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Published in:
Proceedings of the IEEE International Symposium on Electronics and the Environment

Link to article, DOI:
10.1109/ISEE.1995.514963

Publication date:
1995

Document Version
Publisher's PDF, also known as Version of record

Sustainability Issues in Circuit Board Recycling

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Abstract-The resource recovery and environmental impact issues of printed circuit board recycling by secondary copper smelters are discussed. Guidelines concerning material selection for circuit board manufacture and concerning the recycling processes are given to enhance recovery efficiency and to lower the impacts on the external environment from recycling.

I. INTRODUCTION.

The issues of environmental preservation have attracted increased worldwide attention throughout the latter part of this century, reaching new hights at the UNCED conference in Rio de Janeiro in 1992. Seemingly pre-set factors like the ever growing world population and the increasing demand for wealth by the less developed countries are threatening to exhaust our so-called environmental space [1] - the reserves of natural resources and the amount of pollution the earth can cope with. To be able to still fit into the available environmental space also in the future, the concept of sustainable development first introduced in the Brundtland report [2], is now gaining momentum in many areas of human activity. Not least in the manufacturing industry, where the truly great contemporary challenge lies in supplying the world community with material wealth, utilizing a limited amount of environmental space. Contributing to a sustainable society is becoming a survival issue in corporate development.[3]

In practice this means reducing the draw on natural resources and lowering the impact on the external environment. These are the very parameters measured by so-called life cycle assessments, and the life cycle concept is proving a truly essential tool in reaching the goals of a sustainable society [4][5]. Manufacturers are becoming responsible for the environmental performance of their products throughout the products life cycle, from extracting the raw materials to the disposal of the products at their end-of-life.

The product life cycle is defined by the manufacturer. Life cycle engineering is the art of designing the product life cycle through choices about product concept, structure, materials and processes, and life cycle assessments is the tool that visualizes the environmental and resource consequences of these choices [6]. Consequences may arise in any of the life cycle phases, but the production and disposal phases have received special attention, because these are the phases, which the manufacturer may most easily influence.

We shall focus on the disposal phase, which is relevant both with regard to resource conservation (through recycling) and with regard to impacts on the external environment. The waste problem has attracted special attention because of the shortage of landfill sites in the western world, but there is a whole range of other relevant impact types from the end-of-life phase, including the toxicity issue, global warming and the regional and local effects on the external environment.

Many complex products in the modern society rely on electricity to function, and are categorized as electric or electronic products. There are three sources of environmental problems in the disposal of these products, namely the cathode ray tubes containing heavy metals, the technical thermoplastics containing various problematic additives, and finally the printed circuit boards with their complex mixture of chemical substances [7]. The circuit boards constitute a special challenge due to their complexity, and we shall focus on the analysis of resource conservation issues and environmental impacts from the contemporary recycling of printed circuit boards by secondary copper smelters.

II. CONTEMPORARY CIRCUIT BOARD RECYCLING.

Secondary copper smelters recover copper, some other base metals and the noble metals gold, silver, platinum and palladium from printed circuit board (PCB) scrap. About 95% of the value is recovered, due to the recovery of copper and noble metals [8]. From an economical point of view, PCB scrap is simply a noble metal source for the secondary copper smelter, and it is for this reason that the

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smelters receive and process high value computer PCB scrap. Computer PCB scrap is a quite valuable scrap type, the total metal value being in the range of several thousand US dollars per metric ton, depending on noble metal content.

The secondary copper smelters ordinarily operate with the so-called Knudsen process, a shaft furnace and converter technique, followed by anode casting, electrolytic copper refining and copper cathode casting. The secondary smelter in Brixlegg, Austria is a well described smelter [9][10][11], and we shall use it as a case for further study.

In Brixlegg PCB scrap and other scrap with a copper content of up to 30% is fed to a shaft furnace along with returned slag from the converter and anode furnaces. Typically 8-12 % coke is added along with flux (lime and quartz), and the coke delivers the heat for the melting and the reductive agent CO. The melting in the shaft furnace is done in order to separate base metals such as iron, aluminum, zinc, lead, nickel and tin from the copper. The primary product is black copper with a copper content of approx. 80 % and minor amounts of the other base metals. The black copper serves also as a so-called collector metal for the noble metals. About 90 % of the silver and about 100 % of the gold is recovered in the black copper. As by-products a slag poor in copper but rich in flux and iron oxide is formed which may be used for sand blasting, and a filter dust containing primarily zinc oxide, but also tin and lead oxides and some copper.

The liquid black copper is charged in the side blown converter with oil firing along with other copper rich scrap (30-80% copper). The process is bessemerization in the presence of 5-10 % iron. The iron oxidizes, and this delivers the main part of the necessary heat. For this reason iron is added to the charge. In the process volatile base metal oxides are formed at the nozzles, and they evaporate to collect in the filter dust. The main product is so-called crude copper with approx. 96 % copper. A primary slag with high iron oxide content is first removed and as the process continues a slag with iron -, tin -, nickel - and zinc oxides and about 25 % copper is formed (this slag is returned to the shaft furnace). A filter dust rich in zinc, lead and tin oxides is also formed.

Crude copper is charged in an anode furnace with high-quality copper scrap. This pyrometallurgical refining process is primarily an oxidation of the rest of the base metal impurities, which are slagged or collected in a filter dust. The 99 % copper melt is cast to anodes, which contain all the noble metals.

The anodes are electrolytically refined in a copper tank-house to high purity cathodes in a sulfuric acid based electrolyte. During the electrolysis noble metals concentrate in a solid slime forming under the anode, the so-called anode slime (ca. 10 kg per metric ton anode). The anode slime is collected. Nickel sulphate is formed and collected during the electrolysis for use in the galvanic industry.

Finally, the cathodes are cast and shaped to commercial grades of high purity copper.

In the course of these processes two side products are formed: A base metal rich filter dust and a noble metal rich anode slime. The filter dust contains major amounts of zinc, copper, tin and lead, and since quite a lot of filter dust is formed, the dust is a valuable source of these base metals. The treatment of anode slime and filter dusts is hydrometallurgical, and has minor relevance with respect to impacts on the external environment, but is important with respect to the recourse conservation issue.

TABLE I
TYPICAL RECOVERY RATES BY SECONDARY COPPER SMELTERS

Metal	Au	Ag	Pt	Pd	Cu
Recovery rate %	98	90	90	90	99
Metal	Ni	Pb	Sn	Zn	
Recovery rate %	85	85	80	85	

The efficiency of Brixlegg secondary copper smelter in recovering metals from scrap may be assessed from the general literature about Brixlegg and secondary copper smelters [9][10][11][12][13][14][15]. Typical recovery rates E_i are given in table I - they are thought to be representative, but, of course, they vary from batch to batch.

III. THE RESOURCE CONSERVATION ISSUE.

When dealing with the evaluation of resource consumption or resource recovery, a quantitative measure is needed, which allows the scientist to make a simple statement about the quantity of resources consumed or recovered. We propose such a quantitative measure which states resource recovery in terms of one number: The resource recovery efficiency (RRE). We further propose a similar quantitative measure of the basis of resource recovery: The resource recovery potential (RRP). The RRE states how much of the RRP is realized by a recycling system.

In constructing the RRP the starting point is a factor describing the consequences of the recycling action - the time of primary production saved by the recycling action. This is a measure of how long the use of the primary resource may be prolonged because of the recycling action - using todays primary consumption rate as the basis of the prognosis. In practice this factor is calculated by dividing the amount of the resource (to be recycled) in one metric ton of scrap by the annual primary production of the resource in question, also measured in metric tons.

The above factor is then multiplied with another factor indicating the importance of resource conservation, which is defined as the annual primary consumption of the resource in question divided by the total world reserves of the resource, both measured in metric tons. This product is calculated for each of the resources in the scrap and the RRP is the sum of factor products RRP_i. The RRP for one kind of scrap may be compared with the RRP for another kind of scrap to see which scrap has the higher RRP, but here we shall use the RRP merely as a potential, which may be realized to a certain degree by some recycling system, and on the basis of which it is possible to point out the important resources in PCBs.

Assuming that the annual primary resource production corresponds to the annual primary resource consumption in the year of the calculation, a simpler expression arises, namely the sum of the amount of the resource in one metric ton of scrap divided by the world reserves estimated in the year of the calculation. This approximation will be used in the following.

$$RRP = \sum_i \frac{F_i}{P_i} \cdot \frac{C_i}{R_i} \sim \sum_i \frac{F_i}{R_i} \qquad \textbf{(1)}$$

F is the amount of the resource in one ton of scrap, P is the annual primary production of the resource, C is the annual consumption of primary resource, R is the world reserves of the resource, and $_i$ counts the types of resources in the scrap.

The RRE is constructed from the RRP by multiplying each of the factor products RRP_i by the percentage of the resource actually recovered by the recycling system E_i. Whereas the RRP is solely connected to the scrap, the RRE is connected to the recycling system, and there may be more than one RRE for each RRP corresponding to more than one way of recycling the scrap. The RRE states the performance of the recycling system in realizing the potential RRP, in that RRE divided by RRP can be interpreted as an efficiency, expressed as a fraction or a percentage.

$$RRE = \sum_i E_i \cdot \frac{F_i}{P_i} \cdot \frac{C_i}{R_i} \sim \sum_i E_i \cdot \frac{F_i}{R_i} \qquad \textbf{(2)}$$

A PCB case is needed in order to calculate the resource recovery potential of printed circuit boards and the resource recovery efficiency for the secondary copper smelter. We have chosen a computer PCB case [16][17], computer PCB being the typical PCB scrap recycled by secondary copper smelters. The case is shown in figure 1.

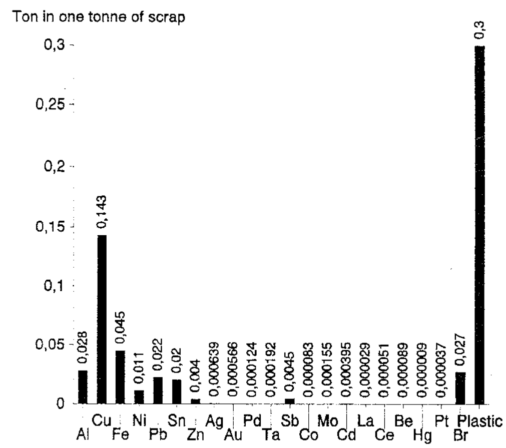

Fig. 1. A typical computer PCB composition.

The assessments of the RRP_i and the RRE_i values are shown in figure 2. (Reserve estimates from [18]). Total RRP reaches approx. 175 times E-10 and total RRE approx. 142 times E-10, resulting in a recovery efficiency of about 80%. This efficiency is a maximum, because not all PCB constituents are accounted for in the calculation of the total RRP. (Critical resources in PCB scrap not accounted for in this analysis probably include gallium and some platinum group metals, most prominently ruthenium.)

It is clear that the noble metals and tin, tantalum, antimony, cadmium and beryllium account for most of the total resource recovery potential. These are the critical resources used in PCBs as opposed to e.g. iron and aluminum, which receive rather low RRP_i scores. Tin and the noble metals are recovered to a large extend, but tantalum, antimony, cadmium and beryllium are not recovered. The total lack in efficiency is about 20%. A 90% recovery of tantalum, antimony, cadmium and beryllium would increase the efficiency to about 94%.

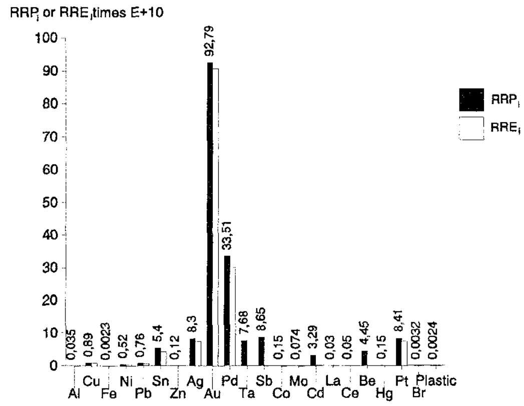

Fig. 2. The resource recovery potential and - efficiency.

IV. ENVIRONMENTAL IMPACTS FROM RECYCLING.

In the following we shall analyze the recycling of printed circuit boards by secondary copper smelters with respect to potential impacts on the external environment. Using the paradigm of life cycle assessments we go through steps of inventory and impact assessment.

The unit processes of the recycling system are investigated in the inventory step, where emissions to land, water and air, energy consumption and consumption of materials are quantified corresponding to the production of one metric ton of copper from the above mentioned PCB case. These parameters govern the impact on the external environment, directly through emissions from the recycling processes, or indirectly from the production of the energy and materials consumed.

The data from the inventory are subsequently translated into measures of the potential impact on the external environment in the impact assessment step. We use the impact assessment methodology of the Life Cycle Center, Denmark [6][19][20][21]. The result is an environmental profile, expressing the potential impact on the external environment in terms of so-called personal equivalents (PEs). One PE indicates the average share that one person living in the region affected by the environmental effect has in the total annual potential impact on the regions environment from the environmental effect in question. Effects may be global (e.g. global warming), regional (e.g. acidification) or local (e.g. toxicity). We have chosen to focus on the effects global warming, acidification, nutrient enrichment and photochemical ozone creation (photosmog), excluding ozone depletion, because there are no contributions to this effect, and excluding toxicity because the baseline data available cannot support a representative investigation.

TABLE II
BASELINE DATA

Key parameters per ton copper produced from the PCB case			
Process	**Input/output**	**Quant.**	**References**
Shaft furnace	Coke	400 kg	[10][22][23]
	Lime	132 kg	ass. from [9]
	Quartz	296 kg	ass. from [9]
	Process air	2600 m^3	[10]
Converter	Process air	1220 m^3	[10]
	Iron	120 kg	ass. from [11]
Anode furnace	Process air	(30 MJ)	[23]
	Heavy fuel oil	100 kg	[10]
Tankhouse	Electricity	400 kWh	[10]
	Steam	560 kg	ass. from [10]
	Heavy fuel oil	19 kg	ass. from [10]
Cathode casting	Electricity	360 kWh	[10]

Observing these considerations, the system under investigation is the very core of the smelter operation (shaft furnace, converter, anode furnace, tankhouse, cathode casting), disregarding environmental impacts from plant support (administration etc.) and environmental protection routines (fans for filters, the operation of flue gas cleaning systems etc.). We have restricted our study to the core of the operation, because this is where important suggestions to altered operational practices or information on which materials to avoid in PCBs can be derived from.

The environmentally significant baseline data for the five major smelter operations are shown in table II. The data are representative, but may vary from batch to batch. The data are predominantly energy consumption data and data on major material consumptions, including the amounts of oxygen enriched process air. From these data it is possible to calculate the potential environmental impacts from the smelter core operations, using the EDIP database and impact assessment tool of the Life Cycle Center, Denmark. The total potential contributions to the four environmental effect types per ton copper produced are shown in table III along with those from the production of primary copper, for comparison.

In order to make solid suggestions to altered operational practices and on which materials to avoid in printed circuit boards, it is important to know exactly where the impacts come from. In figure 3 the sources of the potential impacts are traced.

TABLE III

TOTAL ENVIRONMENTAL IMPACTS FROM SMELTER CORE OPERATIONS

Effect type	Global Warming	Acidification	Nutrient Enrich.	Photo-smog
From PCB	334 mPE	47.8 mPE	56.2 mPE	37.0 mPE
Primary	567 mPE	429 mPE	138 mPE	181 mPE

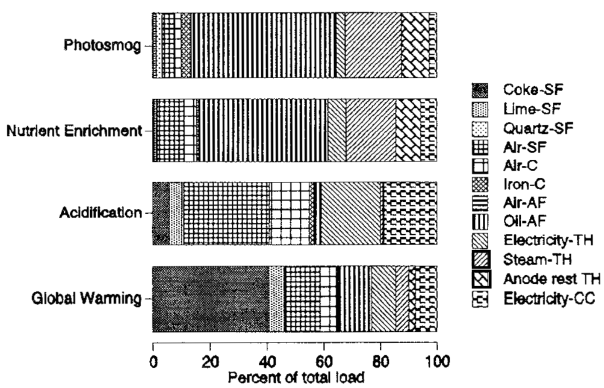

Fig. 3. Breakdown on impact sources.

Contributions to global warming are associated with any use of energy, which is produced from fossil fuels, either the direct burning of coke or oil in the furnaces or the production of electrical energy in power plants. In the scenario under investigation, coke burning contributes with 40% of the total potential global warming impact, and the use of electricity associated with the use of oxygen enriched process air in the shaft furnace and the burning of heavy fuel oil in the anode furnace contribute with 12% each.

Because the secondary copper smelter uses an effective sulfur dioxide quenching, the sulfur in coke and heavy fuel oil does not contribute much to the total potential acidification impact. The major acidification contributions come from electricity production, and as electricity is used primarily to produce oxygen enriched process air (45% of acidification potential) and for the tankhouse (21%) and cathode casting (19%) operations, these are the operations giving rise to acidification in the region.

Nutrient enrichment contributions are almost uniquely associated with the production and burning of heavy fuel oil, the use of heavy fuel oil in the anode furnace contributing with 55% of the total potential impact alone. Exactly the same goes for photochemical ozone creation (photosmog), where the heavy fuel oil consumption in the anode furnace contributes with 51% of the total potential photosmog impact.

But what can be achieved by adjusting PCB metal composition? The major amount of the impurities from the PCB metal mixture is removed in the shaft furnace and in the converter. These are the true refining processes, whereas the anode furnace and tankhouse operations rather are steps of purification. The cathode casting is only done to achieve marketable copper shapes. So it is evident that whereas an adjustment of the PCB metal composition may influence the potential environmental impacts from the shaft furnace and converter operations, it may influence those from the anode furnace and tankhouse only to a much lesser degree.

In the shaft furnace major non-copper metals are either slagged or collected as filter dust, involving the oxidation of the metals in both cases. The oxidation is achieved by blowing oxygen enriched air through the melt, and the very environmental impacts associated with the use of oxygen enriched air are those arising most directly from having to remove the major metal impurities. Since major contributions to the overall environmental impact comes from the use of oxygen enriched air, a reduction in the consumption of this "material" would lead to notable impact reductions.

The major shaft furnace slag constituents are iron, zinc and aluminum oxides, and the major shaft furnace flue dust constituents are zinc and lead oxides. A similar reasoning applies to the converter operation, where the iron added for the bessemerization process and the rest of the impurities are removed. So major reductions in environmental impact may be achieved by reducing the PCB scraps content of primarily iron and aluminum.

V. COURSE OF ACTION

There are two ways to reduce the environmental impacts or the resource loss from PCB recycling in secondary copper smelters, either by changing the material composition of the PCBs themselves or by altering the recycling practices.

Turning first to the resource conservation issue. The resource loss is mainly due to the lack of recovery of the metals tantalum, antimony, cadmium and beryllium. These metals occur only in trace amounts, and to improve the recovery processes of the secondary copper smelter to recover these constituents will be associated with high costs and presumably relatively high energy consumptions, ruling this course of action out. The best way of avoiding the loss of these resources is simply not to use them in electronic components at all. Cadmium and beryllium are toxic, and the use of these elements will probably phase out due to increased general environmental awareness alone. Antimony is used in flame retardant systems along with brominated compounds, and the toxicity problems associated with the formation of dioxins and furans from the brominated compounds is already leading to new products, f.x. laminates, with non-antimony and non-bromine flame retardants. Tantalum is used in tantalum capacitors, and only by finding competitive substitutes may the loss of this critical recourse be avoided.

Regarding the impacts on the external environment, major reductions in acidification impact may be achieved by avoiding the use of iron and aluminum in electronic components. From an environmental point of view, considering the disposal phase, a good substitute would be copper itself.

Concerning the global warming contributions; these are associated with using fossil fuels for melting and vaporizing, and in general the less non-copper need to be melted or vaporized, the lower the impact. So again the culprits are the major non-copper constituents of the PCB metal mixture, primarily iron and aluminum.

Concerning nutrient enrichment and photosmog, both associated with the use of heavy fuel oil, a reduction may be achieved by using fuel with less organic nitrogen, NO_x being the major contributor to nutrient enrichment, and by the installment of after burners, reducing the photosmog contributions from insufficient combustion of the petrochemical substances.

Although the issue has not been quantified in the analysis, any toxicity contribution may, of course, be reduced by avoiding toxic elements such as cadmium, mercury, beryllium, arsenic, lead and chromium. Lead-free soldering techniques would be a good step in the right direction. Concerning the necessary information on component material content, a recent Danish study is very helpful [24].

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