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The end of life treatment of second generation mobile phone networks: Strategies to reduce the environmental impact

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Abstract

A life cycle assessment was carried out based on a detailed life cycle inventory for a typical GSM 900 mobile phone network and related *E*nd *o*f *L*ife (EOL) treatment infrastructure. The environmental relevance of the three life cycle phases: production, use and EOL treatment was analysed using IMPACT2002+. The environmentally preferable EOL treatment alternative was identified on the basis of six previously developed EOL treatment scenarios.

The results indicate that the environmental impacts attributable to the use phase dominate the environmental impacts incurred over the entire life cycle of the network. The impacts of the production phase are primarily attributable to the energy intensive manufacturing of printed wiring boards (PWB). The EOL phase dominates the impacts on ecosystem quality. In particular the long-term emissions of heavy metals have critical effects. Detailed analysis of the EOL phase shows that recycling of network materials in general leads to a two fold reduction of environmental impacts: in the EOL phase itself as well as by means of the avoided primary production of materials recovered in

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the EOL phase. An increase in the material quality of the secondary precious and rare materials leads to a significant reduction in the impacts on human health.

Keywords: LCA; End of life scenarios; Waste management; Recycling benefit; Value correction factor; Mobile phone network

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1. Introduction

Mobile telephony, today an indispensable service facilitating every-day life, has experienced a tremendous increase in penetration since the implementation of the innovative Global System for Mobile communication (GSM) standard in the early 1990's. Expressed in today's figures: more than 1.32 billion GSM subscribers (GSM world 2005) are connected to 626 GSM networks operated in presently 198 countries worldwide (GSMAssociation, 2004). Numerous further countries, in particular in the Latin-American and in the Asian-Pacific regions have just started the implementation of second generation (2G) mobile phone networks such as GSM networks (GSMAssociation, 2004). Forecasts on the evolution of the third generation (3G) *U*niversal *M*obile *T*elecommunication *S*ystems (UMTS) standard predict growth rates in networks and subscribers similar to those achieved with the GSM standard. If realistic, this progression would lead to about 500 million mobile phone users in 2010 in China alone (Friedl and Partners, 2001).

Closely associated with these trends is a fast-growing amount of mobile phone network infrastructure as well as subscriber equipment that need to be replaced. This is due to the fact that the different network components either no longer meet technical requirements or have reached their physical *E*nd *o*f *L*ife (EOL) due to damages or defects.

In recent years, national governmental authorities, manufacturers, operators and recyclers have discovered more and more adverse environmental implications caused by the processing of network components as well as by improper EOL treatment. Restrictive regulations seek to prevent the dumping of valuable electronic scrap and aim to increase the recycling rates of electronic devices (CEC, 2003a). Supporting regulations prohibit the usage of several materials thought to be environmentally toxic (CEC, 2003a,b). In order to meet the regulation requirements and to reduce the overall environmental impacts of mobile phone networks, manufacturers have endeavored to replace environmentally critical materials. Recyclers have updated their EOL treatment processes constantly to meet the latest environmental requirements. However, several major issues have not been addressed sufficiently yet:

a) The regulations on environmentally safe EOL treatment methods and emissions caused by processing the scrap are not consistent world wide.
b) The environmental impacts related to the EOL treatment of entire mobile phone networks have not yet been quantified from a life cycle perspective.
c) The implications of the increased amount of network scrap to be treated due to the change-over from 2G to 3G networks have not thus far been studied.

Current and forthcoming governmental regulations require a sound understanding of the environmental performance of mobile phone network components during their EOL phases. The potential benefits need to be known in order to provide incentives for processing network scrap in appropriate EOL treatment systems.

Several studies have concentrated on the life cycle assessment of mobile phones (RANDA-GROUP, 2000; Singhal, 2005) and networks (Faist-Emmenegger et al., 2004; Weidman and Lundberg, 2001). For individual network components, e.g. transceiver units built in antenna racks, a few simple EOL scenarios have been investigated (Furuhjelm et al.; Grunewald and Gustavsson, 1999). Tanskanen and Takala demonstrated a practical approach to reduce the environmental impact of the EOL phase of a network component (Tanskanen and Takala, 2001).

However, most of the studies lack a reliable modelling of the EOL phase with respect to emissions, emission paths and emission sources. The environmental benefits of recuperating materials from scrap through sound EOL treatment have not yet been estimated. Likewise the relative environmental importance of the EOL phase has not been compared in depth with the impacts of the other phases. In a previous study, we analysed the environmental impact caused by the EOL phase of a single GSM 900 network component (Scharnhorst et al., 2005).

In the study presented here, the environmental impacts caused by the overall life cycles of all major network components of a typical GSM 900 network were investigated. The environmental impacts caused in the EOL phase were studied in detail.

In order to assess the relative importance of the EOL phase, the environmental impacts related to this phase were compared with the environmental impacts caused by the other life cycle phases. Six different EOL treatment scenarios, varying from direct disposal excluding any material recycling from electronic scrap to current state-of-the-art EOL treatment techniques, were adopted from a previous study (Scharnhorst et al., 2005) in order to compare the environmental benefits of different possible recycling strategies. The IMPACT2002+ method (Jolliet et al., 2003) was used to assess environmental impacts.

In conformance with the ISO14040 series (ISO, 1998) this paper is structured in goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. It concludes with a discussion and recommendations to concerned actors.

2. Goal and scope

2.1. Study objective

The goal of the study reported here is

- to identify the relative importance of the EOL phase of a mobile phone network compared with the other life cycle phases,
- to identify the environmental benefits attributable to different recycling strategies,
- to determine the network component that has the greatest impact from a life cycle perspective,

- to identify an environmentally preferable combination of the EOL treatment processes currently in use for a generic GSM 900 mobile phone network, and
- to specify environmentally critical EOL treatment processes and materials causing critical impacts in these processes.

The study was carried out applying the *P*rocess *L*ife *C*ycle *A*ssessment (PLCA) method. The results are intended to deepen the understanding of the environmental consequences related to the processing of mobile phone network scrap and to formulate recommendations how to reduce environmental impacts in the production and the EOL phase. The outcome is also meant to support the decision making of network operators, network component manufacturers as well as recyclers.

2.1.1. Functional unit and reference flow

The transmission of 1 data bit from one mobile phone to another one within a representative GSM 900 network was selected as functional unit. One bit transmitted represents the reference flow.

2.1.2. Data requirements

The following data requirements are set:

- representative for Switzerland and Western Europe,
- representative for the year 2000.

2.1.3. System boundaries

The system under study consists of all life cycle phases of a representative GSM 900 mobile phone network (Fig. 1). The EOL phase of the network is modelled in detail. The network is assumed to be operated at the maximum possible data transmission rate (9600 bit/s). This assumption was chosen for a lack of data for the average transmission rate, even though it implies an overestimation of the use phase. Maintenance and repair services are not included.

The EOL phase of a network component begins with the dismounting of the respective device from the network and ends with the final output of the secondary raw material production and/or the final disposal (incineration or landfilling) of waste products (Fig. 1). The EOL phase is further subdivided into final disposal processes (incineration of waste, by-products) and recovery processes (pre-separation, dismantling, shredding, fractionation, material recovery, secondary raw material production). In order to represent the effect of the potentially limited range of application of secondary raw materials compared to virgin (primary) materials, different value correction factors were applied whenever secondary materials from recycled electronic scrap were substituted for primary materials (Werner, 2002).

In order to depict the environmental benefits attributable to the adoption of more or less advanced recycling strategies, the six EOL treatment scenarios developed in Scharnhorst et al. (2005) were adopted (see Table 1). Substitution of metal output of the recycling for metal inputs in the production phase was modelled to study the environmental consequences of the different EOL scenarios. The substitution of energy

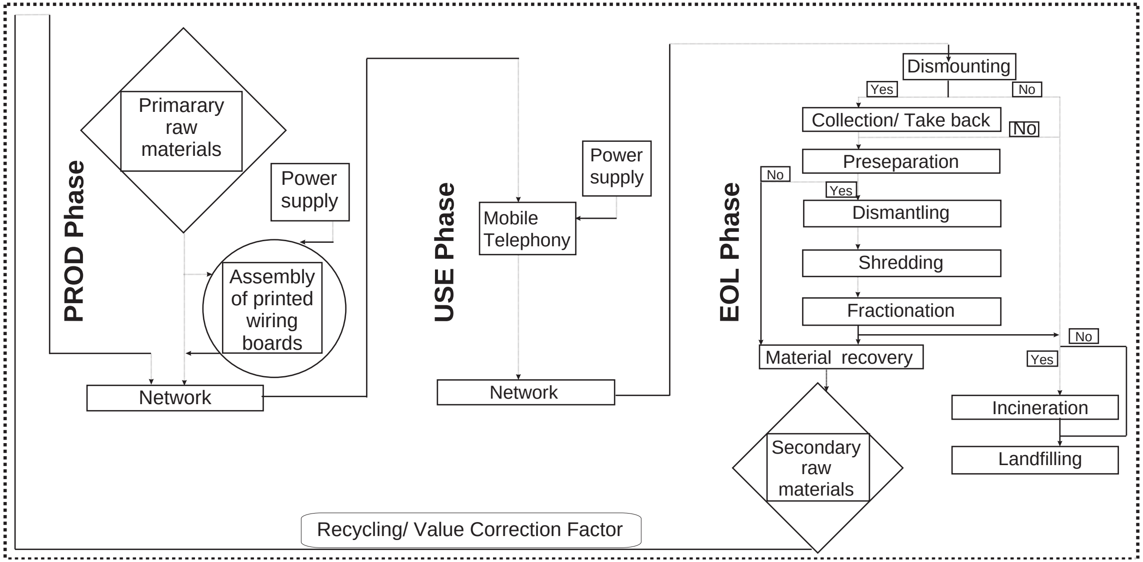

Fig. 1. Flow chart and system boundaries of the life cycle phases of the mobile phone network studied.

Table 1
The scenarios used for modelling the EOL phase (Scharnhorst et al., 2005)

Scenario no.	Description Treatment after dismounting from the network	Recycling rate for aluminium and steel of masts and housings	Recycling rate for precious and rare materials of electronic devices
0	Landfilling	85%	0
1	Collection, storage, and landfilling	85%	0
2	Incineration and subsequent landfilling	85%	0
3	Pre-treatment and material recovery and recycling (by-products/residuals are incinerated and finally landfilled)	85%	85%
4	Pre-treatment, fractionation and material recovery and recycling (by-products are directly landfilled)	85%	85%
5	Pre-treatment, fractionation and material recovery and recycling (by-products are incinerated and then landfilled)	85%	85%

recovered in EOL for energy demand in the production phase was not modelled because its impact in the given context is negligible. The environmental impacts of the use phase were assumed to be identical for each of the scenarios. Therefore the use phase has been excluded from the presentation of the results of the EOL scenario analysis.

Scenarios 0–2 represent the recovery of aluminium and steel from network components other than the switching elements and mobile phones, e.g. the steel of the BTS masts, housings, etc. The technical recycling rate for these materials is assumed to be 85% (BDSV, 2001). Fifteen percent are lost in the recovery processes and disposed of. A value correction of 85% is assumed due to downcycling in the processes. Scenarios 0–2 do not contain materials recycled from the scrap of switching network elements such as mobile phones, BTS racks, etc. The recycling rate equals 0% and thus 100% primary materials need to be produced for these network elements.

Scenarios 3–5 represent the recovery of materials, i.e. of metallic materials, switching elements and mobile phones. All electronic components of the switching network units (BTS, BSC, and MSC) and 80% of the mobile stations (MS) collected by the recyclers, are put through recycling processes. Plastic materials are separated and processed in *M*unicipal *S*olid *W*aste *I*ncineration plants (MSWI). Residues from incineration are finally landfilled. Twenty percent of the MS is assumed to be incinerated in MSWI and their residues finally landfilled. In Scenario 3 all precious metals containing electronic components are processed immediately in a facilitated material recycling plant. All residuals and by-products are processed in MSWI and finally landfilled. Scenarios 4–5 include an advanced fractionation of the electronic scrap into a ferrous-and a non-ferrous metal fraction and a plastic fraction prior to material recycling/secondary raw material production. In Scenario 4 the residuals of the secondary raw material production are directly landfilled and in Scenario 5 the residuals are first incinerated and the ash is landfilled.

A sensitivity analysis was performed varying the value correction factor in order to determine the effect of quality variations of secondary raw materials recovered from electronic scrap on the overall environmental profile of the network. Based on the results, the amount of secondary raw materials (expressed by the value correction factor) that are substituted for primary raw materials were defined (see Figs. 3–6. For Scenarios 3–5 a value correction factor of 85% for precious and rare metals was chosen. The remaining 15% of raw metals were provided by primary raw materials.

2.1.4. Allocation

Allocation based on physical properties (Ekvall and Finnveden, 2001) was applied to the foreground system (e.g. shredder use is allocated to mass of treated scrap).

2.1.5. Impact assessment

The IMPACT2002+ method (Jolliet et al., 2003) was used to determine the environmental impacts related to the emissions released and resources consumed in the system under study. This impact assessment method covers more impact categories than other methods and includes more substances.

This method links the emissions and resource consumptions compiled in the life cycle inventory to so-called midpoint categories representing their environmental impacts as effect scores of various reference substances. These scores are linked to damage categories (endpoints) representing the impacts on human health, ecosystem quality, climate change and resources, respectively (Humbert et al., 2004).

In order to enable us 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 endpoint level.

2.1.6. Interpretation and weighting

The results of the impact assessment were interpreted for each impact category. No normalisation or weighting, and thus no total aggregation was applied.

2.1.7. Review process

The collection of the data and the modelling of the entire life cycle of the network were subject to internal peer review performed among the authors.

2.2. Study objects

2.2.1. Mobile phone network

The GSM 900 network analysed is representative for mobile phone networks of this standard, as they are presently operated in Western Europe (Fig. 2). According to the GSM standard, mobile phone networks are separated into three subsystems: the *N*etwork *S*witching *S*ubsystem to which the *M*obile *S*witching *C*entres (MSC) belongs, the *B*ase *S*tation *S*ubsystem to which the *B*ase *S*tation *C*ontroller (BSC) and the *B*ase *T*ransceiver

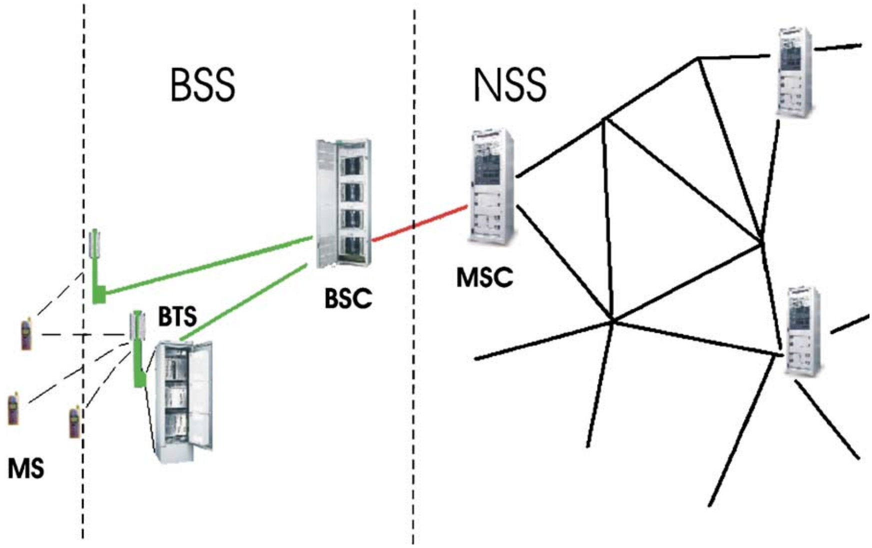

Fig. 2. Structure of a typical GSM mobile phone network. The three subsystems (the user subsystem, the Network Switching Subsystem, NSS, and the Base Station Subsystem BSS, including the network components according to the GSM standard, are shown. The core electronic equipment of each major network component (i.e. MS, BTS rack, BSC rack, MSC rack) is depicted.

*S*tations (BTS) belong, and finally the user subsystem to which the *M*obile *S*tations (MS) including the *S*ubscriber *I*dentity *M*odules (SIM) belong. The network analysed in the study is assumed to be operated in the 900 MHz range.

2.2.1.1. Mobile stations. The mobile phones, or mobile stations (MS) in GSM terms, are user-owned telephonic devices able to send and receive data simultaneously. Mobile stations are connected to base transceiver stations (BTS) via the air interface. A typical MS weighs about 100 g and is composed of a keyboard, a battery, an LCD, an antenna and a PWB. Three types of batteries are in use today: (i) nickel–cadmium batteries (MS NICD), (ii) nickel-metal hydride batteries (MS NIMH) and (iii) lithium-ion batteries (MS LIIO). Nickel–cadmium batteries are being deployed less and less. Lithium-ion batteries have recently had their breakthrough.

2.2.1.2. Base transceiver stations (antenna station). Antenna stations, or base transceiver stations (BTS) in GSM terms, represent the interface between the mobile stations and the stationary part of the mobile phone network. A BTS typically consists of the following elements:

- a cabinet housing
- three to four antenna racks;
- a set of back-up batteries (typically lead accumulator batteries), and
- an antenna mast, bearing the
- radiating units.

The allocation of radio channels and the exchange of data with both the subscriber and the network are the core functions of the BTS. There are different hardware configurations and operation modes of the antenna racks deployed in BTS. The operation mode shown in Table 2 is assumed to be applied in the investigated network. It determines the necessary hardware configuration (Bekkers and Smits, 1997; Eberspächer et al., 2001).

2.2.1.3. Base station controllers. Typically about 100 BTS are connected with and controlled by a single base station controller (BSC). This network component can be seen as a major switch allocating radio resources to the different BTS and managing the handover procedures (Duque-Antón, 2002). Typically a BSC consists of up to four racks containing the switching electronic equipment.

2.2.1.4. Mobile switching centres. A mobile switching centre (MSC) typically controls 1–2 BSC connected to it. One of its main tasks is to route the different services such as phone calls, text messages and faxes, etc. (Duque-Antón, 2002). From a technical perspective, the MSC represents an ISDN switch and connects mobile phone networks to each other as well as mobile phone networks to fixed networks. Typically a MSC consists of at least four racks containing the various switching units.

2.2.2. Life cycle phases and EOL stages

2.2.2.1. Production phase. The production phase of a mobile phone network component starts with the extraction of ores and energy sources and ends as the network component assembly is finalised and the component is ready for use. The production phase consists of the following major steps:

- Extraction of raw materials such as ores and their processing to basic materials such as metal alloys, ceramics or plastics.
- Manufacturing of basic network component parts such as cables, shelves or PWBs.
- Assembly of network component sub-units such as transceivers, servers or fans.
- Final assembly of the network component, e.g. an antenna rack.

Table 2
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

These specifications determine the hardware design.

2.2.2.2. Use phase. This phase follows the production phase and begins with the local installation of the network component and its integration into the network structure. In the course of the further operation the component is used for the services it is designed for. This phase also includes maintenance such as periodical services and updates as well as the repair of defective network components or component devices (e.g. transceiver, etc.).

2.2.2.3. EOL phase. The EOL phase begins with the dismounting of a network component that has come to the end of its service life. The EOL phase of a mobile phone network component can be divided into eight major stages: dismounting, collection and storage, pre-separation, dismantling, fractionation, material recovery and production of secondary raw materials, thermal treatment, and final disposal. Thermal EOL treatment processes have different functions: (i) compaction of scrap, (ii) extraction of energy and (iii) extraction of secondary raw materials.

In order to analyse the environmental implications of different EOL treatment strategies, the EOL scenarios described in (Scharnhorst et al., 2005) were adopted and the following parameters were varied:

- the share of network components that go directly to incineration/final disposal, the other components being processed in recycling facilities, and
- the value correction factor.

3. Life cycle inventory—data description

3.1. Study objects

The compilation of inventory data, the modelling of the networks life cycle and the scenario assembly were carried out using the GaBi4 software (IKP and PE, 2003). For the background system, cumulative datasets provided by the Swiss national database for life cycle inventories—ecoinvent v1.01 (ecoinventCentre, 2003)—were adopted. Transport processes[1] were modelled using the relevant data sets included in the GaBi4 database (IKP and PE, 2003).

3.1.1. Mobile phone network

i. Network modelling: A representative GSM 900 network was modelled based on the technical network component specifications of (LucentTechnologies, 2000; 2001; SiemensAG, 2000). The network modelled represents Swiss conditions (Bambrilla, 2004; SunriseAG, 2005). The maximum possible bit transmission rate was assumed for the operation of mobile phones and the other network elements. The network component devices such as connectors, filters, transceiving units or servers were approximated from the basic materials of which they are made.

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[1] i.) Klein-Transporter / 3,5 t zul.GGW / 2t NL / Nah, ii.) LKW-Zug / 38t zul.GGW / 26t NL / Fern.

ii. Data collection: Technical data as well as information on the component compositions were compiled from the original component data sheets published by manufacturers (ERICSSON, 2003; LucentTechnologies, 2000, 2001). Supplementary information was compiled from manufacturers' Websites (LucentTechnologies, 2005) and from relevant books (Bekkers and Smits, 1997; Duque-Antón, 2002). Network infrastructure information such as overall network architecture, operation modes, etc. was obtained from network operators (SunriseAG, 2005) and from related literature (Scoullos et al., 2001). Technical data on individual network component devices such as transceivers and servers were collected from technical specification sheets (SiemensAG, 2002). Some of such data were determined by the author. Mass balance data, i.e. qualitative and quantitative information on the specific materials the component sub-units are made of, were partly adopted from the literature and partly determined empirically.

iii. Data quality, validity, assumptions and limitations: The network data compiled for the investigation are valid for Western Europe and may not hold for other regions. The network components inventoried correspond to the GSM 900 standard valid for the period from 1999 to 2002 and refer to 2G specifications (ETSI, 1996a; ETSI, 1996b; ETSI, 1998). The network components of the base station subsystem (BTS, BSC) and of the network switching system (MSC) were assumed to be configured for indoor use. The components were fully equipped, i.e. there was no room for component expansion. The specifications adopted do not hold for outdoor configurations. Replacement of component devices such as transceivers, servers, fans or any other unit was not envisaged during component operation time. The network components analysed in the study represent generic network elements and do not correspond to any existing network component type. The data compiled corresponds to the data requirements given above.

3.1.2. Production, use and EOL system

i. Life cycle modelling: The life cycle of the entire mobile phone network was divided into the production, the use and the EOL phase. The production phase covers the extraction processes of raw materials and their further processing into wires, sheet metal, etc. It also includes the energy consumed for the fabrication of PWBs. Secondary raw materials produced in the EOL phase were assumed to act as partial substitutes for primary raw materials in the production phase. The assembly of the network components (e.g. transceivers, filters, etc.) and the installation of the network was not modelled. In the use phase only the energy consumed to operate the network was considered. Maintenance services were excluded. The EOL phase was split up into consecutive stages as described. Each of the stages includes substages representing the different EOL treatment processes (Scharnhorst et al., 2005). These processes include the EOL treatment infrastructure needed in the respective stage and energy supply.

ii. Data collection: Information on the basic materials the network components consist of was taken from Goosey and Kellner (2002), Ludwig et al. (2003) and Conrad (2000). Information on the production of PWBs was gathered from the literature (Kincaid and Geibig, 1998; Malmodin et al., 2001). For the use phase information on the power consumption of the switching network components was adopted from manufacturer data sheets (SiemensAG, 2000). Energy consumption data of the mobile phones was estimated by the author. Information on the dismounting and storage of network components was obtained from manufacturers (Hausammann, 2005). Transport distances in the EOL phase were estimated based on the regional distribution of the network components and of the EOL treatment facilities in Switzerland. Information on the processing of network components (pre-treatment, fractionation, etc.) after dismounting was partly obtained from recyclers (Stengele, 2004) and partly from literature (Ludwig et al., 2003). Technical specifications of the recycling facilities were compiled from manufacturer data sheets (BückmannGmbH, 2001a,b,c). Most process data were adopted directly from the ecoinvent database (v1.01) (ecoinventCentre, 2003). Transport process data were adopted from the GaBi4-data base (IKP and PE, 2003). Most data for incineration and final disposal processes were adapted from the ecoinvent database, based on closely related processes (Scharnhorst et al., 2005). Transfer coefficients and transfer fractions for incineration and landfill processes were adopted from Scharnhorst et al. (2005). Detailed inventory information is given in Scharnhorst et al. (2005).

iii. Data quality, validity, assumptions and limitations: The data adopted for the analysis is applicable to Western European conditions and may not hold outside that region. Also, the data are valid for the time periods indicated below and may not be applicable in other time periods. The energy consumption data for the manufacturing of PWBs is valid for 1998. Data on the energy consumption in the use phase is valid for 1999 through 2005. The data for the EOL stages pre-treatment, dismantling and fractionation represent Swiss conditions between 2000 and 2004. Technical specifications on the material recovery processes apply to the Swedish BOLIDEN plant (HELCOM, 2002). Incineration and final disposal data are valid for the period from 2000 to 2004.

Administration processes were not considered in any of the life cycle phases.

4. Life cycle inventory—selected datasets

A large data base has been compiled in order to investigate the environmental consequences of the EOL treatment of a 2G mobile phone network. Presentation of all data here would be impossible[2]. Therefore a selection of important data used in the study is presented here.

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[2] The corresponding author of the presented study can be contacted in order to obtain further detailed data sets.

Table 3
Total energy consumed in the manufacturing of PWB

Source	Energy consumption during PWB manufacturing [MJ/kg]	Year	Comment
(Malmodin et al., 2001)	652.1	2001	Calculated based on given specification
(Kincaid and Geibig, 1998)	633.1	1998	Value has been selected for this study
(Anonymous, 2003)	390.7	2003	Calculated based on given specification

Table 4
Material inventory of a representative PWB of an antenna rack

Materials	Material content [%] in a PWB (populated)	Source	Data quality	Evaluated[a]	Represented by data sets from...
Metals	33.40262492				
Fe	10.6	Estimated based on (Ludwig et al., 2003)	O	X	Ecoinvent
Al	4.8	(Ludwig et al., 2003)	+	X	Ecoinvent
Cu	3.5	Estimated based on	O	X	Ecoinvent
Sn	3.0	(Ludwig et al., 2003)	++	X	Ecoinvent
Pb	3		++	X	Ecoinvent
Br	2.7	(Ludwig et al., 2003)	++	X	Own estimation
Mn	2.1	Estimated based on	+	X	Ecoinvent
Zn	1.4	(Ludwig et al., 2003)	++	X	Ecoinvent
Sb	0.45	(Ludwig et al., 2003)	++	X	Own estimation
Ni	0.3		+	X	Ecoinvent
Cl	0.15		O	–	Ecoinvent
Na	0.15	Estimated based on	O	–	Ecoinvent
Cr	0.131	(Ludwig et al., 2003)	++	X	Ecoinvent
Cd	0.0395		+	X	Ecoinvent
Co	0.0083		++	X	Ecoinvent
Hg	0.0009		++	–	Ecoinvent
Ag	0.1		++	X	Own estimation
Pt	0.02		O	–	Ecoinvent
Au	0.0005	(Ludwig et al., 2003)	+	X	Own estimation
Pd	0.142863739		+	X	Ecoinvent
Ge	0.142863739		O	–	Own estimation
Ga	0.142863739		O	X	Own estimation
Ta	0.071431869		+	–	Own estimation
In	0.071431869		+	–	Own estimation
Be	0.071431869		+	–	Own estimation
Eu	0.047621246		O	–	Own estimation
Ru	0.142863739		O	–	Own estimation
Bi	0.071431869		++	X	Own estimation
As	0.047621246	Estimated based on	O	X	Own estimation
Se	0.043545	(Conrad, 2000)	O	–	Eoinvent
Ceramics/Glasses	49	(Ludwig et al., 2003)	+	X	Ecoinvent
Plastics	17.7	Estimated based on (Ludwig et al., 2003)	++	X	Ecoinvent
TOTAL	100.1026249				

Data quality: ++ (excellent), + (good), O (sufficient). Data evaluation: X (data available), – (no data available).

[a] Compared with measured data.

Key components of electronic devices in general are the controlling parts, i.e. the printed wiring boards (PWB) with all the chips, sensors, switching elements, etc. In the tables below the most important inventory data are compiled.

Table 3 gives an overview of the available data describing the energy consumed during the production of a typical PWB (populated). The data (given in MJ/kg) were determined based on the information found in the respective sources. The value derived from Kincaid and Geibig (1998) has been used in the study presented here due to its transparency.

The basic material composition of a PWB is given in Table 4. In most cases the data had to be estimated based on the data for electronic devices (e.g. PCs) as such. In a few cases it was possible to adapt data directly. The inventoried data was compared with data recently derived from the PWB in an antenna rack and a mobile phone respectively. The quality of the inventoried data was estimated based on this comparison.

In Table 5 the most important inputs and outputs related to the EOL treatment of 1 kg of PWB scrap are compiled. The data refer to the thermal treatment of the PWB scrap in a smelter unit.

Table 5
Input and output data determined for the thermal treatment of 7.3 kg of network and 1 kg of PWB scrap

Input			[kg]
	EOL goods		
		PWB	1.0000
		Other scrap	6.2986
	Technosphere		
		Lignite	0.2792
		Natural gas	0.3393
		Raw oil	0.3046
		Gravel	0.3650
		Hard coal	0.3470
Output			
	Emissions to air		
		Carbon dioxide	3.1602
		Nitrogen oxide	0.0094125
		Sulphur dioxide	0.0053869
		Carbon monoxide	0.0046318
	Emissions to water		
		Hydrocarbons to water	0.071393
	Emissions to soil		
		Oil (unspecified)	0.00053053
	Secondary raw materials		
		Aluminium	1.3355
		Iron	0.04082
		Gold	1.91E-06
		Copper	0.41289
		Palladium	0.00054465
		Selenium	0.00016601
		Silver	0.00038123
		Steel	4.963

5. Life cycle impact assessment

The results of the impact assessment are presented in the following chapter. In the first step, results are compiled to yield the level of damages incurred during the three life cycle phases, production, use, and EOL treatment, of a mobile phone network. In the second step, the environmental implications for different EOL treatment scenarios are presented.

5.1. Damage category: human health

This damage category is dominated by the effects of inorganic emissions on human respiratory organs (impact category: respiratory inorganic effects). The use phase and production phase dominate the total impact in nearly equal shares (50.9% and 44.5% respectively). The production, operation and EOL treatment of the BTS, i.e. the BTS racks, cause the largest environmental impacts (24.3%, 36.8% and 0.4% respectively of the total category impact). In the use phase particle emissions to air as well as secondary particle creating emissions of SO_2 and NO_x to air during the generation of electricity represent the major impacting sources (39.1%, 34.1% and 25.8% of the use phase impact). The impact of the production phase is dominated by direct SO_2 emissions to air released in the processing of primary palladium and platinum (43.7% and 190% of the production phase impact). Large SO_2 emissions to air are caused by the roasting of the platinum group metal ores in Russia (Althaus et al., 2003). The contribution of the EOL phase to this impact category is comparatively low (4.6% of the total category impact). Major sources are landfill processes of construction waste of BTS housings.

Major non-carcinogenic effects are wreaked by heavy-metal emissions to water (in particular zinc and arsenic) during the electricity generation for the use phase. Again the energy intensive operation of the BTS increases the release of these environmentally critical elements (51.9% of the total category impact). To a lesser extent, the energy-intensive fabrication of PWBs for the BTS racks as well as the production of lead for the BTS back-up batteries contribute to the total category impact with 11.2%. In particular water-borne emissions of zinc and arsenic in the primary lead production contribute to this impact category. In the EOL phase direct emissions of heavy metals such as arsenic and cadmium from landfill contribute to that impact category.

Organic emissions released in the use phase (68.3% of the overall impact category) contribute mainly to the photochemical oxidation reaction category. This impact category is dominated by releases of *N*on-*M*ethane *V*olatile *O*rganic *C*ompounds (NMVOC) to air during the generation of electricity for the use phase (consumed by the BTS racks). In the production phase the energy produced for the assembly of PWBs and the production of primary steel cause major NMVOC emissions to air. These two processes contribute to the total production phase impact with 28.0% and 41.1%, respectively. In the EOL phase the disposal of waste from the construction of BTS housings causes direct NMVOC emissions to air contributing partly to this impact category.

Carcinogenic effects derived from the use phase are dominated by releases of Benzo(a)pyrene to air (24.2% of the total impact), arsenic to air (20.2% of the total impact) and to water (23.1% of the total impact). The source of these indirect emissions is the electricity generated for and consumed primarily by the BTS racks. In the production phase the production of lead for the BTS back-up batteries causes significant emissions of arsenic to water contributing to this impact category. Indirect Benzo(a)pyrene emissions to air from the energy generated for PWB manufacturing as well as direct arsenic emissions to water in the production of steel also contribute to the carcinogenic effects deriving from the production phase. Direct impacts by the EOL phase are primarily attributable to landfilled arsenic.

The respiratory organic effects are dominated by NMVOC emissions to air released from electricity generation processes. The BTS, in particular the racks, dominate this impact category. In the production phase, the energy supplied and consumed for PWB assembly as well as for the production of primary steel cause major NMVOC emissions to air (23.6% and 37.5% of the total production phase impact). In the EOL phase the disposal of construction waste of BTS cabins causes direct NMVOC releases to air contributing to this impact category.

Ionising radiation and ozone depletion contribute only little to this damage category. Both impact categories are dominated by the use phase. The production and the EOL phase cause marginal effects. Radon (Rn222) and carbon (C14) emissions to air originating from electricity generation dominantly contribute to the ionising radiation category. Releases of CFC-114 and Halon 1211 from electricity generation dominate the ozone depletion category. The Halon 1211 emissions are attributable to gas transportation processes and to offshore natural gas and oil production.

Fig. 3 indicates that recycling of basic materials shows a distinct reduction of impacts on human health both in the EOL phase and the production phase (if substitution of secondary for primary materials according to the selected value correction factor is assumed).

5.2. Damage category: ecosystem quality

The effects on terrestrial ecotoxicity dominate overall ecosystem quality. The EOL phase causes the largest effects (57.7% of the total terrestrial ecotox category), followed by the use phase (36.3%). A small impact is attributable to the production phase.

Disposal processes in the EOL phase of the mobile phones and the BTS (accounting for 52.9% and 4.4%, respectively, of the total terrestrial ecotoxicity effects) represent the major impact sources. The emissions, in particular the long-term emissions, of the nickel released from landfilled mobile phones to soil contribute with 45.8% to the total category impact. To a minor extent, zinc emissions to air during the recycling of the lead containing BTS back-up batteries contribute to this category.

The aquatic ecotoxicity category contributes to a lesser extent to ecosystem quality. Here the EOL phase has the lowest impact, compared with the use phase (80.6% of the category impact) and the production phase (15.2% of the category impact). Aluminium emissions released to water in the electricity generation contribute significantly to the aquatic ecotoxicity category. Thus, the energy-intensive operation

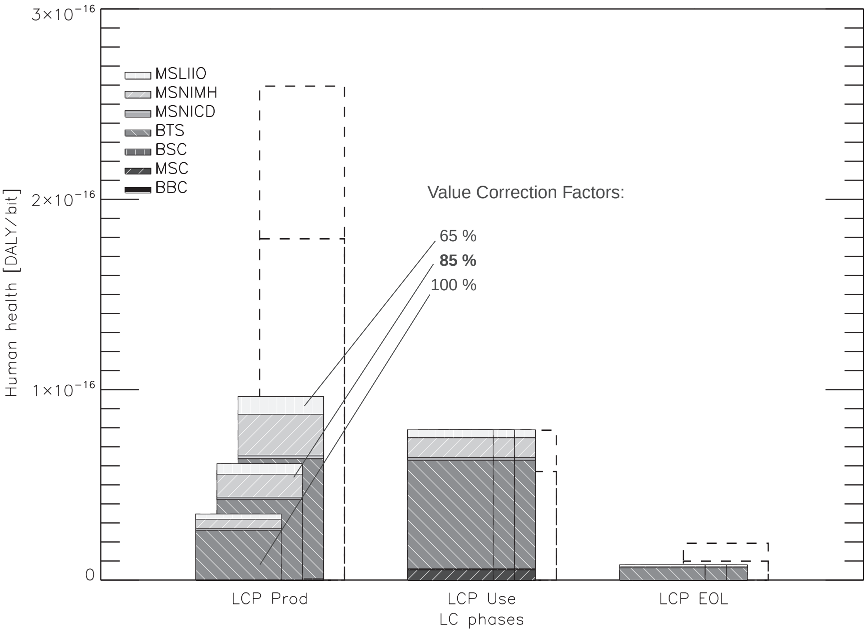

Fig. 3. Contributions of the life cycle phases: production (Prod), use (Use) and EOL (EOL) of the GSM 900 network to the overall impact on human health (HH). "BBC" denotes the backbone cable network. The dashed bars indicate the networks environmental impact if no recycling takes place at all. Not even aluminium and steel from the antenna stations are recycled (cf. Table 1).

of the BTS (72.5% of all network components) dominates this impact category in the use phase, while the energy intensive assembly of the PWBs (48.3% of the production phase impact) contributes significantly to this impact category in the production phase.

Fig. 4 indicates that recycling of electronic scrap instead of landfilling it entails significant environmental benefits in the EOL phase.

5.3. Damage category: resources

The energy-intensive operation of the mobile phone network (use phase) contributes dominantly to the depletion of non-renewable energy resources. The switching network components (MSC, BSC, and BTS) contribute to this impact category with 68.5% and the mobile network components (MS) contribute with 10.1%. The consumption of uranium, hard coal and natural gas in energy supply processes dominate this impact category. The resource depletion effects in the production phase are attributable to the energy-intensive manufacturing and assembly of PWBs.

The other processes such as the production of basic materials have only a minor impact. Recycling and substitution of the recovered materials for basic materials does not lead to notable impact reductions. The small effect of the EOL phase can almost

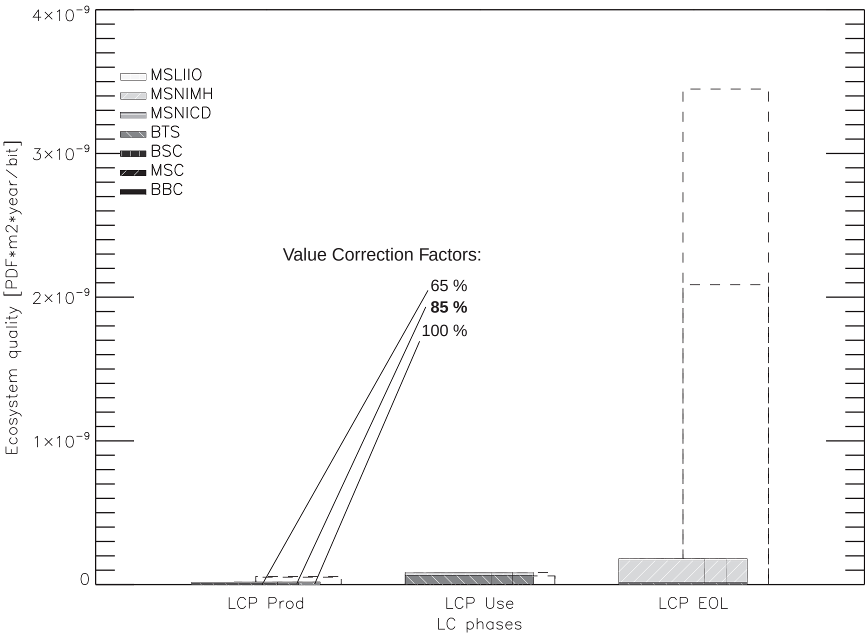

Fig. 4. Contributions of the life cycle phases: production (Prod), use (Use) and EOL (EOL) of the GSM 900 network to the overall impact on ecosystem quality (EQ). "BBC" denotes the backbone cable network. The dashed bars indicate the networks environmental impact if no recycling takes place at all. Not even aluminium and steel from the antenna stations are recycled (cf. Table 1).

exclusively be attributed to the energy consumption for the recovery of the BTS back-up batteries.

5.4. Damage category: climate change

Comparing the life cycle phases reveals that CO_2 emissions from power generation for the use phase dominate the total effect on global warming. The power consumption of the BTS (contributing with 59.7% to the total climate change effects) and MS (contributing with 16.4% to the total climate change effect) cause large CO_2 emissions.

The energy-intensive manufacturing of PWBs in the production phase causes large indirect CO_2 emissions and dominates the effects on climate change in this phase with 56.4%. The production of basic materials such as aluminium, steel or palladium has only minor direct and indirect effects on climate change. Recycling and substitution of other materials for basic materials only leads to a small reduction in the CO_2 emissions from the production phase. Consequently, an increase of the value correction factor for precious metals such as gold or silver and other materials known to require energy intensive processing does not lead to any significant reduction in the overall global warming impact.

The small effect of the EOL phase is almost exclusively attributable to the combustion of natural gas in the production of secondary steel.

5.5. EOL scenario analysis

Fig. 7 shows the environmental impacts of the six EOL scenarios for the mobile phone network. The impacts of the production phase are added to the EOL impacts here because recovered materials are assumed to be recycled to production (at scenario-specific recycling rates) in order to measure the environmental benefit of recycling. The use phase impacts are not included in Fig. 7 because they are not affected by the EOL scenarios. The impact assessment results are given at non-normalised midpoint level in the following impact categories: carcinogenic effects (CarcEff), non-carcinogenic effects (NonCarcEff), respiratory organic effects (RespOrg), respiratory inorganic effects (RespInorg), ozone layer depletion (Ozone), photochemical oxidation (PhotoOx), ionising radiation (IonRad), aquatic ecotoxicity (AquEcox), terrestrial ecotoxicity (TerrEcox), non-renewable energy (NonReE), mineral extraction (MinEx), and global warming potential (GlobWarm).

The environmental impact of the production phase dominates in almost all categories (except in aquatic and terrestrial ecotoxicity). The recycling of electronic scrap in the EOL phase (Scenarios 3–5) helps to reduce environmental impacts. The differences between Scenario Groups 0–2 and 3–5 are especially large with reference to terrestrial and aquatic ecotoxicity as well as to respiratory inorganic and non-carcinogenic effects. On the other hand, the differences within Scenario Groups 0–2 and 3–5, respectively, are not

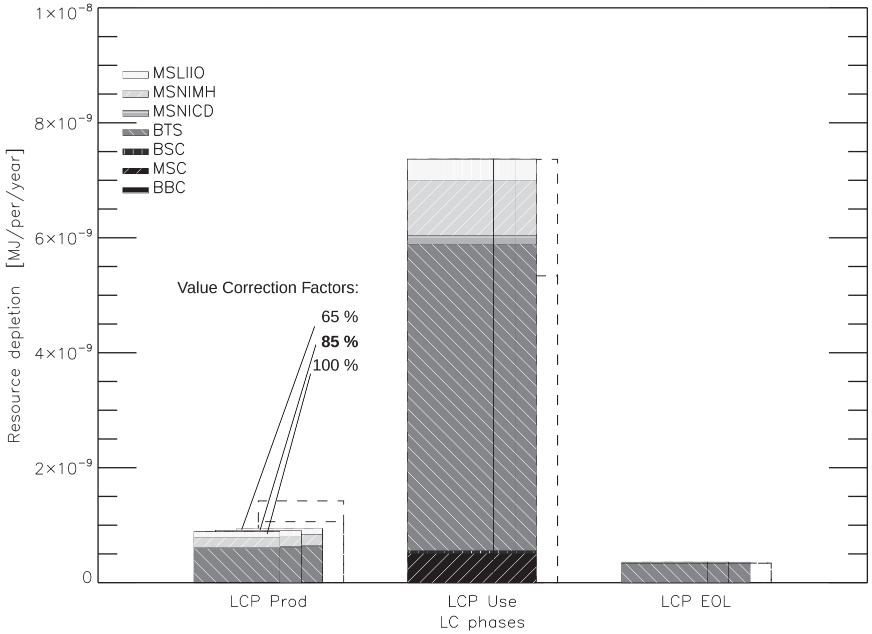

Fig. 5. Contributions of the life cycle phases: production (Prod), use (Use) and EOL (EOL) of the GSM 900 network to the overall impact on resource depletion (RD). "BBC" denotes the backbone cable network. The dashed bars indicate the networks environmental impact if no recycling takes place at all. Not even aluminium and steel from the antenna stations are recycled (cf. Table 1).

significant, i.e. variations in processing of scrap in these two groups of scenarios are only of minor importance.

Comparing the environmental impacts of the different EOL treatment scenarios category by category indicates that Scenario 3 causes the least environmental impact (Fig. 7) and represents the preferable option therefore. The results further indicate that all electronic scrap containing precious metals should be treated in specialised metal recovery plants. The small increase in the environmental impact on resource quality attributable to the recycling of precious metal scrap (Fig. 6) is countervailed by a significant reduction in the environmental impact attributable to the avoidance of the production of primary materials (Figs. 3–6). The diagram shows that fractionation has no relevant adverse environmental impacts. Thus, this treatment prior to the recovery of precious materials also can be omitted. It does not improve the production of secondary materials, i.e. the environmental impacts of the secondary material production are not reduced.

The energy needed for the assembly of PWBs and, to a lesser extent, the production of primary materials to replace lost materials cause major contributions to each of the selected impact categories.

Long-term emissions of copper, zinc and arsenic to soil and of copper and aluminium to water due to landfilling have distinct terrestrial and aquatic ecotoxic as well as non-carcinogenic effects in all scenarios.

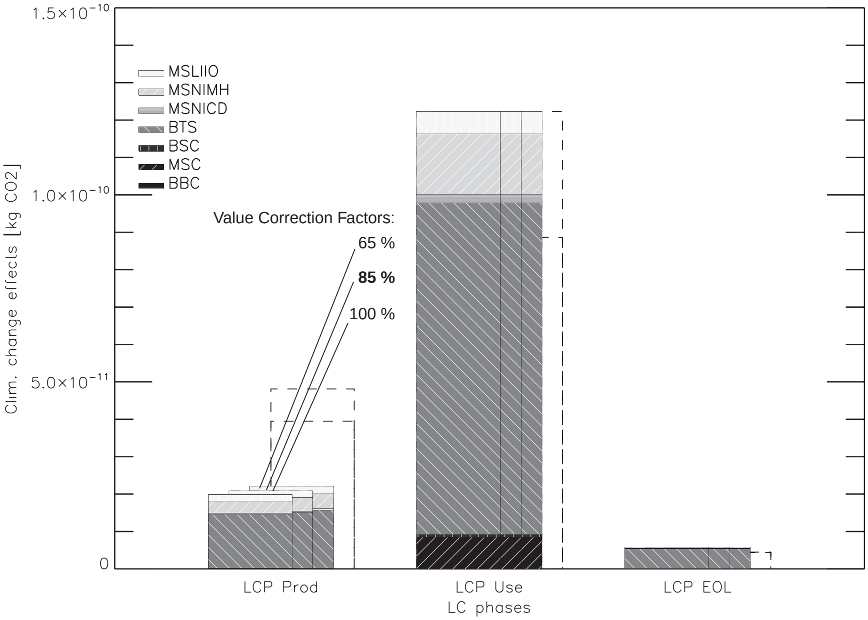

Fig. 6. Contributions of the life cycle phases: production (Prod), use (Use) and EOL (EOL) of the GSM 900 network to the overall impact on climate change (CC). “BBC” denotes the backbone cable network. The dashed bars indicate the networks environmental impact if no recycling takes place at all. Not even aluminium and steel from the antenna stations are recycled (cf. Table 1).

Less or no detectable impacts result for lead, cadmium and other heavy metals known to cause toxic impacts. Scenario 2 (immediate network component incineration and subsequent landfilling) causes a significant amount of harmful emissions and should therefore be avoided.

Thermal treatment of electronic scrap and/or of residuals in municipal solid waste incineration (MSWI) plants prior to landfilling (Scenario 2) can cause the release of highly volatile materials, e.g. arsenic and bromine, contributing to all impact categories except respiratory inorganic effects, ionising radiation and depletion of non-renewable energy. These volatile materials can increase the environmental impacts and thus combustion in such plants prior to landfilling should be avoided, unless the ashes are well stabilised, which would reduce long-term emissions, and significant energy recovery could be achieved by incinerating by-products.

6. Discussion and recommendations

6.1. General

The environmental impacts of a 2G mobile phone network are dominated by the use phase for most damage categories. In the case of human health, the production phase contributes significantly to the overall impact of the network. Ecosystem quality is primarily affected by impacts attributable to the EOL phase. It has been shown that the recycling of materials, in particular of precious and rare metals, reduces environmental impact both by reducing the EOL phase's own impact and by avoiding the production of primary materials.

Key impacts during the life cycle of a complete 2G mobile phone network are attributable to:

a.) the energy intensive operation of the base transceiver stations and (to a lesser extent) of the mobile phones,
b.) the energy intensive manufacturing and assembly of printed wiring boards (Singhal, 2005),
c.) distinct inorganic emissions to air during the primary production of precious metals affecting human health, and
d.) direct emissions of heavy metals from final disposal processes.

The results show that final disposal without material recycling can cause significant ecotoxic and non-carcinogenic health effects (Fig. 7). However, it has to be mentioned that the emissions inventoried and assessed for the landfill processes have to be interpreted with certain qualifications. Firstly, current LCA methodology considers overall integrated emissions. These emissions relate to landfill processes occurring over long time periods (i.e. 60,000 years). Secondly, neither the data bases used for the analysis nor the IMPACT2002+ method distinguishes explicitly the particular chemical state of each element, especially the metal speciation, in which it is released to the environment. That means that the method does not take into account whether a certain metal is effectively bio-available or not.

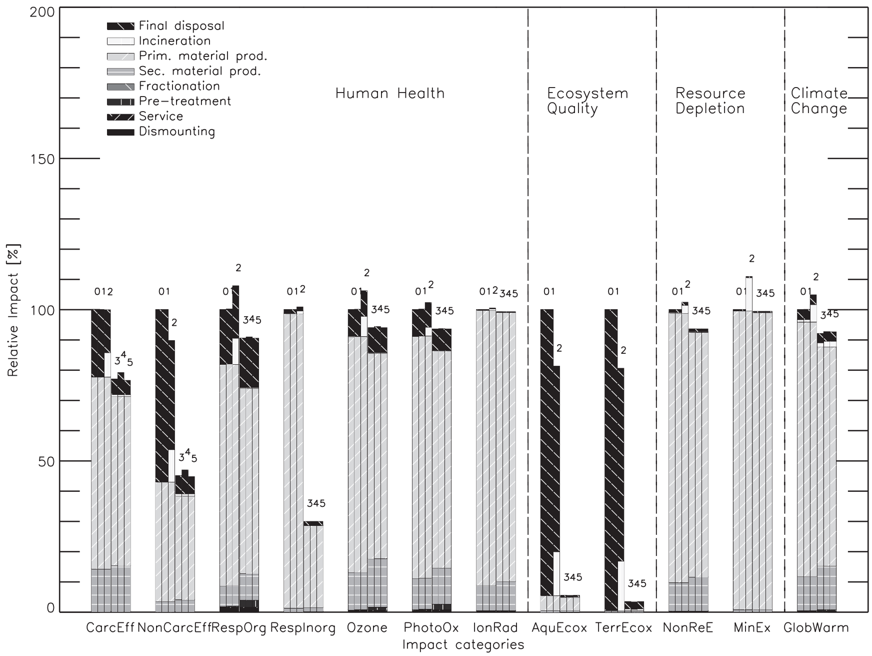

Fig. 7. Comparison of the EOL treatment scenarios for a typical GSM 900 network (0=Scenario 0, 1=Scenario 1, etc.). The impact categories (at non-normalised midpoint level) are grouped according to damage categories. In each impact category Scenario 0 was set to 100%. Impacts are related to the transmission of 1 data bit (functional unit of the study).

It has also been shown that advanced fractionation, i.e. a material-specific separation of electronic scrap prior to material recovery neither significantly contributes to the environmental impact of EOL treatment nor significantly improves the material recovery processes. Weidman and Lundberg (2001) and Grunewald and Gustavsson (1999) arrive at comparable conclusions. Thus, under the assumptions underlying our study, fractionation can be omitted without incurring any environmental disadvantages.

6.2. Recommendations to recyclers and operators

As the network components reach the end of their service lives, they should be dismounted and adequately processed. BTS masts as well as BTS-, BSC- and MSC-housings should be re-used as infrastructure parts.

Disassembling the racks of the switching network elements (BTS-, BSC- and MSC-racks) and removing the rack sub-units (transceivers, etc.) would be sufficient to achieve an environmental optimum. All electronic scrap containing precious metals should be treated in specialised metal recovery plants to effectively recover precious metals. Aluminium and steel should be treated in steel works and aluminium plants. The rest of these materials should be used in other production processes. Landfilling should be avoided.

Additional incineration can lead to emissions of heavy metals, in particular of arsenic and arsenic-compounds in dispersed form, which may react toxic to the environment (Uryu et al., 2003). Therefore incineration of electronic scrap, as e.g. printed wiring board assemblies or parts of them, prior to landfilling should only be performed if appropriate filter facilities are used and if ashes are long-term stabilized and recoverable energy is significant.

Landfilling electronic and/or infrastructure components containing precious or toxic metals should be avoided. Precious metals are lost and have to be replaced at the cost of high environmental impacts and, due to the unnaturally high concentration of metals in landfill sites, potentially toxic emissions are released to soil and water.

6.3. Recommendations to manufacturers and operators

In order to reduce the environmental impacts of mobile phone networks, the following two issues need to be addressed:

i.) reduction of the energy consumption in the use phase,
ii.) reduction of the energy consumption for the manufacturing and assembly of printed wiring boards.

In the use phase, advanced operation plans focussing on the avoidance of full-load traffic of single switching network components can help to reduce the environmental impacts of this phase.

The electronic components, i.e. the different electronic sub-units (e.g. transceivers, servers, etc.) containing printed wiring boards, should have standardised shapes and interfaces to facilitate re-use. Prolonged upgradeability of the sub-units could lead to an extended service life of these units. Furthermore, a reduction of the energy consumption for the operation of components can contribute to a reduced environmental impact.

Wherever possible, the palladium and platinum metals used in contact materials of printed wiring board assemblies should be either recycled at the highest possible rates or they should be replaced by less precious materials.

7. Outlook

Environmentally safe production, operation and EOL treatment of mobile telephone technology is very important in a world of growing numbers of mobile phone networks and increasingly complex component assemblies.

Recent information indicates that future network components such as the NodeB antenna racks of the UMTS antenna stations are heavier and have a more complex construction compared with, e.g., the BTS racks (LucentTechnologies, 2001; SiemensAG, 2002; Wilén, 2000). It may be expected that these racks require more complex EOL treatment methods to ensure environmentally safe recycling and final disposal. This increased complexity may lead to an increased environmental impact per component. However, when comparing a GSM 900 network with a UMTS network, the latter might have environmental improvements, as would be the case if fewer macro NodeBs but more small and lightweight micro and pico NodeBs are installed. A follow-up study will address these issues in more detail.

The environmental impacts of electronic components caused by thermal treatment as well as landfilling are currently not plausibly resolved. In particular, long-term emissions of landfilling can play an important role for human and ecotoxicity. Further research is required to improve the assessment quality and reduce the high uncertainty related with these impacts, and to assess expected environmental impacts of future mobile phone networks.

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