in particular of arsenic in dispersed form, which may react toxic to the environment (Uryu et al. 2003).

Landfilling of entire racks, rack components and even small component units should also be avoided. Precious metals are lost and have to be newly produced which leads to high impacts. Likewise, due to the unnaturally high concentration of metals in the landfill site, emissions are released which are toxic to the local environment.

4.3 Recommendations to manufacturers / operators

To reduce the environmental impacts due to processing of rack materials, two issues are of importance. Firstly, rack components, e.g. the rack housing, should have a standardised shape to facilitate re-use. That could lead to a prolonged use time of the rack housing and eventually of the rack ventilation units (supposing that the ventilation capacity is sufficient). Material flows are thus reduced and environmental load is diminished.

Secondly, the palladium used in contact materials of printed wiring board assemblies, if feasible, should be either recycled at the highest possible rates or it should be replaced by a different material.

Recent information indicates, that the racks of the UMTS antenna stations (NodeB) are heavier and have a more complex construction compared with the BTS racks (LucentTechnologies 2001,SiemensAG 2002,Wilén 2000). It is expected that the NodeB racks require more complex EOL treatment methods to ensure environmentally safe recycling and disposal. That increased complexity of both the antenna racks, as well as of the treatment methods associated with an expected decrease in the content of precious metals per rack, may lead to an increased environmental impact per rack.

However, when comparing a whole GSM900 network with a UMTS network, the latter one might perform environmentally better due to the fact that fewer macro NodeB, but more small and lightweight micro and pico NodeB's are installed. A forthcoming study will address these issues in detail.

5 Outlook

Environmentally safe EOL treatment of electronic scrap, in particular of mobile communication technology scrap, is of urgent importance in a world of rapidly growing numbers of networks and network components, and increasingly complex component assemblies.

The presented study gives a first analysis of the environmental consequences related to different EOL treatment alternatives applied to a generic GSM 900 antenna rack. EOL treatment scenarios are developed and an environmentally safe treatment alternative is identified. Additionally, the relative contributions of the single EOL treatment stages, from rack dismounting to final disposal, to the overall environmental load are identified quantitatively and qualitatively. Sources and sinks of environmentally relevant emissions are identified.

The relative environmental importance of the antenna rack in an entire mobile phone network comprising mobile phones, antenna and antenna controller sites, as well as the switching units and the back bone cable network during the

EOL phase, was not considered in the study reported here, but is examined in an ongoing investigation. Also, the effects of different data rates used in different mobile phone standards (e.g. GSM, GPRS, UMTS) have not been addressed in the presented study, but are the subject of a study presently in preparation. Studying the environmental profiles of the individual mobile phone network components, that study aims at recommending:

- optimal network configurations allowing for environmentally safe EOL treatment as well as
- environmentally sound EOL treatment alternatives for individual network components.

As long-term emissions can indeed play an important role for human toxicity and ecotoxicity, further research is required to improve the assessment quality and reduce the high uncertainty related with these impacts.

Acknowledgement. The authors would like to thank Mr. M. Classen for reviewing the inventoried data and the modelling and Mr. G. Rebitzer for his professional comments and critics. The authors would like to express their gratitude to the anonymous reviewers of the paper for the fruitful discussions improving the quality of the paper substantially.

References

Althaus H-J, Classen M, Blaser S, Jungbluth N (2003): Life Cycle Inventories of Metals. 10, Swiss Centre for Life Cycel Inventories, Dübendorf

BDSV (2001): Stahlschrott – ein 'grüner' Rohstoff. Bundesvereinigung Deutscher Stahlrecycling- und Entsorgungsunternehmen, Düsseldorf

Bekkers R, Smits J (1997): Mobile Telecommunications: Standards, Regulation, and Applications. 1st Edition, Artech House, Boston, London

Biester H, Müller G, Schöler HF (2002): Binding and mobility of mercury in soils contaminated by emissions from chlor-alkali plants. Sci Total Environ 284, 191–203

BUWAL (2004): Abfallmengen und Recycling 2003 im Überblick. Bundesamt für Umwelt, Wald und Landschaft, Bern

CEC (2003a): Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). European Parliament, Brussels

CEC (2003b): Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS). European Parliament, Brussels

Chirenje T, Rivero C, Ma LQ (2002): Leachability of Cu and Ni in wood ash-amended soil as impact by humic and fulvic acid. Geoderma 108, 31–47

Doka G (2003): Life cycle inventories of waste treatment services: Landfills – Underground deposits – Landfarming. ecoinvent report No. 13, Swiss centre for life cycle inventories, Dübendorf

Eberspächer J, Vogel H-J, Bettstetter C (2001): GSM Global System for Mobile Communication – Vermittlung, Dienste und Protokolle in digitalen Mobilfunknetzen. 3. Auflage, B.G. Teubner GmbH, Stuttgart, Leipzig, Wiesbaden

ecoinventCentre (2003): ecoinvent data v1.01. Swiss Centre for Life Cycle Inventories

Ekvall T, Finnveden G (2001): Allocation in ISO 14041 – A critical review. J Clean Prod 9, 197–208

ETSI (1996): Digital cellular telecommunications system (Phase 2+); Radio transmission and reception (GSM 05.05). European Telecommunications Standards Institute, Sophia Antipolis

Faist-Emmenegger M, Frischknecht R, Jungblut N (2003): LCA des Mobilfunksystems UMTS. ESU Services, Uster

Friedl&Partners (2001): China Mobile Phone Market Research Report. Friedl Business Information and Partners, Shanghai

Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Heck T, Hellweg S, Hischier R, Nemecek T, Rebitzer G, Spielmann M (2004): The ecoinvent Database: Overview and Methodological Framework. Int J LCA 10 (1) 3–9

Furuhjelm J, Yasuda Y, Trankell R (2000) Recycling of telecommunication products in Europe, Japan and USA. ERICSSON A.B., Stockholm

Goedkoop M, Spriensma R (2000): The Eco-indicator 99, A Damage Oriented Method for Life Cycle Impact Assessment, Methodology Report. 2nd ed., Pré Consultants B.V., Amersfoort

Grunewald A, Gustavsson J (1999): End-of-life Treatment of Radio Base Station Transceivers in Europe, Japan and the USA – A Life Cycle Assessment Study. TRITA-KET-IM 1999:25, Industrial Ecology Royal Institute of Technology/ Chemical Engineering Linköping Institute of Technology, Stockholm

GSMAssociation (2004): GSMA statistics Q2/04. GSM Association <http://www.gsmworld.com/news/statistics/pdf/gsma_stats_q2_04.pdf>

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Wegener Sleesewijk A, Suh S, Udo de Haes HA, de Brujin H, van Duin R, Huijbregts MAJ, Lindeijer EW, Roorda AAH, van der Ven BL, Weidema BP (2001): Life Cycle Assessment; An Operational Guide to the ISO Standards; Final Report, May 2001. Ministry of Housing, Spatial Planning and Environment (VROM) and Centrum voor Milieukunde (CML), Rijksuniversiteit, Den Haag and Leiden

Hartley W, Edwards R, Lepp NW (2004): Arsenic and heavy metal mobility in iron oxid-amended contaminated soils as evaluated by short- and long-term leaching tests. Environ Pollut 131, 495–504

HELCOM (2002): Land-based Pollution Group – 6h Meeting. Matters related to HELCOM, HELCOM HOD, other HELCOM Groups and HELCOM PITF, HELCOM, Vilnius

Hellweg S, Fischer U, Hofstetter TB, Hungerbühler K (2004): Site-dependent fate assessment in LCA: transport of heavy metals in soil. J Clean Prod (in press)

Humbert S, Margni M, Jolliet O (2004): IMPACT2002+: User Guide – Draft for version 2.0. Industrial Ecology & Life Cycle Systems Group, GECOS, Lausanne

IKP&PE (2003): GaBi4: Software und Datenbank zur Ganzheitlichen Bilanzierung. IKP Universität Stuttgart und PE Europe GmbH, Stuttgart

ISO (1998): ISO 14042: Environmental management – Life cycle assessment – Life cycle impact assessment. International Organisation for Standardisation, Brussels

Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003): IMPACT2002+: A new life cycle impact assessment methodology. Int J LCA 8 (6) 324–330

Lehner T (2001): Recovery of precious metals using plastics as reducing agent. Identi plast, Brussels

LucentTechnologies (2000): FLEXENT™ GSM Macrocell. Bell Labs, Wiltshire

LucentTechnologies (2001): Flexent™ OneBTS™ NodeB. Bell Labs, Wiltshire

Lumsdon DG (1996): Modelling cadmium retention by soils and the effects of aluminium competition. Appl Geochem 11, 285–291

Martínez CE, Motto HL (2000): Solubility of lead, zinc and copper added to mineral soils. Environ Pollut 107, 153–158

RANDA-GROUP (2000): Life Cycle Assessment of a Mobile Phone. Telefónica Servicios Móviles S.A.

Rinehart TL, Schulze DG, Bricka RM, Bajt S, Blatchley ER (1997): Chromium leaching vs. oxidation state for a contaminated solidified/stabilized soil. J Hazard Mater 52, 213–221

Rothus (2002): Nichtionisierende Strahlung. In: Umwelt Schweiz 2002 – Statistiken und Analysen. Bundesamt für Statistik, Neuchâtel, 189–195

Scharnhorst W (2003): Calculation of BTS rack elements

SiemensAG (2000): BS-240/BS-241 Base Transceiver Stations. Siemens AG, München

SiemensAG (2002): @vantage: UTRAN Product family – Equipment for 3G and Future Radio Networks. Siemens AG, Munich

Tanskanen P, Takala R (2001): Concept of a mobile terminal with active disassembly mechanism. NOKIA Research Centre, Helsinki

Uryu T, Yoshinaga J, Yanagisawa Y (2003): Environmental fate of gallium arsenide semiconductor disposal. J Ind Ecol 7 (2) 103–112

VSSV (2005): Information über Stahlrecycling in der Schweiz. *personal communication*, telephone call

Wang MC, Chen HM (2003): Forms and distribution of selenium at different depths and among particle size fractions of three Taiwan soils. Chemosphere 52, 585–593

Weidman E, Lundberg S (2001): Life Cycle Assessment of ERICSSON Third Generation Systems. ERICSSON A.B., Stockholm

Wilén P (2000): The RBS 2206-A flexible ticket to third generation wireless systems. Ericsson Review, Stockholm, 93–95

Wilson NJ, Craw D, Hunter K (2004): Antimony distribution and environmental mobility at an historic antimony smelter site, New Zealand. Environ Pollut 129, 257–266

Received: December 24th, 2004
Accepted: August 2nd, 2005
OnlineFirst: August 3rd, 2005

Appendices A, B, C <online only: http://dx.doi.org/10.1065/lca2005.08.216>

Appendix A: Technical specifications of the studied antenna rack

	GSM 900 Base transceiver station rack (BTS rack)
Rack specifications	
Weight [kg]	220.59
Size (w x h x d) [mm]	600 x 1800 x 450
Power consumption [kWh]	1.85
Rack device specifications	
Antenna connector units	
Number	4
Weight [kg] each	1.7696
Sub-components	Housing, Screws, PWB, Cable
Size (w x h x d) [mm]	50 x 300 x 200
Transceiver unit	
Number	12
Weight [kg]	2.31
Sub-components	Housing, Screws, PWB, Cable
Size (w x h x d) [mm]	50 x 300 x 400
Core basic modules	
Number	4
Weight [kg]	2.0605
Sub-components	Housing, PWB, Cable
Size (w x h x d) [mm]	50 x 300 x 200
Cables	
Length [m]	20
Mass [kg]	7.5496
Typical material	PVC, Copper wire
Rack housing	
Weight [kg]	170
Typical material	Steel, Aluminium
Size (w x h x d) [mm]	see rack specifications above

Appendix B: Overview on EOL modules and the major processes they consist of

EOL stages												
	Master processes	**EOL processes**										
		Electricity (UCTE mix) [MJ/kg]	**Energy**			**Additives**				**Building infrastructure [m^2/kg]**	**EOL treatment facilities / tools [–/kg]**	**Transport mix (lorry, incl. fuel supply) [kg/kg]**
			Crude oil [kg/kg]	**Hard coal [kg/kg]**	**Natural gas burned in industrial furnace) [MJ/kg]**	**Lubricating oil [kg/kg]**	**Oxygen (liquid) [kg/kg]**	**Lime-stone [kg/kg]**	**Hard coal dust [kg/kg]**			
Rack dismounting	Dismounting	0.001259										
Rack service	Storage	0.005961			0.002483					8.27999E-6		0.0061568
Rack de-housing[1]	De-housing	5.2784E-7								1.95498E-11		0.0098509
Rack pre-separation	Pre-separation	0.000776			0.000310							0.0098509
Rack component dismantling	Dismantling	0.000517			0.000207							
Rack component fractionation	Cross-flow machining	0.0025				2.5E-6				4.49E-04[2]	3.96E-10	
	Magnetic separator	0.0002				3.1E-6				2.23E-06[1]	4.96E-10	
	Cut mill	0.000792				2.5E-6				2.16E-06[1]	3.96E-10	
	Standard cone sifter	0.000792				2.5E-6				2.42E-06[1]	3.96E-10	
	Sift table	0.000144				2.5E-6				2.95E-06[1]	3.96E-10	
Material recovery	Kaldo smelter	0.5054	2.96E-03	0.01373	0.000134		1.23E-04	6.15E-4	6.15E-4	1.10E-05[3]	4.920E-11	0.0288
	Aisle converter	0.5054	2.96E-03	0.01373	0.000134					2.03E-05[2]	2E-7	
	Anode casting plant	0.5054	2.96E-03	0.01373	0.000134					1.00E-04[2]	2E-7	
	Electrolytic refinement plant	0.5054	2.96E-03	0.01373	0.000134					8.93E-05[2]	2E-7	
	Precious metal plant	0.5054	2.96E-03	0.01373	0.000134					5.12E-02[2]	3.33E-7	
Material incineration	Incineration										5.5E-10	0.00985
Material landfilling	Landfilling										5.5E-10	0.00985

[1] Belongs to the EOL stage Rack service, but has been denoted here for clarification
[2] Base material mix the infrastructure is made of [kg/kg]
[3] Base material mix the infrastructure is made of [kg/kg]

Appendix C1: Transfer coefficients applied to rack landfill processes

The assumption of complete metal leaching (TC = 1) was adopted from ecoinvent (Doka 2003) for nearly all metals. In some special cases, reduced TCs were applied. Those reduced TCs were applied either as literature suggests the application of those values or as otherwise unreasonable results were obtained. All transfer coefficients equal to one (TC = 1) were subject to sensitivity analysis. The original values were replaced by 0.5 and 0.1, respectively. The reduced values did not change the results of the impact assessment.

Chemical element	Overall transfer coefficient (TC) for the landfill site
Ag	1
Al	1
As	0.5
Au	1
Be	1
Bi	1
Br	1
Cd	1
Cl	1
Co	1
Cr	0.9
Cr VI+	0.1
Cu	1
Eu	1
Fe	1
Ga	1
Ge	1
Hg	1
In	1
Mn	1
Na	1
Ni	1
Pb	1
Pd	1
Pt	1
Ru	1
Sb	1
Se	1
Si	1
Sn	1
Th	1
Zn	1

Appendix C2: Transfer fractions applied to rack landfill processes

The transfer fractions applied to the overall emissions released during the rack landfill process are compiled below. Most of the values were estimated based on general chemical and physical element properties and on the environmental conditions prevailing in a landfill site. Swiss soil conditions were used to define the landfill conditions (Hellweg et al. 2004). Some transfer fractions were estimated based on more detailed background information on their behaviour under landfill conditions found in the literature. The corresponding references are given in the table. The values compiled represent average data.

Several of the fractions that belong together, e.g. cadmium, have fractions not equal to one. This indicates that not all of the cadmium released was bio available, but that a certain fraction is either retained in the soil matrix or has no detectable environmental impact.

To specify the individual emission paths and the fractions of the specific total emissions released to that paths the transfer fractions were multiplied by the above given transfer coefficients and the respective total emissions.

Emission path (to air, soil and water)	Fraction	Comments/ References
Ag_air	0.05	estimated value;
Ag_soil	0.3	estimated value;
Ag_wat	0.65	estimated value;
Al_air	0.05	estimated value; small transfer to air
Al_soil	0.3	based on (Lumsdon 1996)
Al_wat	0.25	based on (Lumsdon 1996)
As_air	0.1	estimated value;
As_soil	0.3	based on (Hartley et al. 2004)
As_wat	0.6	based on (Hartley et al. 2004)
Au_air	0.01	estimated value;
Au_soil	0.24	estimated value;
Au_wat	0.75	estimated value;
Be_air	0.05	estimated value;
Be_soil	0.4	estimated value;
Be_wat	0.55	estimated value;
Bi_air	0.01	estimated value;
Bi_soil	0.44	estimated value;
Bi_wat	0.55	estimated value;
Br_air	0.1	estimated value;
Br_soil	0.2	estimated value;
Br_wat	0.7	estimated value;
Cd_air	0.05	estimated value; small transfer to air
Cd_soil	0.45	based on (Lumsdon 1996)
Cd_wat	0.35	based on (Lumsdon 1996)
Cl_air	0.24	estimated value;
Cl_soil	0.3	estimated value;
Cl_wat	0.46	estimated value;
Co_air	0.01	estimated value;
Co_soil	0.24	estimated value;
Co_wat	0.75	estimated value;
Cr_air	0.05	estimated value; small transfer to air
Cr_soil	0.35	based on (Rinehart et al. 1997)
Cr_wat	0.25	based on (Rinehart et al. 1997)
Cr_VI_air	0.005	estimated value; small transfer to air
Cr_VI_soil	0.25	based on (Rinehart et al. 1997)
Cr_VI_wat	0.7	based on (Rinehart et al. 1997)
Cu_air	0.05	estimated value; small transfer to air
Cu_soil	0.45	based on (Hartley et al. 2004)
Cu_wat	0.35	based on (Hartley et al. 2004)
Eu_air	0.1	estimated value;
Eu_soil	0.3	estimated value;
Eu_wat	0.6	estimated value;
Fe_air	0.01	estimated value;
Fe_soil	0.14	estimated value;
Fe_wat	0.85	estimated value;
Ga_wat	0.7	estimated value;
Ge_air	0.01	estimated value;
Ge_soil	0.65	estimated value;
Ge_wat	0.34	estimated value;
Hg_air	0.12	estimated value; partly transfer to air
Hg_soil	0.55	based on (Biester et al. 2002)
Hg_wat	0.33	based on (Biester et al. 2002)
In_air	0.01	estimated value;
In_soil	0.65	estimated value;
In_wat	0.34	estimated value;
Mn_air	0.05	estimated value;
Mn_soil	0.35	estimated value;
Mn_wat	0.6	estimated value;
Na_air	0.3	estimated value;
Na_soil	0.1	estimated value;
Na_wat	0.6	estimated value;
Ni_air	0.01	estimated value; small transfer to air
Ni_soil	0.55	based on (Chirenje et al. 2002)
Ni_wat	0.14	based on (Chirenje et al. 2002)
Pb_air	0.01	estimated value; small transfer to air
Pb_soil	0.34	based on (Hartley et al. 2004, Hellweg et al. 2004)
Pb_wat	0.2	based on (Hartley et al. 2004, Hellweg et al. 2004)

Appendix C2 (*cont'd*)

Emission path (to air, soil and water)	Fraction	Comments/ References
Pb_air	0.01	estimated value; small transfer to air
Pb_soil	0.34	based on (Hartley et al. 2004, Hellweg et al. 2004)
Pb_wat	0.2	based on (Hartley et al. 2004, Hellweg et al. 2004)
Pd_air	0.04	estimated value;
Pd_soil	0.36	estimated value;
Pd_wat	0.6	estimated value;
Pt_air	0.01	estimated value;
Pt_soil	0.34	estimated value;
Pt_wat	0.65	estimated value;
Ru_air	0.05	estimated value;
Ru_soil	0.35	estimated value;
Ru_wat	0.6	estimated value;
Sb_air	0.05	estimated value; small transfer to air
Sb_soil	0.75	based on (Wilson et al. 2004)
Sb_wat	0.2	based on (Wilson et al. 2004)

Appendix C2 (*cont'd*)

Emission path (to air, soil and water)	Fraction	Comments/ References
Se_air	0.05	estimated value; small transfer to air
Se_soil	0.65	based on (Wang et al. 2003)
Se_wat	0.3	based on (Wang et al. 2003)
Si_air	0.05	estimated value;
Si_soil	0.85	estimated value;
Si_wat	0.1	estimated value;
Sn_air	0.01	estimated value;
Sn_soil	0.34	estimated value;
Sn_wat	0.65	estimated value;
Th_air	0.01	estimated value;
Th_soil	0.29	estimated value;
Th_wat	0.7	estimated value;
Zn_air	0.01	estimated value; small transfer to air
Zn_soil	0.65	based on (Hellweg et al. 2004, Martínez et al. 2000)
Zn_wat	0.24	based on (Hellweg et al. 2004, Martínez et al. 2000)

Appendix C3: Transfer coefficients applied to rack incineration processes

It was assumed that high quality filter techniques were applied to retain metals posing critical environmental impacts. Larger transfer coefficients indicate that the respective elements are highly volatile and are only partly retained by the filter technique applied. All other elements were assumed to be retained in the slag transferred finally to the landfill site.

Chemical element	Overall transfer coefficient (TC) for the incineration site	Comments
Ag	0.01	assumed to be retained
Al	0.2	some aluminium particles leave the incinerator
As	0.3	volatile
Au	0.01	assumed to be retained
Be	0.75	volatile
Bi	0.01	assumed to be retained
Br	0.75	volatile
Cd	0.5	volatile
Cl	0.75	volatile
Co	0.01	assumed to be retained
Cr	0.01	assumed to be retained
Cr VI+	0.1	volatile
Cu	0.1	some copper particles leave the incinerator
Eu	0.01	assumed to be retained
Fe	0.01	assumed to be retained
Ga	0.2	some gallium particles leave the incinerator
Ge	0.01	assumed to be retained
Hg	0.75	volatile
In	0.01	assumed to be retained
Mn	0.1	some manganese particles leave the incinerator
Na	0.5	volatile
Ni	0.1	some nickel particles leave the incinerator
Pb	0.2	some lead particles leave the incinerator
Pd	0.01	assumed to be retained
Pt	0.01	assumed to be retained
Ru	0.01	assumed to be retained
Sb	0.2	some antimony particles leave the incinerator
Se	0.01	assumed to be retained
Si	0.2	some silicon particles leave the incinerator
Sn	0.01	assumed to be retained
Th	0.01	assumed to be retained
Zn	0.01	assumed to be retained

Appendix C4: Transfer fractions applied to rack incineration processes

Below, the transfer fractions applied to the overall emissions released during the rack incineration process are compiled. The fractions were multiplied with the above given transfer coefficients and the respective emissions inventoried. As no information was found on the fractionation of the emissions released during the rack incineration process, all values were estimated based on general chemical and physical element properties, and of the environmental conditions prevailing in a municipal waste incineration oven. The values compiled represent average data.

Emission path	Fraction	Comments
Ag_air	0.9	estimated value
Ag_soil	0.05	estimated value
Ag_wat	0.05	estimated value
Al_air	0.95	estimated value
Al_soil	0.025	estimated value
Al_wat	0.025	estimated value
As_air	0.99	estimated value
As_soil	0.005	estimated value
As_wat	0.005	estimated value
Au_air	0.4	estimated value
Au_soil	0.4	estimated value
Au_wat	0.2	estimated value
Be_air	0.9	estimated value
Be_soil	0.05	estimated value
Be_wat	0.05	estimated value
Bi_air	0.1	estimated value
Bi_soil	0.8	estimated value
Bi_wat	0.1	estimated value
Br_air	0.9	estimated value
Br_soil	0.05	estimated value
Br_wat	0.05	estimated value
Cd_air	0.8	estimated value
Cd_soil	0.15	estimated value
Cd_wat	0.05	estimated value
Cl_air	0.5	estimated value
Cl_soil	0.1	estimated value
Cl_wat	0.4	estimated value
Co_air	0.1	estimated value
Co_soil	0.6	estimated value
Co_wat	0.3	estimated value
Cr_air	0.2	estimated value
Cr_soil	0.7	estimated value
Cr_VI_air	0.6	estimated value
Cr_VI_soil	0.3	estimated value
Cr_VI_wat	0.1	estimated value
Cr_wat	0.1	estimated value
Cu_air	0.1	estimated value
Cu_soil	0.8	estimated value
Cu_wat	0.1	estimated value
Eu_air	0.1	estimated value
Eu_soil	0.7	estimated value
Eu_wat	0.2	estimated value
Fe_air	0.1	estimated value
Fe_soil	0.6	estimated value
Fe_wat	0.3	estimated value
Ga_air	0.2	estimated value
Ga_soil	0.4	estimated value
Ga_wat	0.4	estimated value
Ge_air	0.1	estimated value
Ge_soil	0.7	estimated value
Ge_wat	0.2	estimated value
Hg_air	0.99	estimated value
Hg_soil	0.005	estimated value
Hg_wat	0.005	estimated value
In_air	0.1	estimated value
In_soil	0.6	estimated value
In_wat	0.3	estimated value
Mn_air	0.1	estimated value
Mn_soil	0.6	estimated value
Mn_wat	0.3	estimated value
Na_air	0.4	estimated value
Na_soil	0.1	estimated value
Na_wat	0.5	estimated value
Ni_air	0.1	estimated value
Ni_soil	0.6	estimated value
Ni_wat	0.3	estimated value
Pb_air	0.1	estimated value
Pb_soil	0.6	estimated value
Pb_wat	0.3	estimated value
Pd_air	0.1	estimated value
Pd_soil	0.6	estimated value
Pd_wat	0.3	estimated value
Pt_air	0.1	estimated value
Pt_soil	0.7	estimated value
Pt_wat	0.2	estimated value
Ru_air	0.1	estimated value
Ru_soil	0.6	estimated value
Ru_wat	0.3	estimated value
Sb_air	0.2	estimated value
Sb_soil	0.6	estimated value
Sb_wat	0.2	estimated value
Se_air	0.1	estimated value
Se_soil	0.7	estimated value
Se_wat	0.2	estimated value
Si_air	0.3	estimated value
Si_soil	0.4	estimated value
Si_wat	0.3	estimated value
Sn_air	0.1	estimated value
Sn_soil	0.6	estimated value
Sn_wat	0.3	estimated value
Th_air	0.1	estimated value
Th_soil	0.6	estimated value
Th_wat	0.3	estimated value
Zn_air	0.1	estimated value
Zn_soil	0.7	estimated value
Zn_wat	0.2	estimated value