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Metal recovery from high-grade WEEE: A life cycle assessment

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ABSTRACT

Based on available data in the literature the recovery of aluminium, copper, gold, iron, nickel, palladium and silver from high-grade WEEE was modeled by LCA. The pre-treatment of WEEE included manual sorting, shredding, magnetic sorting, Eddy-current sorting, air classification and optical sorting. The modeled metallurgical treatment facility included a Kaldo plant, a converter aisle, an anode refinery and a precious metal refinery.

The metallurgic treatment showed significant environmental savings when credited the environmental load from avoided production of the same amount of metals by mining and refining of ore. The resource recovery per tonne of high-grade WEEE ranged from 2 g of palladium to 386 kg of iron. Quantified in terms of person-equivalents the recovery of palladium, gold, silver, nickel and copper constituted the major environmental benefit of the recovery of metals from WEEE. These benefits are most likely underestimated in the model, since we did not find adequate data to include all the burdens from mining and refining of ore; burdens that are avoided when metals are recovered from WEEE.

The processes connected to the pre-treatment of WEEE were found to have little environmental effect compared to the metallurgical treatment. However only 12-26% of silver, gold and palladium are recovered during pre-treatment, which suggest that the reduction of the apparent losses of precious metals as palladium, gold and silver during pre-treatment of WEEE is of environmental importance.

Our results support in a quantitative manner that metal recovery from WEEE should be quantified with respect to the individual metals recovered and not as a bulk metal recovery rate.

1. Introduction

Waste electrical and electronic equipment (WEEE) is considered to be one of the fastest growing waste streams in Europe. WEEE is discarded electrical and electronic equipment (EEE), which in the WEEE directive [1] is listed as ten different categories as shown in Table 1. With respect to treatment some of these categories are managed together while others are split into subfractions prior to treatment. Table 2 shows the six most common WEEE "treatment categories" in Europe [2].

The European Union has by the implementation of the Restriction of Hazardous Substances (RoHS) [3] and the WEEE directive [1] recognized the environmental significance of WEEE regarding both its content of hazardous substances and its high content of recyclable materials. Tsydenova and Bengtsson [4] summarized the existing knowledge on WEEE as a hazardous waste fraction and UNEP [5] concluded that WEEE could be a significant source for recovery of metals.

Quantitative assessments of the environmental and resource issues of WEEE management are however few. Life cycle assessments (LCA) involving WEEE have typically been done on a single product and from a product life point of view (e.g. Andrea and Andersen [6]), eventually including focus on different waste management alternatives [7,8]. Hagelüken and Meskers [9] evaluated the savings in CO_2 emissions from recycling of metals in WEEE based on measurements at the Umicore facility (Belgium) and saved CO_2 emissions from the avoided production of metals from virgin sources (data from Ecoinvent [10]). The resource issues are however often primarily related to iron, aluminium and copper (e.g. Mayers [7] and Hischier [11]) and often the LCA studies have not in any detail included the minor but precious metals. This may be critical since the environmental burden of producing these precious metals from virgin source may be high. The importance of not focusing on only mass recovery from WEEE was also addressed by Huisman [12] using a slightly broader evaluation approach to WEEE.

The aim of this study is to establish Life Cycle Inventories (LCIs) for the recycling and recovery of copper, gold, nickel, palladium and silver and, by an LCA approach, to assess the environmental impacts connected to the recovery of metals (aluminium, copper, gold, iron, nickel, palladium, and silver) from high-grade WEEE including the avoidance of extraction of similar metals from virgin sources. High-grade WEEE is the fraction richest on precious metals consisting of products from WEEE directive category 3 and 4 (see also Table 2).

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Table 1
The ten WEEE directive categories [1].

#	Category name
1	Large household appliances
2	Small household appliances
3	IT and telecommunications equipment
4	Consumer equipment
5	Lighting equipment
6	Electrical and electronic tools
7	Toys, leisure and sports equipment
8	Medical devices
9	Monitoring and control instruments
10	Automatic dispensers

2. Approach and methods

2.1. Treatment of high-grade WEEE

High-grade WEEE is after collection sent to a pre-treatment facility. There are numerous pre-treatment facilities in Europe and the treatment steps within these vary except for the mandatory removal of certain components according to the WEEE-directive. The removal of these components is done in a sorting and de-pollution step. In this step the pre-treatment facility will typically also remove bigger metallic parts which are not beneficial to shred. The actual set-up of the pre-treatment facility is often considered proprietary information, and in this study a pre-treatment facility consisting of manual de-pollution, shredding, air classifiers/hoods, magnetic sorting, Eddy-current separation and optical sorting was suggested. Fig. 1 shows the general material flow in the pre-treatment plant. The major outputs are the manually sorted components (29%), the magnetic-iron (33%) and the residual plastic fraction (26%). The other fractions each constitute 2–3% of the flow. The destiny of the plastic varies [2] depending on quality and market needs and because of this uncertainty we chose not to include this fraction in the further environmental assessment. Also it is unlikely that metals are recovered from this fraction. The manually sorted fraction is further separated and 40% of this fraction is sent to special treatment as required by EU regulation, the remaining 60% are bigger metallic parts which are recycled. The overall outputs from the pre-treatment plant per 1000 kg of received high-grade WEEE are:

- 114 kg of substances requiring special treatment according to regulation (not modeled further)
- 165 kg of copper and precious-metal fraction (to the metallurgic plant modeled in this study)
- 381 kg of iron and magnetic steel (to general recycling; modeled)
- 22 kg of aluminum (to general recycling; modeled)
- 53 kg of fluff and residual waste (to incineration; modeled)
- 265 kg of plastic (to incineration, cement kilns, further upgrading, recycling; not modeled further because of uncertain destiny).

The iron and aluminium fractions for recycling are assumed to be managed via the scrap market and the incineration of fluff and residual waste is assumed to take place at a municipal waste incinerator with an electricity production of 20% and heat production of 65% based on the lower heating value of the waste fraction.

Table 2
The six most common WEEE "treatment categories" in Europe [2] and their associated WEEE directive category numbers (Table 1). WEEE directive category 5 is in the treatment categories subdivided into luminaries (5a) and lamps (5b). Small WEEE is typically collected together and can then be further separated into a low-grade and a high-grade fraction.

Treatment categories	Categories of EEE
Large equipment	1, 10
Cooling white goods	1
Small WEEE: low-grade fraction	2, 5a, 6, 7, 8, 9
Small WEEE: high-grade fraction	3, 4
TV and monitors	3, 4
Lighting equipment	5b

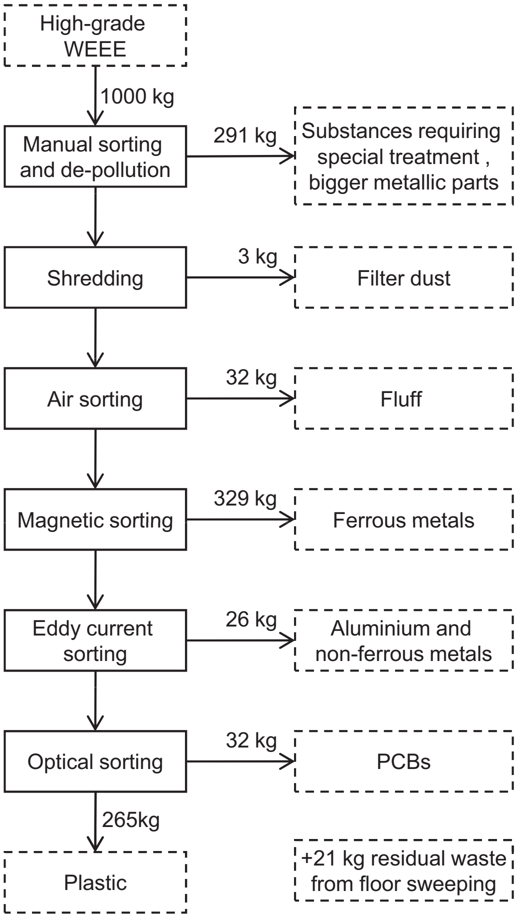

Fig. 1. Schematical view of the modeled pre-treatment facility and its output.

The precious-metal rich fraction containing among other elements copper, gold, nickel, palladium and silver was assumed to be processed at an integrated metallurgical treatment facility processing both virgin and secondary resources; a detailed description of the metallurgical process was presented by Cui and Zhang [13]. Fig. 2 presents the outline of the plant with respect to the WEEE fraction. The Rönnskär facility (Boliden) Sweden was used as a model for the refining. The copper and precious-metal fraction from the WEEE are fed to the plant in a mix with lead concentrate prior to melting. The melted lead is hereafter sent for lead refining and the melted WEEE (black copper) is transferred to the converter aisle. The anode refinery consists of the anode casting plant and the electrolytic refinery. The anode casting plant deoxidizes the blister copper and cast the resulting anode copper which is then transferred to the electrolytic refinery. The electrolytic refinery converts the anode copper into the product copper cathodes. The conversion results in a production of anode slime containing gold, silver and platinum group metals (PGM) which is pumped to the precious metals refinery. The electrolytic refinery receives a flow from the precious metals refinery from which additional copper and nickel sulphate is produced [14]. The precious metals refinery also produces a residue from which gold, silver, palladium and PGM sludge is produced. The silver is granulated and the gold either granulated or sold as bars [14]. Classen et al. [15] states that the palladium is recovered as a solid metal from the precious metals refinery and that the remaining platinum group metals are in the PGM sludge which is sold for further treatment. However, Boliden [14] states

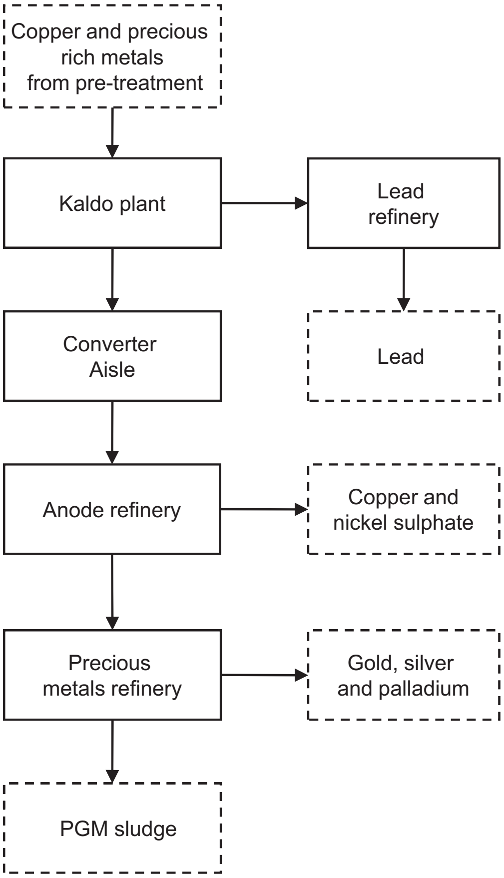

Fig. 2. Schematical view of the modeled metallurgic facility and its output.

that palladium is included in the PGM sludge. In this study palladium is considered recovered as a solid metal from the precious metals refinery as this corresponds to the available data.

2.2. Life cycle inventories (LCIs)

Life cycle inventories (LCIs) are the collected environmentally relevant information used in an environmental assessment. LCIs were established for the WEEE treatment processes based on European data: the pre-treatment plant and the metallurgic plant. The data for the pre-treatment facility was based on Hischier et al. [16] (Ecoinvent v.2.0) (Table 3). The metallurgic plant was split into the individual processes as recommended by Ekvall and Finnveden [17]. Tables 4–7 present the LCIs and refer to the data sources. The electricity consumption of the Kaldo plant was estimated to be 5% of the annual electricity consumption for the whole metallurgical treatment facility as suggested by Classen et al. [15]. This is considered a very rough estimation.

Aluminum and iron sorted from the pre-treatment plant were via the market recycled at other plants. LCI data for their recycling were taken from the EASEWASTE database and are European data. This includes the reprocessing of the secondary metal as well as the saved virgin production.

LCI data on virgin production of precious metals was needed in order to quantify the savings obtained by recovering the precious metals from the WEEE. Data on the mining of virgin metals are primarily based on Classen et al. [15] (Ecoinvent v.2.0). Gold and silver are modelled as mined from Papua New Guinea (not the most representative mine, but the one with the best data quality), palladium and nickel from mines in Zambia and Russia, and copper as “global data”. The data in Ecoinvent of the refining of the virgin metals were not as detailed and thorough as the data available in Borell et al. [19] on refining of recovered metals. Refining of the virgin metals was therefore modeled as having the same burdens as the recovery process using the data by Borell et al. [19]. There is most likely an underestimation of the burdens of the virgin production, because of likely underestimates of the use of chemicals and the waste produced.

Table 3
LCI data for the pre-treatment facility used in this study based on Hischier et al. [16].

Pre-treatment facility (per tonne incoming mass)		
Description	Value	Unit
Energy		
Electricity	66	kWh
Emissions to air		
Aluminum	1×10^{-6}	tonne
Antimony	1×10^{-7}	tonne
Bromine	2×10^{-7}	tonne
Cadmium	2×10^{-8}	tonne
Chlorine	3×10^{-7}	tonne
Chromium	5×10^{-8}	tonne
Copper	4×10^{-7}	tonne
Iron	5×10^{-6}	tonne
Lead	4×10^{-7}	tonne
Mercury	1×10^{-10}	tonne
Nickel	2×10^{-7}	tonne
Phosphorus	1×10^{-8}	tonne
Polychlorinated biphenyls	2×10^{-9}	tonne
Tin	3×10^{-7}	tonne
Zinc	1×10^{-6}	tonne

The pre-treatment of WEEE as well as the recovery of metals at the metallurgic plants cause loss of metal to dust, rejects etc. The recovery rates of the metals for pre-treatment are modelled as determined by Chancerel et al. [21]; for nickel no loss was considered during pre-treatment. The recovery rates for the metallurgic processing were estimated according to Huisman [12] and for aluminium and iron from available EASEWASTE data. The recoveries are shown in Table 8 together with a listing of the original content of the metals in the WEEE.

2.3. Life cycle assessment (LCA)

Life cycle assessment (LCA) is the method to environmentally asses a system using the LCIs of the processes and technologies representing the system of the processes and technologies

Table 4
LCI data for the Kaldo plant used in this study. Electricity use is based on Classen et al. [15] and Boliden [18], other data are based on Borell et al. [19].

Kaldo plant (per tonne incoming mass)		
Description	Value	Unit
Energy		
Electricity	4×10^{-1}	kWh
Materials and resources		
Quick lime (CaO)	5×10^{-2}	tonne
Emissions to air		
Arsenic	4×10^{-8}	tonne
Cadmium	4×10^{-8}	tonne
Chlorine	3×10^{-6}	tonne
Copper	5×10^{-7}	tonne
Dioxins	1×10^{-12}	tonne
Lead	9×10^{-8}	tonne
Mercury	2×10^{-8}	tonne
Nitrogen oxides	4×10^{-4}	tonne
Particulates (<2.5 μm)	1×10^{-5}	tonne
Particulates (>2.5 μm and <10 μm)	8×10^{-6}	tonne
Particulates (>10 μm)	4×10^{-6}	tonne
Sulfur dioxide	2×10^{-3}	tonne
Zinc	1×10^{-6}	tonne

Table 5
LCI data for the converter aisle used in this study. No data was available for the electricity consumption. Emissions to air are based on Borell et al. [19] and emissions to water on Umweltbundsamt [20] and Borell et al. [19].

Converter aisle (per tonne incoming mass)		
Description	Value	Unit
Energy		
Electricity	Unknown	kWh
Emissions to air		
Arsenic	2×10^{-7}	tonne
Cadmium	1×10^{-7}	tonne
Copper	1×10^{-6}	tonne
Dioxins	4×10^{-13}	tonne
Lead	1×10^{-6}	tonne
Nitrogen oxides	8×10^{-5}	tonne
Particulates (<2.5 μm)	7×10^{-6}	tonne
Particulates (>2.5 μm and <10 μm)	4×10^{-6}	tonne
Particulates (>10 μm)	2×10^{-6}	tonne
Sulfur dioxide	5×10^{-3}	tonne
Zinc	1×10^{-6}	tonne
Emissions to water		
Arsenic, ion	2×10^{-9}	tonne
Cadmium, ion	9×10^{-11}	tonne
Copper, ion	2×10^{-8}	tonne
Lead	9×10^{-9}	tonne
Mercury	5×10^{-11}	tonne
Zinc, ion	9×10^{-9}	tonne
Nickel, ion	3×10^{-10}	tonne

representing the system. In this case the LCA was performed using the EASEWASTE model which is a tool specifically developed for environmental assessment of waste management [25]. EASEWASTE uses the EDIP method [26] for quantifying "environmental impacts" and "resource consumption". The impacts and resources are normalized into person equivalents (PE) by the normalizations references presented in Table 9. One PE refers to the annual impact caused by all the activities of one person (energy, housing, industrial production and consumption, travel, etc.).

An LCA on a multiple input–output system, such as the metallurgic plant, requires allocation of emissions and resource consumption as system expansion is not an option. In this study two allocation methods were possible: mass allocation and economic allocation. From a waste management perspective the allocation should be performed according to the incoming *mass* of WEEE as the "function" is to treat the received waste. For the production of virgin materials the allocation should however be conducted according to the *value* (economic) of the output of metals, as it is the value of the metals that are the reason for the production taking place. This creates a dilemma of choice. Ekvall and Finnveden [17] discusses this aspect and recommends that in the case of suspecting that the allocation method might have an influence, then allocation should be avoided as much as possible using subdivision and any unavoidable allocation should be done using a "physical, causal relationship between the functions and environmental burdens". However, it was not possible to find such a common relationship and we chose to apply both allocation methods: The LCI data was allocated according to both mass and economic allocation separately. The data used for the two allocation approaches are shown in Table 10.

Table 6
LCI data for the anode refinery used in this study. Energy consumptions and material use are based on Classen et al. [15], emissions to air on Umweltbundsamt [20], emissions to water are based on Umweltbundsamt [20] and Borell et al. [19].

Anode refinery (per tonne incoming mass)		
Description	Value	Unit
Energy		
Electricity	310	kWh
Natural gas (heat)	4×10^{-2}	MJ
Materials and resources		
Sulphuric acid	4×10^{-2}	tonne
Emissions to air		
Arsenic	6×10^{-8}	tonne
Copper	1×10^{-7}	tonne
Lead	2×10^{-7}	tonne
Nickel	4×10^{-8}	tonne
Particulates (<2.5 μm)	3×10^{-6}	tonne
Particulates (>2.5 μm and <10 μm)	2×10^{-6}	tonne
Particulates (>10 μm)	9×10^{-7}	tonne
Emission to water		
Arsenic, ion	8×10^{-8}	tonne
Cadmium, ion	5×10^{-5}	tonne
Copper, ion	1×10^{-6}	tonne
Lead	7×10^{-8}	tonne
Mercury	1×10^{-10}	tonne
Nickel, ion	1×10^{-7}	tonne
Zinc, ion	3×10^{-7}	tonne

Table 7
LCI data for the precious metal refinery used in this study. Electricity consumption is based on Classen et al. [15] and Boliden [18], the consumption of light fuel oil on Classen et al. [15], emissions to air are based on Borell et al. [19].

Precious metal refinery (per tonne incoming mass)		
Description	Value	Unit
Energy		
Electricity	308	kWh
Light fuel oil	41	L
Materials and resources		
Oxygen (liquid)	95	tonne
Emissions to air		
Lead	1×10^{-5}	tonne
Silver to air	1×10^{-5}	tonne
Selenium to air	3×10^{-5}	tonne
Particulates (<2.5 μm)	8×10^{-5}	tonne
Particulates (>2.5 μm and <10 μm)	5×10^{-5}	tonne
Particulates (>10 μm)	3×10^{-5}	tonne
SO_3	6×10^{-4}	tonne
Sulfur dioxide	2×10^{-3}	tonne

The functional unit of the study is "recovery of aluminium, copper, gold, iron, nickel, palladium and silver from 1 tonne of high-grade WEEE". The assessment is attributional (using average data for the energy substitution).

The study assesses the environmental impact of the recovery of metals from WEEE including the avoided burdens from the production of the same virgin metals. As it is only the environmental impact of the recovery of metals from WEEE that is evaluated and not the overall environmental cost of treating high-grade WEEE, the removal and subsequent treatment of hazardous components could be excluded.

Table 8
The metal content of high-grade WEEE and the recovery rates for pre-treatment, recovery processes and overall.

	Metal content high-grade WEEE		Recovered [%]		
	Value	Unit	Pre-treatment[a]	Recovery process	Overall
Palladium	7[a]	g/tonne	26	98[d]	25
Gold	22[a]	g/tonne	26	98[d]	25
Silver	313[a]	g/tonne	12	97[d]	12
Nickel	3[b]	kg/tonne	100	90[d]	90
Aluminium	33[c]	kg/tonne	86[c]	79[e]	68
Copper	44[a]	kg/tonne	60	95[d]	57
Iron	402[a]	kg/tonne	96	100[e]	96

[a] Chancerel et al. [21].
[b] Legarth et al. [22].
[c] Chancerel [23].
[d] Huisman [12].
[e] EASEWASTE [24].

Table 9
EASEWASTE normalization factors for the impact categories in EDIP97 [27].

Impact categories Environmental impacts	Normalization reference EDIP97 environmental impact potentials	
Global		
Global warming	kg CO_2 (eq/pers/year)	8700
Stratospheric ozone depletion	kg CFC11 (eq/pers/year)	1.03×10^{-1}
Regional and local		
Acidification	kg SO_2 (eq/pers/year)	74
Nutrient enrichment	kg NO_3^- (eq/pers/year)	119
Photochemical ozone formation	kg C_2H_4 (eq/pers/year)	25
Human toxicity		
Human toxicity via air	m^3 (air/air/pers/year)	6.09×10^{10}
Persistant toxicity		
Ecotoxicity in soil	m^3 (soil/pers/year)	964,000
Ecotoxicity in water (chronic)	m^3 (water/pers/year)	352,000
Human toxicity via soil	m^3 (soil/pers/year)	127
Human toxicity via water	m^3 (water/pers/year)	50,000
Impact categories Resource consumptions	Normalization reference EDIP97 resource consumption (2004)	
Non-renewable		
Aluminum	kg/pers/year	4.52
Brown coal (lignite)	kg/pers/year	264
Chromium	kg/pers/year	8.28×10^{-1}
Copper	kg/pers/year	2.27
Crude oil	kg/pers/year	604
Gold	kg/pers/year	3.86×10^{-4}
Hard coal	kg/pers/year	602
Iron	kg/pers/year	97.7
Lead	kg/pers/year	4.92×10^{-1}
Manganese	kg/pers/year	1.72
Natural gas	kg/pers/year	353
Nickel	kg/pers/year	2.19×10^{-1}
Palladium	kg/pers/year	2.97×10^{-5}
Silver	kg/pers/year	3.05×10^{-3}
Uranium	kg/pers/year	5.63×10^{-3}
Zinc	kg/pers/year	1.42

Table 10
Allocation of burdens [%] per treatment step. The Economic allocated burdens are dependent on the values of the outputs which are also shown (January 2009 prices).

	\$ per kg	Mass [%]	Economic [%]
Pre-treatment			
Aluminium	1.49	4.05	8.09
Iron	0.36	55.6	26.9
Plastic	0.20	36.4	9.75
Lead	1.04	0.14	0.20
Copper	3.07	3.76	15.5
Gold	31300	0.00	36.0
Silver	356	0.01	2.53
Palladium	5950	0.00	0.02
Nickel	12.8	0.04	0.73
PGM slime	2360	0.00	0.33
Kaldo plant			
Lead	1.04	71.8	12.9
Copper	3.07	27.9	14.9
Gold	31300	0.01	34.7
Silver	356	0.04	2.43
Palladium	5950	0.00	2.19
Nickel	12.8	0.32	0.70
PGM slime	2360	0.08	32.2
Converter aisle			
Copper	3.07	98.7	27.8
Gold	31300	0.01	21.6
Silver	356	0.19	6.22
Palladium	5950	0.01	2.75
Nickel	12.8	0.96	1.13
PGM slime	2360	0.19	40.4
Anode refinery			
Copper	3.07	98.7	27.8
Gold	31300	0.01	21.6
Silver	356	0.19	6.22
Palladium	5950	0.01	2.75
Nickel	12.8	0.96	1.13
PGM slime	2360	0.19	40.4
Precious metals refinery			
Gold	31300	1.93	30.5
Silver	356	48.8	8.76
Palladium	5950	1.29	3.87
PGM slime	2360	48.0	56.9

Table 11
Environmental assessment of recovery of aluminum, copper, gold, iron, nickel, palladium and silver per tonne high-grade WEEE. The unit PE is used for the normalized impacts, thus relating the environmental assessment to the environmental burdens of an equivalent number of persons.

	Mass	Economic
Environmental impact categories	PE	PE
Acidification	−0.25	−0.27
Ecotoxicity in soil	-1.13×10^{-3}	-1.10×10^{-3}
Ecotoxicity in water (chronic)	−7.83	−4.41
Global warming 100 years	−0.25	−0.38
Human toxicity via air	−0.98	−1.00
Human toxicity via soil	−0.26	−0.50
Human toxicity via water	−0.48	−0.25
Nutrient enrichment	−0.05	−0.07
Photochemical ozone formation	−0.02	−0.04
Stratospheric ozone depletion	-1.01×10^{-4}	-2.16×10^{-3}
Resource consumption		
Aluminum	−5.07	−5.07
Brown coal (lignite)	−0.41	−2.18
Copper	−11.0	−11.0
Crude oil	−0.21	−0.49
Gold	−14.6	−14.6
Hard coal	−0.62	−0.91
Iron	−3.93	−3.94
Lead	-2.50×10^{-4}	-5.21×10^{-3}
Manganese	−1.44	−1.44
Natural gas	−0.18	−0.43
Nickel	−12.3	−12.3
Palladium	−63.0	−63.0
Silver	−11.7	−11.7
Uranium	−0.20	−0.03
Zinc	−0.04	−0.01

3. Results and discussion

The results of the LCA modeling of the recovery of metals from 1 tonne of high-grade WEEE for recovery of metals are shown in Table 11, allocating the environmental loads and benefits either according to the mass flows or to the economic of the mass flows.

The environmental impacts all show negative values corresponding to savings. This means that the environmental costs of pre-treating the WEEE and recovering the metals are less than the cost of producing similar amounts of metals from virgin ore. The savings are per tonne of WEEE somewhat higher than savings observed for municipal solid waste subject to extensive material recycling and energy recovery (see e.g. Kirkeby et al. [28]). The pre-treatment is a load to the environment (data not shown) but constitutes in magnitude only a few percentage of what is saved in the mining and metallurgic process and thus is insignificant in the overall picture. The actual savings are expected to be even higher, since we did not include all the environmental burdens from the mining and refining of virgin metals due to lack of reliable data. If included, this would have increased the avoided impacts and made the overall savings more significant. The environmental impacts of handling and disposal of tailings (Engels [29] suggests that impacts from tailings are significant) were not properly quantified and some of the chemicals used not identified to a level where it was possible to include them in the modeling. These would be issues to address in the future.

The metal resources recovered are significant in mass, ranging from 2 g (palladium) to 386 kg (iron) corresponding to several PE per tonne of high-grade WEEE. Although PE-values for various environmental and resource consumption categories should not be compared directly, the high PE-values for the saved resource consumption suggest that the savings in metal resources are significant compared to the the savings in environmental impacts from avoided production of virgin metals. This is in particular important because some of the recovered metals are considered to have a short supply horizon and potentially may be of strategic importance (see e.g. EC [30] regarding economically important resources in the EU). The saving in energy resources is also significant (lignite, crude oil) and this is related to high energy cost from mining and refining of ore. In terms of PE, the recovery of metals like palladium, gold, silver, nickel and copper seems to play a more important role than the recovery of more common metals like iron and aluminum although the later two metals are recovered in much higher quantities. This is in particular of importance since the precious metals have relatively low recovery rates; only a modest fraction of the precious metals present in the high-grade WEEE was recovered. For palladium, gold and silver the recovery rates range 12–25%. The majority of the losses takes place in the pre-treatment suggesting that, if the pre-treatment could be improved leading to a reduced loss of precious metals, the overall treatment and recovery of metals from high-grade WEEE would be even more attractive from a resource point of view and probably also from an environmental point of view. Chancerel et al. [21] suggested that an improved recovery of these metals could be achieved with an increased focus on manually removing precious metal-rich components in an early stage and by not shredding these components, thus to avoid dispersion over the output fractions. This is supported by the conclusion from Johansson and Björklund [31] that states that targeted disassembly prior to shredding of WEEE may have an effect on overall resource consumption and global warming potential. Chancerel et al. [21] also concluded that political focus on improved collection and better control of the flow is a necessary step to ensure effective treatment and increase the recovery of precious metals. The results of the LCA clearly shows that the recovery of metals, although the overall process has low recovery rates for some precious metals, is a significant feature of WEEE treatment. This supports, as suggested by Chancerel [32], Huisman [12] and UNU [2], that the recycling targets of the WEEE directive should be based on recovery of the individual metals and not on an overall weight basis. The metal recovery rates for the precious metals can vary significantly depending on actual disassembling and shredding [33] and the values we have employed may be low. However, higher recovery rates would only make the results even more outstanding and thus further confirm our conclusions.

The two allocation methods used gave in this study about the same results (Table 11). This may not be a general conclusion since the two methods differ much in the way they performed. The way specific streams, e.g. the PGM slime, were included in one but not the other allocation method has affected the results. Minor effects of the allocation method were observed with respect to ecotoxicity in soil (ETs), ecotoxicity in water (ETw) and stratospheric ozone depletion (SOD). No effects were observed for the resource consumption. We are confident that the conclusion that we made from this study was not sensitive to the allocation method.

4. Conclusion

Based on available data in the literature the recovery of aluminium, copper, gold, iron, nickel, palladium and silver from high-grade WEEE was modeled by LCA. The overall recovery of metal from WEEE results in significant environmental savings as well as savings in resource consumption. These savings are most likely underestimated since we did not find adequate data to include all the burdens from mining and refining of ore; burdens that are avoided when metals are recovered from WEEE.

The resource recovery of metals like copper, gold, nickel, palladium and silver is a significant benefit of treatment of high-grade WEEE. The results confirms that the pre-treatment of WEEE should aim at reducing its apparent losses of precious metals as gold, palladium and silver. Our results also supports in a quantitative manner that metal recovery from WEEE should be quantified with respect to the individual metals recovered and not as a bulk metal recovery rate.

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References

[1] WEEE-Directive, 2002/96/EC of the European parliament and of the council of 27 January 2003 on waste electrical and electronic equipment (WEEE), 2002.

[2] United Nations University (UNU), 2008 Review of directive 2002/96 on waste electrical and electronic equipment (WEEE) final report, contract no.: 07010401/2006/442493/ETU/G4ENV.G.4/ETU/2006/0032, Bonn, Germany, 2007.

[3] 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 (RoHS) in electrical and electronic equipment, 2002.

[4] O. Tsydenova, M. Bengtsson, Chemical hazards associated with treatment of waste electrical and electronic equipment, Waste Manage. 31 (2011) 45–48.

[5] United Nations Environment Programme (UNEP), StEP Task Force "ReCycle" Recycling – From E-waste to Resources, United Nations Avenue, Gigiri PO Box 30552, 00100 Nairobi, Kenya. <www.unep.org/PDF/PressReleases/E-Waste_publication_screen_FINALVERSION-sml.pdf>, 2009 (accessed December 2010).

[6] A. Andrea, O. Andersen, Life cycle assessments of consumer products—are they consistent? Int. J. Life Cycle Assess. 15 (2010) 827–836.

[7] C.K. Mayers, C.M. France, S.J. Cowell, Extended producer responsibility for waste electronics: an example of printer recycling in the United Kingdom, J. Ind. Ecol. 9 (2005) 169–189.

[8] P. Park, K. Tahara, I. Jeong, K. Lee, Comparison of four methods for integrating environmental and economic aspects in the end-of-life stage of a washing machine, Resour. Conserv. Recycl. 48 (2006) 71–85.

[9] C. Hagelüken, C. Meskers, Mining our computers—opportunities and challenges to recover scarce and valuable metals from end-of-life electronic devices, Electronics Goes Green 2008+, Merging Technology and Sustainable Development, Berlin, Germany, 7–10 September 2008. <http://www.preciousmetals.umicore.com/PMR/Media/e-scrap/> (accessed December 2010).

[10] Ecoinvent, V2.0, Swiss Centre for Life Cycle Inventories, 2006, c/o Empa/Technology & Society Lab (TSL), Lerchenfeldstrasse 5, 9014 St-Gallen, Switzerland.

[11] R. Hischier, P. Wäger, J. Gauglhofer, Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling system for waste electrical and electronic equipment (WEEE), Environ. Impact Assess. Rev. 25 (2005) 525–539.

[12] J. Huisman, The QWERTY/EEE concept, quantifying recyclability and eco-efficiency for end-of-life treatment of consumer electronic products, Doctorial thesis, Delft University of Technology, Design for Sustainability program, 2003.

[13] J. Cui, L. Zhang, Metallurgical recovery of metals from electronic waste: a review, J. Hazard. Mater. 158 (2008) 228–256.

[14] Boliden, Rönnskär, Smelter, Boliden, Mineral AB, Rönnskär Smelter, SE-932 81, Skelleftehamn, Sweden. <www.boliden.com>, 2005 (accessed December 2010).

[15] M. Classen, H.-J. Althaus, S. Blaser, M. Tuchschmid, N. Jungbluth, G. Doka, M.F. Emmenegger, W. Scharnhorst, Life Cycle Inventories of Metals. Final Report Ecoinvent Data v2.0, No. 10, EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, 2007 (accessed December 2010) www.ecoinvent.ch.

[16] R. Hischier, M. Classen, M. Lehmann, W. Scharnhorst, Life cycle inventories of Electric and Electronic Equipment: Production, Use and Disposal, Ecoinvent Report No. 18, Empa/Technology & Society Lab, Swiss Centre for Life Cycle Inventories, Dübendorf, 2007.

[17] T. Ekvall, G. Finnveden, Allocation in ISO 14041—a critical review, J. Clean. Prod. 9 (2001) 197–208.

[18] Boliden, Hälsa, Miljä, Säkerhet, Statistik fran 2005, Boliden Mineral AB Rönnskär Smelter, SE-932 81, Skelleftehamn, Sweden. <www.boliden.com>, 2006 (accessed December 2010).

[19] M. Borell, M. Wik-Persson, L. Aberg, Miljörapport 2006 Rönnskärsverken och Rönnskärs Hamn, Boliden Mineral AB, Rönnskär Smelter, SE-932 81, Skelleftehamn, Sweden, 2007.

[20] Umweltbundesamt Data and Information with Respect to the Primary Non-Ferrous Metal Industry (Zinc, Copper, Lead and Nickel Works), Umweltbundesamt, Berlin, 1999.

[21] P. Chancerel, C. Meskers, C. Hagelüken, S. Rotter, E-scrap metals too precious to ignore, E-Scrap Res. (2008) 42–44 (November).

[22] J. Legarth, J. Gregersen, H. Erichsen, Miljøspecifikationer for elektroniske tele-og dataprodukter, Arbejdsrapport fra Miljøstyrelsen 2 (2001) (accessed December 2010) www2.mst.dk/udgiv/Publikationer/2001/87-7944-378-8/pdf/87-7944-379-6.PDF.

[23] P. Chancerel, Techniche Universität Berlin, Department of Environmental Technology, Chair of Solid Waste Management, personal communication, 2008.

[24] EASEWASTE, Life Cycle Assessment Tool for Integrated Solid Waste Management, Department of Environmental Engineering, Bygningstorvet 115, Technical University of Denmark, 2800 Kgs Lyngby, Denmark, 2010.

[25] J.T. Kirkeby, H. Birgisdottir, T.L. Hansen, T.H. Christensen, G.S. Bhander, M. Hauschild, Environmental assessment of solid waste systems and technologies: EASEWASTE, Waste Manage. Res. 24 (2006) 3–15.

[26] H. Wenzel, M. Hauschild, L. Alting, Environmental assessment of products Methodology Tools and Case Studies in Product Development, vol. 1, Chapman & Hall, London, 1997.

[27] H.K. Stranddorf, L. Hoffmann, A. Schmidt, Impact Categories, Normalization and Weighting in LCA, Danish Environmental Protection Agency, Danish Ministry of the Environment, Copenhagen, Denmark, 2005 (updated on selected EDIP97-data. Environmental news no. 78).

[28] J.T. Kirkeby, H. Birgisdottir, T.L. Hansen, T.H. Christensen, G.S. Bhander, M. Hauschild, Evaluation of environmental impacts from municipal solid waste management in the municipality of Aarhus, Denmark (EASEWASTE), Waste Manage. Res. 24 (2006) 16–26.

[29] J. Engels, Expert management system for surface tailings storage, PhD thesis, University of Leeds, 2006. <www.tailings.info/tailings.htm> (accessed December 2010).

[30] European Commission, Critical Resources for the EU, Bruxelles, 2010.

[31] J.G. Johansson, A.E. Björklund, Reducing life cycle environmental impacts of waste electrical and electronic equipment recycling, J. Ind. Ecol. 14 (2009) 258–269.

[32] P. Chancerel, Substance analysis of the recycling small waste electrical and electronic equipment, an assessment of the recovery of gold and palladium, doctorial thesis, Techniche Universität Berlin, Department of Environmental Technology, Chair of Solid Waste Management, 2009.

[33] C.E.M. Meskers, C. Hagelüken, S. Salhofer, M. Spitzbart, Impact of pre-processing routes on precious metal recovery from PCs, in: European Metallurgical Conference (EMC), 2009 (accessed December 2010) http://www.preciousmetals.umicore.com/PMR/Media/e-scrap/show_impactOfDifferentPreprocessing.pdf.