Gold Bulletin
Volume 43 No 3 2010

Recycling of gold from electronics: Cost-effective use through 'Design for Recycling'

Christian Hagelüken[1] and Christopher W Corti[2]

www.goldbulletin.org

Abstract

With over 300 tonnes of gold used in electronics each year, end-of-life electronic equipment offers an important recycling potential for the secondary supply of gold. With gold concentrations reaching 300-350 g/t for mobile phone handsets and 200-250 g/t for computer circuit boards, this "urban mine" is significantly richer than what is available in primary ores.

However, the "mineralogy" in scrap products is much different than in the conventional ores in a gold mine: Up to 60 different elements are closely interlinked in complex assemblies and sub-assemblies, and this requires specialised metallurgical processes with extensive offgas treatment to recover gold and a wide range of other metals cost effectively and in an environmentally sound way. Moreover, the logistics to "excavate" and "haul" the scrap products to the concentrator and further to the smelter are much more challenging than in the primary supply chain. Currently, only a small portion of old products is collected and directed into state-of-the art recycling chains. Significant improvements are needed here to fully utilise this secondary metal resource.

The importance of the gold content of scrap electronics to the economics of recovery of gold and many other valuable metals is not always appreciated and this impacts on the 'design for recycling' approach in selecting materials for new products, particularly in the European Union where the WEEE Directive aims to provide a closed loop economy. With a lower carbon footprint than primary-mined gold, recycled gold represents an important 'green' source. The challenges faced in recycling electronic scrap to achieve a closed loop economy are discussed.

Introduction

Besides its main use in jewellery and investment, gold plays an increasingly important role in industrial applications among which electronics has by far the biggest share. Today well over 300t of gold are used annually in electronic components such as ICs, contacts and bonding wires. Although miniaturisation and thrifting efforts drive down the specific gold input, the booming growth in sales of electronic devices and their inbuilt features to become "smarter and quicker every year" have led to a substantial net increase in gold demand over recent years [1]. Mobile phones and computers are a good example in this context, Figure 1.

At the end of their use, these and other electronic products offer an important recycling potential for the secondary supply of gold. With gold concentrations reaching 300-350 g/t for mobile phone handsets and 200-250 g/t for computer circuit boards, this "urban mine" is significantly richer than what today is available in primary ores. However, the "mineralogy" in scrap products is much different than in the mine: Up to 60 different elements are closely interlinked in complex assemblies and sub-assemblies, usually connected to organics, which often contain halogenated flame

[1] *Umicore Precious Metals Refining, Rodenbacher Chaussee 4, D-63457 Hanau, Germany.*
E-mail: christian.hagelueken@eu.umicore.com
[2] *COReGOLD Technology, Reading, UK.*
E-mail: chris@corti.force9.co.uk

Footnote: *This paper has been adapted from the Plenary Lecture presented by Christian Hagelüken at GOLD 2009, Heidelberg, July 2009*

Figure 1

a) Mobile phones	
1300 Million units	
x 250mg Ag	325 t Ag
x 24mg Au	31 t Au
x 9mg Pd	12 t Pd
x 9 g Cu	12,000 t Cu
1300 Million batteries	
x 3.8 g Co*	4800 t Co
*Li-ion type	

b) PC and laptops	
300 Million units	
x 1000mg Ag	300 t Ag
x 220mg Au	66 t Au
x 80mg Pd	24 t Pd
x 500 g Cu	15,000 t Cu
140 Million laptop batteries	
x 65 g Co*	8100 t Co
*Li-ion type	

c) World mine production	**a+b share**
Ag: 21,000 t/a	3%
Au: 2,400 t/a	4%
Pd: 220 t/a	16%
Cu: 16 Mt/a	<1%
Co: 60,000 t/a	23%

Volume counts – content of gold and other metals in mobile phones and computers in relation to total demand from these appliances and world mine production

retardants (boards, casings and other plastic parts). It requires specialised metallurgical processes with extensive offgas treatment to recover gold and a wide range of other metals cost effectively and in an environmentally sound way. And since the secondary "ore body" is widely spread over millions of households, businesses and individual consumers around the world, logistics to "excavate" and "haul" the scrap products to the concentrator and further to the smelter are much more challenging than in the primary supply chain.

State-of-the-art recovery technologies make use of large scale integrated smelter-refinery operations (such as the Umicore plant at Hoboken/Antwerp). Circuit boards, mobile phone handsets and many other precious metals-containing secondary materials are treated in a complex metallurgical flowsheet. In the case of Umicore, at the end of this, pure gold and 16 other metals are recovered with high yields. This paper examines the importance of gold to the economics of recycling of electronic scrap against the background of the WEEE (Waste Electronic and Electrical Equipment) European Directive that aims to provide a 'closed loop' economy, i.e. to foster environmentally sound reuse/recycling and to preserve natural resources. It demonstrates that using gold in electronic equipment in a 'design for recycling' approach is cost-effective. The recycling processes in use and the significance of the preceding steps of collection and preprocessing to achieve overall high recovery rates is covered. Attention is also given to the current severe deficits in the recycling chain, including illegal and dubious exports of end-of-life electronics and their substandard treatment in backyard recycling operations in many developing and transition countries.

Material composition of electronic equipment

As noted above, electronic equipment contains a wide variety of materials, some of which are valuable, some toxic or hazardous and some are both. These include the following elements:

- Precious metals: gold, silver, palladium and, to a lesser extent, platinum and ruthenium
- Base and special metals: iron, copper, aluminium, nickel, zinc, tin, cobalt, selenium, indium, gallium, etc
- Hazardous substances: mercury, beryllium, lead, cadmium, arsenic, antimony, etc
- Halogens: bromine, fluorine, chlorine
- Other substances: organics such as plastics, fluids, glass, ceramics, etc.

If such scrap is landfilled or not treated in an environmentally sound way, then it poses a high risk of environmental damage. Moreover, it contains valuable resources that can be recovered and reused, reducing the need to mine new metals. The composition of a number of typical electronic items is shown in Table 1, upper part. These figures are indicative; actual content can vary significantly but the order of magnitude is correct. Plastics and steel tend to dominate in terms of weight, but in terms of value, gold and the other precious metals dominate, as shown in the lower part of the table. For PC boards, cell phones and the calculator, gold and the

Table 1. Value versus weight distribution for typical electronic devices/components (at March 2010 prices)

Weight-share	Fe	Al	Cu	plastics	Ag [ppm}	Au [ppm]	Pd [ppm]
Monitor-board	30%	15%	10%	28%	280	20	10
PC-board	7%	5%	18%	23%	900	200	80
Mobile phone	7%	3%	13%	43%	3000	320	120
Portable audio	23%	1%	21%	47%	150	10	4
DVD-player	62%	2%	5%	24%	115	15	4
Calculator	4%	5%	3%	61%	260	50	5
Value-share	**Fe**	**Al**	**Cu**	**Sum PM**	**Ag**	**Au**	**Pd**
Monitor-board	4%	14%	35%	47%	7%	33%	7%
PC-board	0%	1%	13%	86%	5%	69%	12%
Mobile phone	0%	0%	6%	93%	11%	71%	11%
Portable audio	3%	1%	73%	21%	4%	16%	3%
DVD-player	15%	3%	30%	52%	5%	42%	5%
Calculator	1%	4%	10%	85%	6%	76%	3%

other precious metals make up more than 80% of the value, whilst for TV boards and DVDs, they still contribute around 50% of the value. Copper also contributes next in the value ratings.

Hence, any major reduction of precious metals decreases substantially the net recoverable value from electronic scrap and, therefore, the motivation to recycle scrap. WEEE-recycling in the EU and increasingly elsewhere has become a legal requirement. One has to bear in mind that a complete recycling chain needs to be remunerated. On the one hand total costs arise for collection, shipment, pre-treatment and refining within the chain, which by nature are hard to compress, as well for handling of waste fractions that cannot be recovered. On the other hand, as revenue there is the intrinsic recovered metal value and here as shown above especially gold often makes a significant contribution. With the exception of certain products such as mobile phones and computers this results in a net cost for the entire chain, but nevertheless sound recycling remains a societal necessity.

Moreover, the material composition can have a significant impact on recycling requirements – technical processes and emission controls. The varying values between types of equipment also means that mixing of very heterogeneous scrap in the collection/pre-processing stages can negatively influence recycling returns due to dilution and technical constraints. It should also be noted that legislation impacts material composition and hence recycling requirements. For example, the ban on lead (EU ROHS Directive) implies an increased use of other metals such as tin, copper, bismuth, indium and silver in solders. Additionally, new products such as MP3 players and digital cameras as well as new generation products, e.g. the shift from CRT-glass to LCD glass, can bring new material compositions, that impact on recycling requirements.

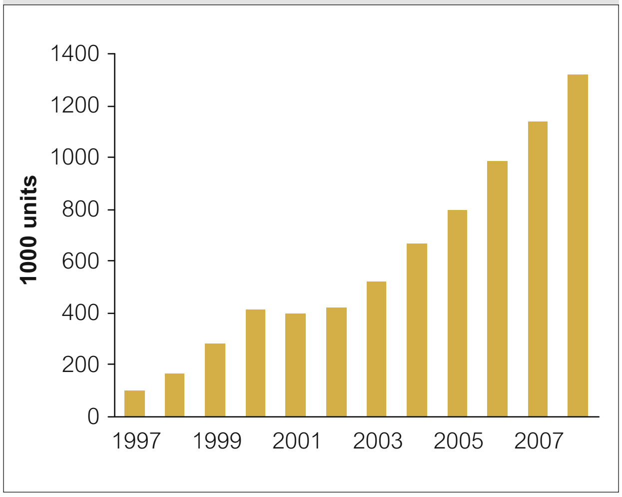
Gold in electronics: The potential market supply from recycling

As noted earlier, around 300 t of gold are utilised in electronics manufacture each year (246 t in 2009, down on 293 t in 2008 due to the effects of the world economic recession) [1]. This is circa 12% of total annual mine production of gold. Its efficient recovery from electronic scrap therefore represents a significant potential recycling source. So what is the potential market supply in gold and other valuable metals? Two examples are examined here.

Mobile phones: Global sales of mobile phones in 2008 were close to 1300 million units. At an average of 24mg Au, 250mg Ag, 9mg Pd and 9g Cu, this equates to 31tonnes Au, 325t Ag, 12t Pd and 12,000t Cu, Figure 1. If we include the batteries (Li ion type) with 3.8g cobalt each, this adds 4,600t Co to the potential supply. Up to 2008, cumulative sales of mobiles numbered 7.2 billion, Figure 2; this equates to 170t Au, 1800t Ag and 70t Pd!

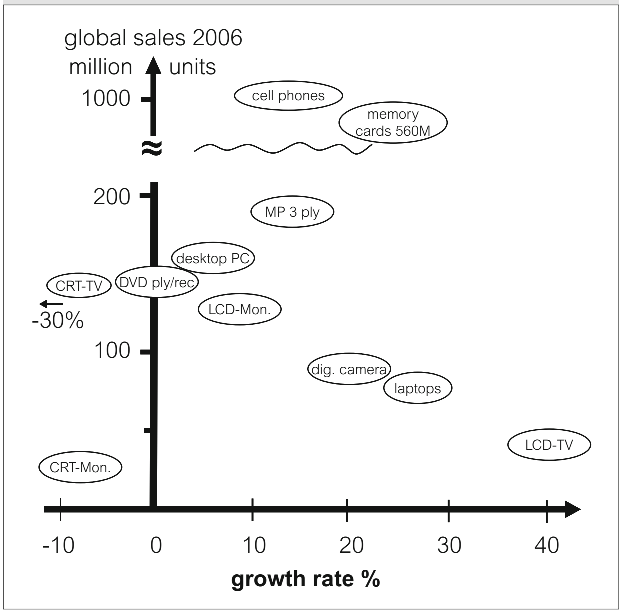
PCs & Laptops: Around 300 million units were sold in 2008. On average, each contains 220mg Au, 1,000mg Ag, 80mg Pd and 500g Cu. Laptop batteries (Li ion type;140m in total) add a further 65g Co/battery. In total this adds up to 66t Au, 300t Ag, 24t Pd, 150,000t Cu and 9,100t Co.

Figure 2



Annual global sales of mobile phones; cumulated sales make 7.2 billion until 2008 (based on sales figures from Gartner)

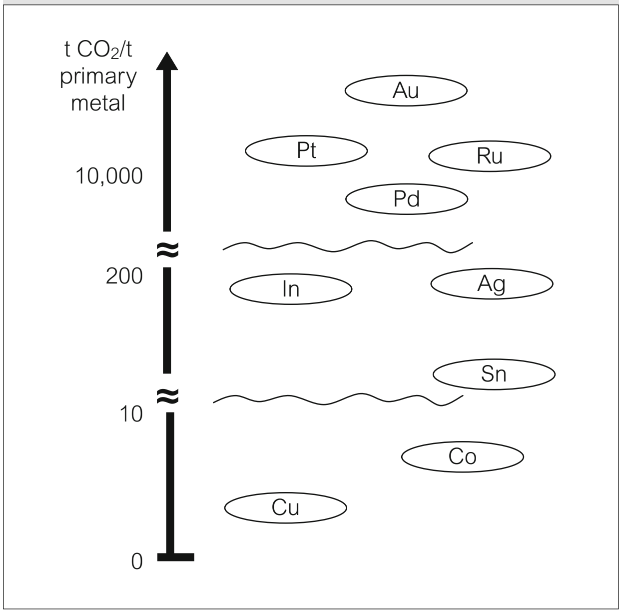
Figure 3



Unit sales versus growth rates 2006 of selected electronic applications

These total potential supplies equate to a significant proportion of world mine production: 4% for gold, 3% for silver, 16% for palladium and <1% for Cu with 23% for cobalt. In terms of the broader electronics market, Figure 3, the market supply is potentially more substantial, with European demand contributing to about 25% of global sales on average. Thus, metals demand for EEE (electronic & electric equipment) continues to grow and hence potential supplies of scrap will continue to grow.

Figure 4



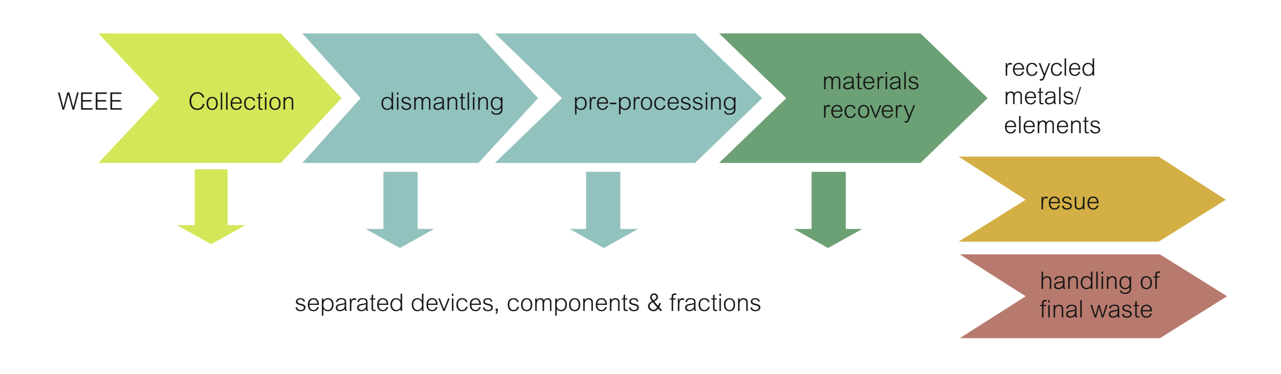
Average CO_2 impact of primary metals production based on ecoinvent 2.0 data of EMPA/ETH-Zürich

In the context of WEEE providing an 'urban' mine for gold, a typical primary gold mine will yield around 5g/tonne of gold. In electronic scrap, this rises to 200-250g/t of computer circuit boards, making it a much more attractive source. If we factor in the high CO_2 impact of primary gold production, Figure 4, due to the low ore concentration, difficult mining conditions and other factors, the recycling of scrap becomes more attractive from a sustainable standpoint. Recycling of scrap has a much lower CO_2 impact for gold production, if state-of-the-art technologies are used. Clearly, EEE scrap cannot replace all primary gold production when total demand is considered; they are complementary systems in the drive for a more sustainable use of gold. [2]

Opportunities in gold recycling: Use of state-of-the-art technologies

Whilst we all wish that recycling and waste management was simple and straightforward, the reality is quite different. As noted earlier, the composition of EEE scrap is much more complex than conventional mineral ores and this makes processing it to recover values more complex too. A mobile phone can contain up to 50 elements, which are closely interlinked in its various components. The tendency to thrift metal use and miniaturisation of components is outweighed by the absolute growth in

Figure 5



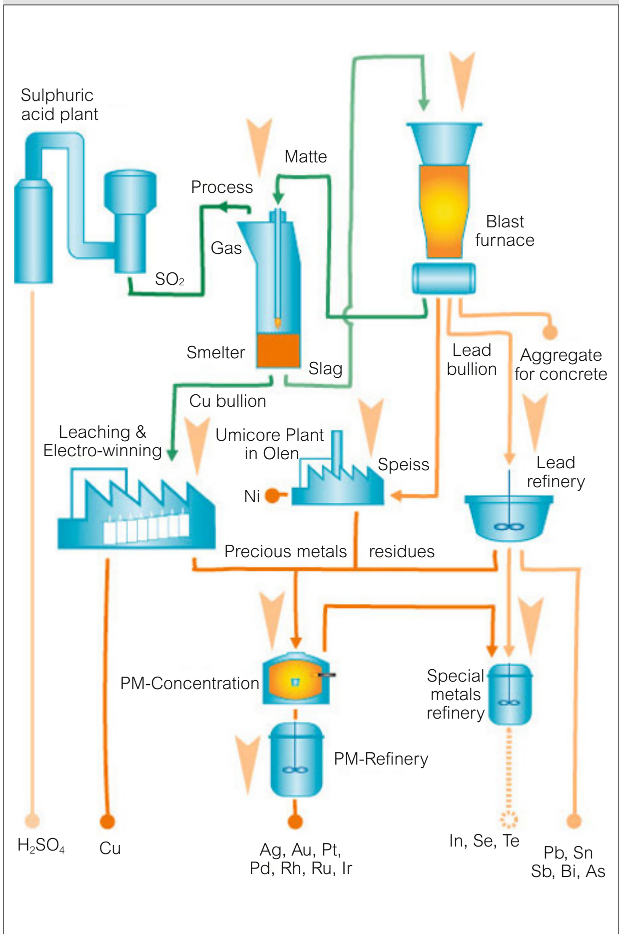
Recycling chain for End-of-Life electronics

electronic and other 'high tech' applications, as well by the trend to manufacture ever smarter devices. As precious and special metals are decisive for increasing functionality, this drives the use of gold and other "technology metals", hence gold demand in electronics is expected to grow further. The valuable metals and most hazardous materials tend to be concentrated in the circuit boards, so efficient and environmentally sound processing of the boards requires special attention.

To recycle WEEE, a well organised and dedicated recycling chain is required, Figure 5, starting with efficient collection. In the dismantling and pre-processing stages, specific material fractions need to be directed into the right end-process. In the end processing (materials recovery) stage, the recovery of the physical metals is decisive for value generation and for toxic control. For successful recycling, the optimisation of the interface between stages, specialisation of technologies and economies of scale are important. No universal recycling processes exist and no company covers all the processes. Hence an optimised flow of WEEE through the chain and a good communication between the various stakeholders is crucial, considering the entire chain and its interdependencies. The efficient metallurgical recovery of low concentration metals from complex products, such as computer circuit boards or mobile phones, needs 'high-tech' large scale processes within an appropriate infrastructure and with access to the right mix of feed materials (including non-*e*-scrap). Such favourite frame conditions are not available in many countries in the world, nor is it economically reasonable to replicate such high investment plants in too many locations. Instead, stakeholders within the recycling chain can benefit from an international division of labour as it is also daily practice in manufacturing of complex products. It needs to be understood that recycling of such products is not just a simple process but the final metals recovery step plays in the same league as their manufacturing.

When precious metal-bearing fractions enter state-of-the-art metallurgical plants, a very efficient recovery of gold and other metal values can be achieved. The integrated smelter-refinery facility at Umicore, Hoboken/Antwerp is an example of what is required, Figure 6. This can treat up to 350,000t p.a. of precious metal-bearing secondary materials of all types. Beside electronic fractions, spent automotive catalysts, process catalysts used in oil refining and chemistry, many other precious metals-bearing materials as well as side streams from non-ferrous metal smelters are treated. Recovery of gold and other precious metals in 2007 totalled US$2.6 billion, with 10 other metals contributing a further $0.4 bn. The output was about 30t Au, 37t of platinum group metals, 1,000t Ag plus 68,500t of the other 10 metals. Gold yield is close to 100%. In addition, the recovered metals represent a CO_2 saving potential of 1m tonnes compared to primary metal production (which would have had a 1.3m tonne impact). The saving represents around 80% of the CO_2 impact. The location of this facility exists since the late 19th century, but over the last 20 years the plant set-up and process technology were completely transferred from a former traditional smelter of mining concentrates to a dedicated smelter refinery of precious metals-bearing secondary materials. Over €400m has been invested just over the last 12 years; a green field replicate of the plant would represent a total investment of well over €1bn [3].

Figure 6



Aerial view and simplified process flowsheet of Umicore's integrated smelter-refinery at Hoboken/Antwerp, Belgium

The challenges and deficits in recycling of the precious metals from WEEE

As should be obvious from Figure 5, the overall recovery rates of the gold and other precious metals depend on the effectiveness of each single stage involved. The very high precious metal yields that are reached in state-of-the-art metallurgical metals recovery operations are rather insignificant if, e.g., only 50% of WEEE is properly collected or if high losses of gold-bearing fractions occur during dismantling and pre-processing. In practice, due to such inefficiencies mainly in the initial steps of the recycling chain, today less than 20% of the gold recycling potential from European WEEE is realised. The weakest part of the chain is the collection stage. There is still a long way to go in Europe and many other countries in organising efficient collection of WEEE. Governments need to take this seriously and facilitate better collection systems.

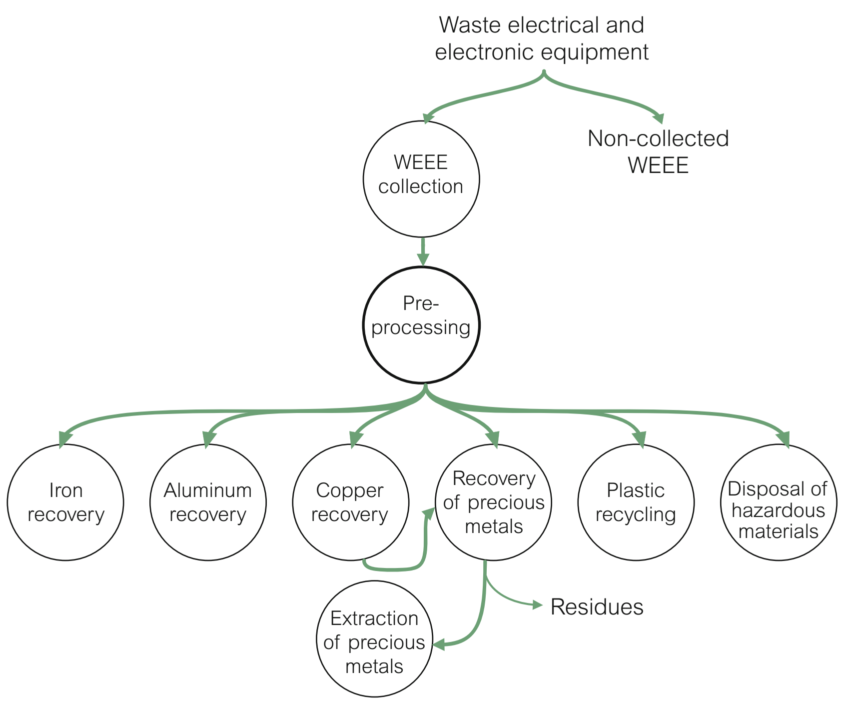
In addition, often in pre-processing high (and avoidable) losses also occur. As displayed in Figure 7, pre-processing breaks up devices into main material fractions and channels these into the appropriate end-processing/material recovery processes. If, e.g., computer circuit boards are not removed at an early stage – to be supplied directly to appropriate metallurgical recovery processes - incomplete metals liberation and dust formation of the shredder process lead to unintended co-separation of precious metals into the sorting output fractions, from where they cannot be recovered anymore. For example, gold would be lost if directed into an Al- or Fe-smelter, or if ending up in a plastics or glass recovery process [4].

However, the biggest loss factor currently is that much WEEE is exported to developing countries in Asia and Africa for treatment or even for just being discarded after some few reusable devices and components have been removed. Most of these exports are illegal or at least dubious. Usually, WEEE is declared as reusable second-hand goods to circumvent the restrictions of the Basel Convention on trans-boundary shipments of waste. In reality, the outgoing containers are filled largely with non-reusable scrap. With ten thousands of containers leaving the European ports every day, controls are challenging and enforcement of the legislation so far is weak [5].

If recycling takes place at all in the WEEE importing country such as China and India, it is usually low-tech 'backyard' recycling with dramatic environment and health impacts, particularly on the workers employed and the local communities [6-8]. Although often collection and dismantling of products work quite efficiently, the weak point is the refining of complex components such as batteries, circuit boards or mobile phones, and the handling of hazardous fractions. Devices and parts thereof are burnt under an open sky to concentrate metals, metals are leached out with cyanide or strong acids without protection methods or effluent treatment, and waste fractions are just discarded into the landscape. Severe environmental impacts from this occur at 3 levels: (a) from the product itself when landfilled, e,g, release of lead and mercury, (b) due to substandard processes, e.g. dioxin formation during incineration of halogenated plastics or smelting without suitable off gas treatment and (c) from the reagents used in processing, leaching effluents, NO_x from leaching, and mercury from amalgamation to recover gold and silver [9].

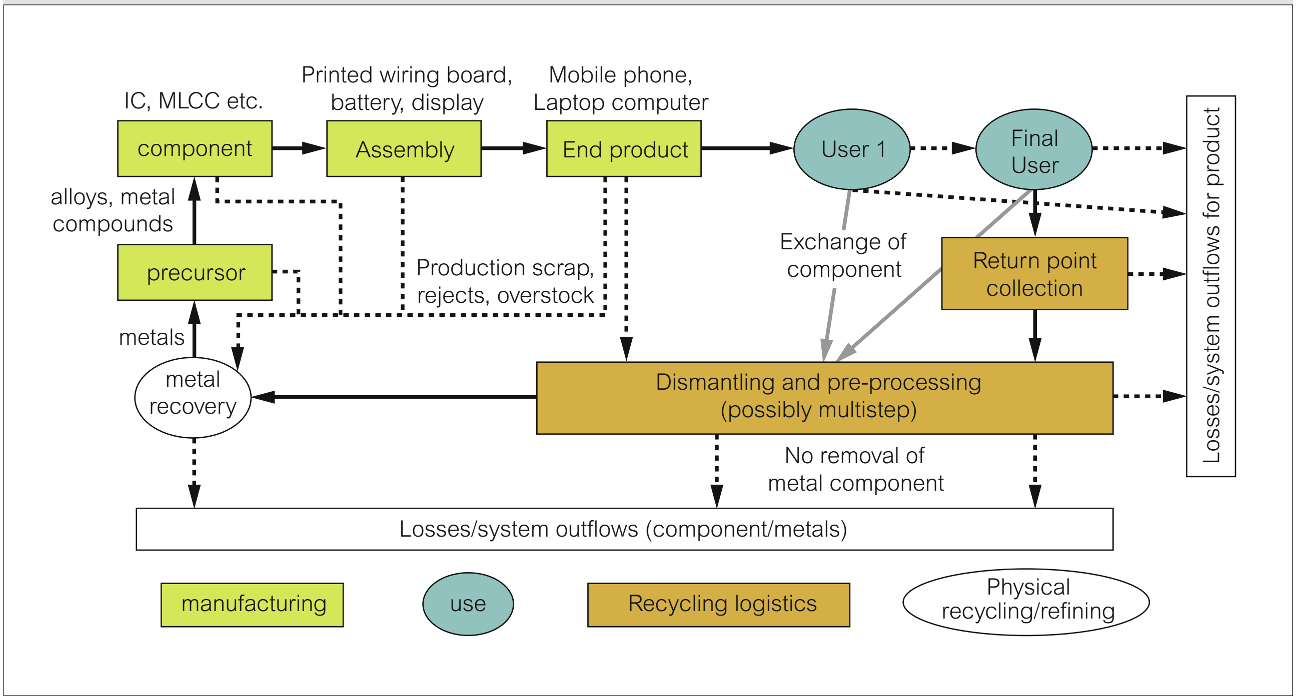
Moreover, such processes are highly inefficient with respect to metals recovery. They focus just on a few valuable metals ('cherry-picking'), but even for gold – being the clear target metal - processing yields are under 25%. Yields for other precious metals are even lower and special metals are lost completely [10]. A recent UNEP report gives a comprehensive overview on the situation in developing countries [11]. To improve this both from an environmental

Figure 7



The channeling function of WEEE-preprocessing – co-separation of gold in wrong end-refining processes must be avoided [4]

Figure 8



The "open loop" structure typical for consumer products

and a resource recovery aspect, the "best of two worlds approach", as described e.g. in [12], offers a promising solution. The idea is to combine efficient collection and dismantling in developing/transition countries with high tech metallurgical refining processes of critical fractions in industrialised countries, as introduced above. The net revenues resulting there from are returned to the companies/associations that shipped out the critical fractions. Such approach follows the same logic in recycling of complex products as is used in their manufacturing – making use of specialisation, economies of scale and an international division of labour. Since critical fractions only make up a small portion of WEEE (< 10% on average), this would lead only to rather low volume shipments to globally sourcing state-of-the-art refining plants, while the bulk of WEEE-fractions that need less sophisticated processes could still be treated locally, generating jobs and revenue there.

It needs to be noted, however, that such concepts are reasonable only for the significantly rising volumes of domestic WEEE in developing/transition countries. It must not target WEEE generated in Europe or other industrialised regions, as this would imply much larger shipment volumes (whole devices) which hardly can be proper monitored in the importing countries. In this context a critical view is also needed on some new industrial appearing refining facilities ("clean leaching plants") that have come on stream mainly in China and India. Reliable information about the processes used, operating and environmental efficiency or destination of output fractions is scarce What is really going on there remains quite opaque and, at least for sound and efficient refining of circuit boards or mobile phones, technological limitations do exist. Hence, shipments from Europe to such plants should not take place unless the operation has been duly certified by an independent and (technical!) knowledgeable body on basis of the same standards that are required for European refining operations.

Summing up, such doubtful or illegal export of European WEEE depletes the 'urban mine', valuable raw material resources are carelessly wasted and significant harm is caused to the environment. The latter can even fall back on the European consumers, as a local contamination of soil, rivers and lakes in Asia can find its way into the food chain and thus into products imported also by Europe. Unfortunately, in a global economy, local problems become globalised!

The main challenge to overcome is the "open loop" structure of materials cycles for most consumer goods as shown schematically in Figure 8. This leads to significant losses for a number of reasons:

- There is a low awareness about valuable resources contained within WEEE or a missing economic driver to recover them, due to the low intrinsic metal value for a single device.
- Consumer products often change ownership during their life cycle and, with each change, the connection between the manufacturer and owner becomes weaker. This is compounded by the fact that change of owner often means a change of location and that highly mobile consumer goods are spread all over the globe. Material flows become unclear and, in most cases, only estimations about real directions and quantities of flows are available.
- Products that have reached their End of Life (EoL) tend to be left (hibernate) in drawers, basements, etc, rather than being given in for recycling.
- In the case where EoL products end up in the Developing Countries, usually an appropriate recycling infrastructure is missing there. This creates problems, even in the case of legitimate exports of reusable products, like working computers given as donations, e.g. to African schools.
- Usually no connection remains between final owner and original product manufacturer. The implementation of 'producer responsibility' thus is difficult to realise. New business models are required, such as leasing, payment of deposits, etc. to transfer the open structures into closed loop systems [13].

A good example of this problem is the mobile phone. Global sales have increased from 400m units in 2001 to 1300m units in 2008 and 2009. In spite of much effort, recycling still largely fails. Taking year 2009, the potential for recycling is around 800m units, which at 100g per unit equates to 80,000t p.a. Of this huge potential, only around 2000 t are really recycled in state-of-the-art facilities. From the few units that are professionally collected [14], most will be reused by other users but some are unfit (typically 25-35%) for reuse and are sent directly to the *bona fide* refiner for recovery. Most reuse finally takes place in developing countries, where they are discarded at end-of-life or, sometimes, go to local 'backyard' refiners with the inherent problems discussed above. The larger portion of mobiles, however, is not collected and either 'stored' in drawers (with a potential for later recycling) or disposed in household waste, which represents an unrecoverable loss.

Design for recycling

The main thrust of the foregoing has centred on recycling WEEE in an effective, efficient and environmentally sound approach and the benefits of recovering precious and other metal values. This is essentially a 'green' sustainable approach. We have noted for gold, it is more effective than primary mining and at a lower environmental cost (e.g. a much lower CO_2 impact and less environmental damage). So, on that basis alone, it has merits. It is, without doubt, economically worthwhile to recover gold and other metal values because the value recovered outweighs the cost of refining of WEEE once the devices have been collected and pre-processed. It is economic to do so if we reasonably undertake the efforts to divert WEEE from our landfills to avoid environmental damage! Moreover, the presence of gold as the most valuable substance in electronics (albeit it's low concentration) is an enabler for the co-recovery of many other metals if modern metallurgical processes are used. Thus gold as the "paying metal" triggers recovery of, e.g., potentially scarce special metals, which would otherwise not be economical. With precious metal prices at a high – gold is currently around \$39/g, (May 2010) – a certain threshold precious metal content of the original equipment is important if recycling is to remain economically worthwhile. That said, it is understandable in a competitive market that original equipment manufacturers (OEMs) and their suppliers look constantly at reducing costs, through miniaturisation and thrifting of expensive metals. For example, there is interest in replacing gold bonding wire with copper, although this is not without technical difficulties and may well lower the technical performance. However, it is shortsighted to view costs purely in terms of the initial cost of production of the equipment. OEMs need to consider lifetime costs which embrace the EoL situation and the cost of disposal. When that is taken into consideration, then it becomes more attractive economically to include materials that have a positive recycling cost benefit as well as technical superiority in the application. This is a 'design for recycling' approach that, perhaps, needs to be considered more seriously by OEMs. This was confirmed by a recent survey conducted by World Gold Council and SEMI in which 50% of chip design companies were unaware that gold reclaimed from waste electronics was a very substantial proportion of the value derived from electronic waste material [15]. The alternative is for the costs of recycling WEEE to be gathered by other means, e.g. by additional taxation on purchasers.

The European Directive on WEEE is aimed at placing the financial responsibility for recycling of WEEE on the equipment OEMs. As discussed earlier, this may require new business models.

There are certainly more "Design for Recycling" rules that need to be considered. Important is a "Design for Disassembly" approach, which facilitates that critical components like circuit boards or rechargeable batteries can easily be removed (manually or mechanically) and channelled into the most appropriate recovery processes without causing losses of valuable materials. An elimination of hazardous substances like mercury from products is another important design measure, but it needs to be secured that, through an early dialogue with recyclers, the impacts of potential substitutes on recycling processes are duly considered. Finally, any dissipative use of precious metals in mass applications should be avoided.

Concluding remarks

This paper has examined the recycling of waste electronics and electrical equipment (WEEE) and the benefits, both economic and environmental, of recovering gold and precious metal values.

Gold demand for electronics is 300t p.a. and growing; there is strong sector growth expected.

Electronic products at their end of life are potentially a substantial source (an 'urban mine') of gold and other valuable metals that can reduce our dependence on primary mining. Recycling of WEEE is a more sustainable, 'green' approach to sourcing such materials.

Electronic equipments are complex products that need sophisticated and integrated recycling systems. Simplistic approaches are not possible or environmentally viable.

There is an urgent need to close the loop in terms of recycling and this needs to be done globally. A holistic approach to life cycle, recycling chain and location is essential at the various levels – system, product, process. All the factors – technological, societal, legislative and economic need to be considered [16].

This approach presents a number of requirements that can be viewed as opportunities:

- Outreach to developing countries is necessary with knowledge transfer and solution-oriented new approaches or business models.
- Design for sustainability without loss of product performance.
- Improved collection systems of consumer goods are critical.
- Optimisation along the entire production and recycling chain with further improvements in energy use and environmental performance at the recycling end.
- Stimulation of the best available technologies and an interdisciplinary approach.

The technology and capacity is available to efficiently recover gold and other precious metals from complex materials such as WEEE. The value of gold present in end-of-life products stimulates recycling and enables recovery of many additional metals.

In spite of legislation, there are high gold losses in Europe due to WEEE exports to overseas countries. If recycling takes place there at all it is very inefficient (gold yields <25%) with a high environmental burden. It is estimated that currently only around 20% of the gold from European WEEE sources is recovered, while 80% of our "urban mine" are still wasted.

Total gold recovery from WEEE ('e-scrap') on a global scale is estimated to be currently only about 30-50 t p.a. This could be increased significantly if collection and treatment systems would be improved world wide. There is hardly any dissipative use of gold in electronics and with appropriate technology gold recovery rates close to 100% can be achieved. Thus, in an "ideal world" the potential gold recovery from WEEE could approach one day the 300 t p.a. which are currently brought into the market.

All gold and other metals recovered from product recycling (WEEE, catalysts, etc) that are used in subsequent product manufacture represents 'green' gold (metals) with a relatively low CO_2 burden and a fully transparent origin. Manufacturers who set up appropriate business models and cooperate with environmentally sound recyclers such as Umicore to secure their access to secondary metals thus can make a significant step towards "ethical sourcing" of their raw materials, a requirement that is in the light of the debate on "conflict metals" becoming increasingly important today.

Acknowledgements

The authors thank Umicore Precious Metals Refining for their support and permission to publish this paper and the organisers of GOLD 2009 in Heidelberg for permission to adapt the plenary lecture for publication in this Special Issue of *Gold Bulletin*.

Editor's Note: The authors recognise that readers may have differing views from those expressed by themselves on this important topic and welcome a debate on the issues. Letters should be addressed to the editor (editor@gold.org)

About the authors

Christian Hagelüken heads the department for business development & market research in Umicore's Precious Metals Refining business unit. Previously, he has held various management positions in the precious metals department of Degussa AG which gained him over 20 years experience in (precious) metals recycling. He holds university degrees in mining engineering and industrial engineering from RWTH Aachen, Germany, where he also received his Ph.D. in 1991. He published books on "Materials Flow of Platinum Group Metals" and on "Automotive Catalysts" and has made numerous contributions to professional books, journals and conferences on topics related to recycling and sustainable resource management. Christian represents Umicore in related associations, work groups and university co-operations. He is among others a contributor to the UNEP-OECD Resource Panel, and to the Raw Materials Initiative of the European Commission.

Christopher Corti is Managing Director of his consultancy, COReGOLD Technology, and was formerly Managing Director, International Technology at the World Gold Council. He was Editor of *Gold Bulletin* 1996-2009 and Chairman of the Gold conferences held in Vancouver (2003), Limerick (2006) and Heidelberg (2009). He obtained his PhD in metallurgy from the University of Surrey and had a career in research and its exploitation at Johnson Matthey plc, the Department of Trade & Industry, Brown Boveri et Cie, Switzerland and the CEGB in the UK. He is a Fellow of the Institute of Materials, Minerals & Mining and a Chartered Engineer. He has published widely on the science, technology and applications of gold.

References

1 GFMS Ltd (2010), *Gold Survey 2010*, London (www.gfms.co.uk)
2 Hagelüken, C., C.E.M. Meskers, (2008). "Mining our computers – Opportunities and challenges to recover scarce and valuable metals", in: Proceedings of Electronics Goes Green Conference 2008, H. Reichl, N. Nissen, J, Müller, O. Deubzer (eds.), Fraunhhofer IRB, Stuttgart, 585-590
3 Vanbellen, F., M. Chintinne (2008), "Extreme Makeover" – UPMR's Hoboken plant", World of Metallurgy – *Erzmetall*, Vol. 61, No. 1 2008, 14-19
4 Chancerel, P., C.E.M. Meskers, C. Hagelüken, V.S. Rotter, (2009), "Assessment of Precious Metal Flows During Preprocessing of Waste Electrical and Electronic Equipment", *J. Indus. Ecol.*, vol.13 (5), 791-810
5 Sander, K., S. Schilling, (2010), "Transboundary shipment of waste electrical/electronic equipment/electronic scrap – optimization of material flows and control", Federal Environment Agency Report No. (UBA-FB) 1331, Dessau. Germany
6 Puckett, J., L. Byster, S. Westervelt, R. Gutierrez, S. Davis, A. Hussain, M. Dutta, (2002), "Exporting harm – The high-tech trashing of Asia". Seattle: Basel Action Network
7 Puckett, J., S. Westervelt, R. Gutierrez, Y. Takamiya, (2005), "The digital dump – exporting re-use and abuse to Africa". Seattle: Basel Action Network
8 Kuper, J., M. Hojsik, (2008), "Poisoning the poor: Electronic waste in Ghana". Amsterdam: Greenpeace International
9 Sepúlveda, A., M. Schluep, F.G. Renaud, M. Streicher, R. Kuehr, C. Hagelüken, A.C. Gerecke, (2009), "A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from China and India". *Environ Impact Asses Rev* (2009), doi:10.1016/j.eiar.2009.04.001
10 Rochat, D., C. Hagelüken, M. Keller, R. Widmer, (2007), "Optimal recycling for printed wiring boards in India" R'07,World Congress - Recovery of materials and energy for resource efficiency. L.M. Hilty, X. Edelmann, A. Ruf (eds.)
11 Schluep, M., C. Hagelueken, R. Kuehr, F. Magalini, C. Maurer, C. Meskers, E. Mueller, F. Wang (2009): Recycling - From e-waste to resources, StEP study report commissioned by UNEP, July 2009 (www.unep.fr/scp/publications/details.asp?id=DTI/1192/PA)
12 Rochat, D., W. Rodrigues, A. Gantenbein (2008), India: Including the existing informal sector in a clean e-waste channel. Proceedings of 19th Waste Management Conf., Durban, 477-483 (www.ewaste.ch/files/Rochat_2008_WasteCon.pdf)
13 Hagelüken, C., (2007), "The challenge of open cycles". R'07 World Congress – Recovery of materials and energy for resource efficiency. L.M. Hilty, X. Edelmann, A. Ruf (eds.)
14 Nokia (2008), 'Global consumer survey reveals that majority

of old mobile phones are lying in drawers at home and not being recycled', (press release, July 8). Helsinki: Nokia Corporation
15 Semi (2010), *Semiconductor Industry Opinions Concerning the Selection of Bonding Wire Material*, Semi market survey, January 2010
16 Hagelüken, C., C.E.M. Meskers, (2010), "Complex lifecycles of precious and special metals", in: Graedel, T., E. van der Voet (eds): *Linkages of Sustainability. Strüngmann Forum Report*, vol. 4. Cambridge, MA: MIT Press, 163-197