UNIT-V RECYCLING FROM E-WASTE TO RESOURCES

PERSPECTIVES OF WEEE/E-WASTE MANAGEMENT

INTRODUCTION: WEEE/E-waste is a complex mixture of hazardous and non-hazardous waste, which consists of items of economic value. Therefore, it requires specialized segregation, collection, transportation, treatment and disposal. The following sections attempt a conceptual understanding of WEEE/ E-waste management based on existing management systems in developed countries. At first the mechanisms of WEEE/E-waste trade, WEEE/E-waste life cycle and material flow have been described followed by a description of components of WEEE/E-waste management. Further, generic status of WEEE/E-waste management in developing countries and stakeholders has been described followed by guidance notes.

MECHANISM OF WEEE/ E-WASTE TRADE: Mechanism of WEEE/ E-waste trade can be explained in terms of three elements. These elements are given below.

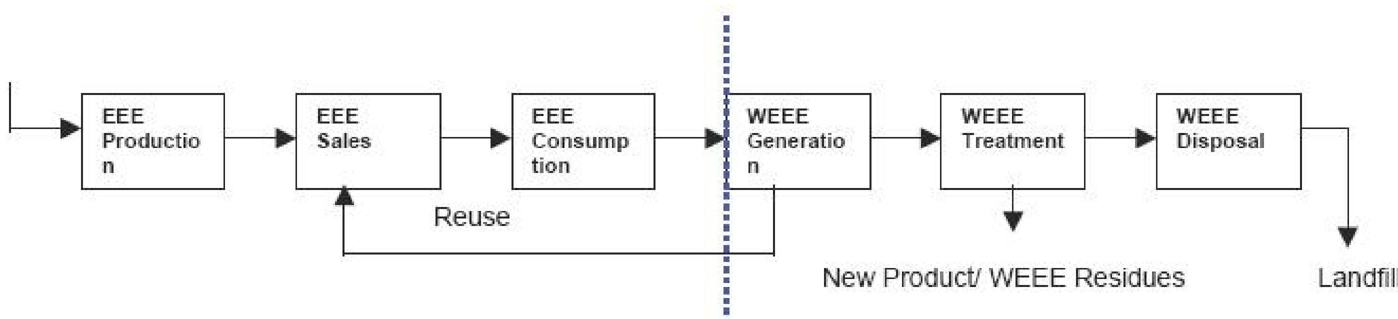
1. Material Flow

2. Life Cycle

3. Geographical Boundary

"Material Flow" along the "Life Cycle" of electrical and electronic equipment including the phase of obsolescence within a "Geographical Boundary" forms the basis of WEEE/ Ewaste generation in cities/ countries. The following sections provide a conceptual understanding of WEEE/E-waste management starting from WEEE/E-waste generation followed by its transformation into new material.

WEEE/E-WASTE LIFE CYCLE: Conceptual life cycle of electrical and electronic equipment is shown in the following figure - The establishment of material flow within a geographical boundary assists in identifying, networks / chain connecting different phases of life cycle of electrical and electronic equipment and associated stakeholders. Once the chain gets established, "material flow balance" eg. Input/ output balances in each phase forms the basis of quantification of WEEE/ E-waste in the life cycle analysis of electrical and electronic equipment. WEEE/E-waste quantification (inventory) in a city/ region forms the basis of WEEE/Ewaste management and starts from the stage shown by blue (dotted) line in figure



FUNDAMENTALS OF E-WASTE RECYCLING

As basis for the following chapters, it is essential to understand the fundamental issues underlying e-waste recycling. These are independent of the recycled material, the device and the recycling location or region and address the:

- ✓ **Significance of e-waste for resource management and toxic control,**

- ✓ **General structure, main steps and interfaces of the recycling chain,**
- ✓ **Objectives to achieve,**
- ✓ **General frame conditions which impact process selection.**

SIGNIFICANCE OF E-WASTE RECYCLING

E-waste is usually regarded as a waste problem, which can cause environmental damage if not dealt with in an appropriate way. However, the enormous resource impact of electrical and electronic equipment (EEE) is widely overlooked. Summarizing the lack of closing the loop for electronic and electrical devices leads not only to significant environmental problems but also to systematic depletion of the resource base in secondary materials.

Modern electronics can contain up to 60 different elements; many are valuable, some are hazardous and some are both. The most complex mix of substances is usually present in the printed wiring boards (PWBs). In its entity electrical and electronic equipment is a major consumer of many precious and special metals and therefore an important contributor to the world's demand for metals. Despite all legislative efforts to establish a circular flow economy in the developed countries/EU, the majority of valuable resources today are lost. Several causes can be identified: firstly, insufficient collection efforts; secondly, partly inappropriate recycling technologies; thirdly, and above all large and often illegal exports streams of E-waste into regions with no or inappropriate recycling infrastructures in place. Large emissions of hazardous substances are associated with this. Unfortunately, these regions with inappropriate recycling infrastructure are often located in developing and transition countries. At the moment the developing and transition countries are striving to implement technologies to deal with the recycling of e-waste and to establish circular flow economies.

Besides the direct impact of effective recycling on the resource base of the recycled metals, state of the art recycling operations 2 also considerably contribute to reducing greenhouse gas emissions. Primary production, i.e. mining, concentrating, smelting and refining, especially of precious and special metals has a significant carbon dioxide (CO2) impact due to the low concentration of these metals in the ores and often difficult mining conditions. "Mining" our old computers to recover the contained metals – if done in an environmentally sound or correct manner – needs only a fraction of energy compared to mining ores in nature.

Furthermore, the environmentally sound management of refrigerators, air-conditioners and similar equipment is significant in mitigating the climate change impact at end-of-life. The ozone depleting substances in these devices, such as CFC and HCFCs, have a very high global warming potential (GWP) and effective recycling will ensure these substances are not released into the environment. In that sense there is still a lot to win.

Essentially, the environmental footprint of a fridge, a computer and other electronic devices could be significantly reduced if treated in environmentally sound managed recycling operations, which prevent hazardous emissions and ensure that a large part of the contained metals are finally recovered for a new life in a new (electronic) device.

IMPACT ON METAL RESOURCES

A wide range of components made of metals, plastics and other substances are contained in electrical and electronic equipment. For example, a mobile phone can contain over 40 elements from the periodic table including base metals like copper (Cu) and tin (Sn), special metals such as cobalt (Co), indium (In) and antimony (Sb), and precious metals including silver (Ag), gold (Au) and palladium (Pd), as shown in Figure 1. Metals represent on average 23% of the

weight of a phone, the majority being copper, while the remainder is plastic and ceramic material. Looking at one ton of phone handsets (without battery) this would be 3.5 kg Ag, 340 g Au, 140 g Pd as well as 130 kg Cu. For a single unit the precious metal content is in the order of milligrams only: 250 mg Ag, 24 mg Au, 9 mg Pd while 9 g Cu is present on average. Furthermore, the Li-ion battery of a phone contains about 3.5 g Co.

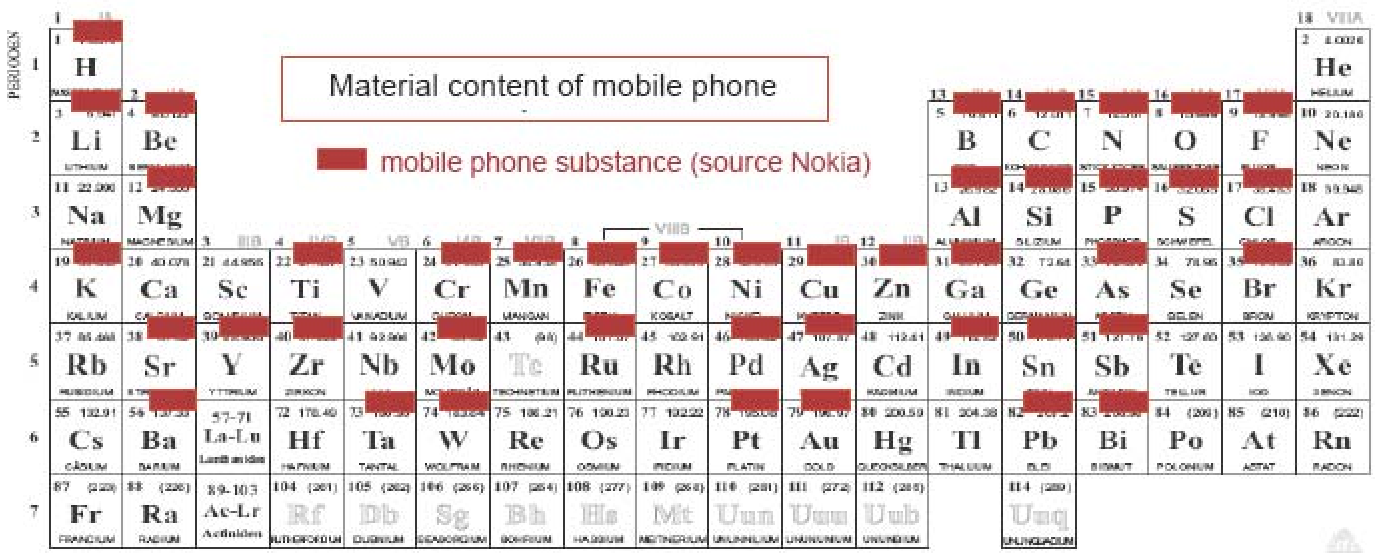
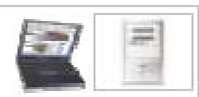


Figure 1: Material content mobile phone [Source Umicore 2008]

a) Mobile phones:

1200 Million units
x 250 mg Ag ≈ 300 t Ag
x 24 mg Au ≈ 29 t Au
x 9 mg Pd ≈ 11 t Pd
x 9 g Cu ≈ 11,000 t Cu
1200 M x 20 g/battery*
x 3.8 g Co ≈ 4500 t Co
* Li-Ion type

b) PC & laptops:



255 Million units
x 1000 mg Ag ≈ 255 t Ag
x 220 mg Au ≈ 56 t Au
x 80 mg Pd ≈ 20 t Pd
x ≈ 500 g Cu ≈ 128,000 t Cu
≈100 M laptop batteries*
x 65 g Co ≈ 6500 t Co
* Li-Ion type is > 90% used in modern laptops

World Mine Production		a+b share
Ag: 20,000	t/y ►	3%
Au: 2,500	t/y ►	3%
Pd: 230	t/y ►	13%
Cu: 16	Mt/y ►	1%
Co: 60,000	t/y ►	15%

Figure 2: Impact of phones and PCs on metals demand, based on global sales 2007 [Source Umicore 2008]

At first sight this appears to be very little, but taking into account the leverage of 1.2 billion mobile phones sold globally in 2007, this leads to a significant metal demand in total. When looking at PCs and laptops, numbers in a similar order of magnitude are found (Figure 2). Also, the use of more common metals such as iron in electronics is considerable: about 6 kg iron/steel for a desktop PC means 930,000 tons are used to manufacture the PCs sold in 2007. The combined 2007 unit sales of mobile phones and personal computers already add up to 3% of the world mine supply of Au and Ag, to 13% of Pd and to 15% of Co

(Figure 2).

Taking into account the highly dynamic growth rates of all the other electronic devices such as liquid crystal display (LCD)-TVs and monitors, MP3 players, electronic toys and digital cameras, it becomes clear that electrical and electronic equipment is a major driver for the development of demand and prices for a number of metals as shown in Table 1. In particular the booming demand for precious and special metals is linked to increasing functionality of the products and the specific metal properties needed to achieve these. For example, electronics make up for almost 80% of the world's demand of indium (transparent conductive layers in LCD glass), over 80% of ruthenium (magnetic properties in hard disks (HD)) and 50% of antimony (flame retardants). Some of these metals are also important for renewable energy generation: selenium (Se), tellurium (Te) and indium (In) are used in thin film photovoltaic panels; platinum (Pt) and ruthenium (Ru) are used for proton exchange membrane (PEM) fuel cells3. Some metal price increases, which we have observed over the last years are directly connected to the developments in the electronic industry. The monetary value of the annual use of important "electrical and electronic equipment metals" represents USD 45.4 billion at 2007 price levels.

The metal resources used yearly for electrical and electronic equipment are added to the existing metal resources in society of the devices in use. These metal resources become available again at final end-of-life of the devices. As mentioned earlier this is a potential material resource of 40 million tons each year. Effective recycling of the metals/materials is crucial to keep them available for the manufacture of new products, be it electronics, renewable energy applications or applications not invented yet. In this manner primary metal and energy resources can be conserved for future generations.

Metal	Primary production*	By-product from	Demand for EEE	Demand/production	Price**	Value in EEE**	Main applications
	t/y		t/y	%	USD/kg	10^6 USD	
Ag	20 000	(Pb, Zn)	6 000	30	430	2.6	Contacts, switches, solders…
Au	2 500	(Cu)	300	12	22 280	6.7	Bonding wire, contacts, integrated circuits…
Pd	230	PGM	33	14	11 413	0.4	Multilayer capacitors, connectors
Pt	210	PGM	13	6	41 957	0.5	Hard disk, thermocouple, fuel cell

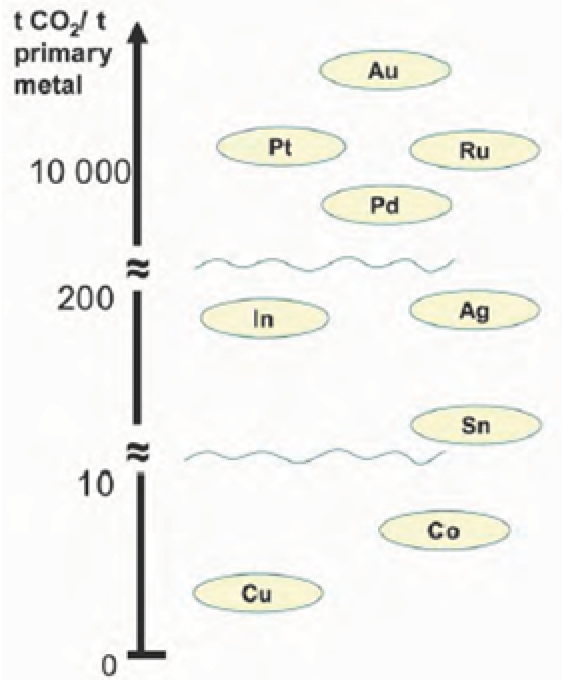
Ru	32	PGM	27	84	18 647	0.5	Hard disk, plasma displays
Cu	15 000 000		4 500 000	30	7	32.1	Cable, wire, connector…
Sn	275 000		90 000	33	15	1.3	Solders
Sb	130 000		65 000	50	6	0.4	Flame retardant, CRT glass
Co	58 000	(Ni, Cu)	11 000	19	62	0.7	Rechargeable batteries
Bi	5 600	Pb, W, Zn	900	16	31	0.03	Solders, capacitor, heat sink…
Se	1 400	Cu	240	17	72	0.02	Electro-optic, copier, solar cell
In	480	Zn, Pb	380	79	682	0.3	LCD glass, solder, semiconductor
Total			**4 670 000**			**45.4**	

* Rounded from [9], [10], [11]. ** Using the average price in 2007.

Table 1: Important metals used for electric and electronic equipment (based on demand in 2006)

IMPACT ON THE ENVIRONMENT

Primary production (mining) plays the most important role in the supply of metals for electrical and electronic equipment applications since secondary metals (recycling) are only available in limited quantities so far. The environmental impact/footprint of the primary metal production is significant, especially for precious and special metals which are mined from ores in which the precious and special metal concentration is low. Considerable amounts of land are used for mining, waste water and sulfur dioxide (SO2) is created and the energy consumption and CO2 emissions are large. For example, to produce 1 ton of gold, palladium or platinum, CO2 emissions of about 10,000 tons are generated. Conversely the production of copper has only an emission of 3.4 t CO2 per ton metal (Figure 3). Combining these numbers with the metal usage in electrical and electronic equipment (given in Table 1) enables calculation of the CO2 emissions associated with the primary production of the metals as shown in the table of Figure 3. For example, the annual demand for gold in EEE is some 300 t at average primary generation of almost 17,000 tons CO2 per ton of gold mined, which leads to gold induced emissions of 5.1 million tons in total. In the case of copper, the specific primary emissions are with 3.4 t/t relatively low, but the high annual total demand in EEE leads to 15.3 million tons of CO2 emissions. As shown in Figure 3 (table) the cumulated values of the metals listed account for an annual CO2 emission level of 23.4 million tons, almost 1/1000 of the world's CO2 emissions. This includes neither CO2 emissions from other metals used in electrical and electronic equipment like steel, nickel or aluminium, nor other CO2 emissions associated with the manufacturing or use of electrical and electronic equipment.



Important EEE metals	demand for EEE t/a (2006)	data for primary production [t CO_2/t metal]	CO_2 emis-sions [Mt]
Copper	4 500 000	3.4	15.30
Cobalt	11 000	7.6	0.08
Tin	90 000	16.1	1.45
Indium	380	142	0.05
Silver	6 000	144	0.86
Gold	300	16 991	5.10
Palladium	32	9 380	0.30
Platinum	13	13 954	0.18
Ruthenium	6	*13 954*	0.08
CO_2 total [t]			**23.4**

Figure 3: CO_2 emissions of primary metal production calculated using the EcoInvent 2.0 database

Recovering metals from state-of-the art recycling processes generates only a fraction of these CO2 emissions and also has significant benefits compared to mining in terms of land use and hazardous emissions. For example, production of 1 kg aluminium by recycling uses only 1/10 or less of the energy required for primary production, and prevents the creation of 1.3 kg of bauxite residue, 2 kg of CO2 emissions and 0.011 kg of SO2 emissions as well as the impacts and emissions associated with the production of the alloying elements used in aluminium. Furthermore, the salt slag created during the recycling process is treated to recover salt flux for the recycling industry, inert oxides for cement industry and aluminium metal. For precious metals the specific emissions saved by state-of-the-art recycling are even higher.

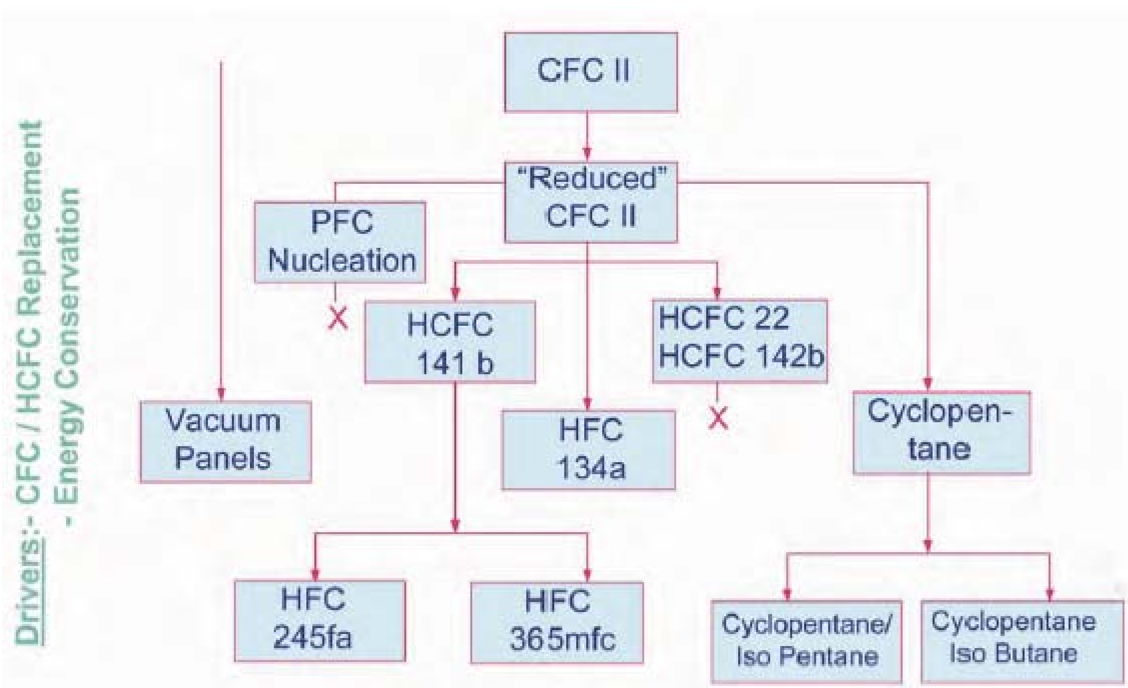


Figure 4: Use of ODS in cooling and freezing appliances over the years

The substances contained in the devices can also have an impact on the environment. Cooling and freezing equipment for example, employ ozone depleting substances (ODS) in the refrigeration system. These substances, such as CFCs and HCFCs, have a huge global warming potential, as shown in Table 2. It must be mentioned that particularly the older devices are those which contain ODS with a high global warming impact; the newer devices use alternative substances. As a consequence it is important to ensure accidental release to the atmosphere because of damages during collection or improper recycling treatment is not taking place. It is in this manner that high environmental impact during end-of-life can be avoided.

Substances	GWP		
CFC-12	10 720	±	3 750
CFC-114	9 880	±	3 460
CFC-115	7 250	±	2 540
CFC-113	6 030	±	2 110
CFC-11	6 800	±	1 640
HCFC-142b	2 270	±	800
HCFC-22	1 780	±	620
HCFC-141b	713	±	250
Halon-1301	7 030	±	2 460
Halon-1211	1 860	±	650
Halon-2402	1 620	±	570

Table 2: Global Warming Potential of refrigerants[4]

On a more local level, uncontrolled discarding or inappropriate waste management/recycling generates significant hazardous emissions, with severe impacts on health and environment. In this context, three levels of toxic emissions have to be distinguished:

- ✓ **Primary emissions: Hazardous substances that are contained in e-waste (e.g. lead5, mercury, arsenic, polychlorinated biphenyls (PCBs), fluorinated cooling fluids etc.),**
- ✓ **Secondary emissions: Hazardous reaction products of e-waste substances as a result of improper treatment (e.g. dioxins or furans formed by incineration/inappropriate smelting of plastics with halogenated flame retardants),**
- ✓ **Tertiary emissions: Hazardous substances or reagents that are used during recycling (e.g. cyanide or other leaching agents, mercury for gold amalgamation) and that are released because of inappropriate handling and treatment.**

It needs to be understood that legislative approaches to restrict the use of hazardous substances (e.g. European Union's Directive 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment RoHS) can address only primary emissions and partly secondary emissions. However, even the "cleanest/greenest" products cannot prevent tertiary emissions if inappropriate recycling technologies are used. The latter is the biggest challenge in particular in developing and transition countries, where "backyard recycling" with open sky incineration, cyanide leaching, "cooking" of circuit boards etc. lead to dramatic effects on health and environment.

MARKETS FOR RECYCLING TECHNOLOGY:

Innovative e-waste recycling technologies

The e-waste recycling chain could be divided into three main subsequent steps – i) collection, ii) dismantling and pre-processing and iii) end-processing for final metal recovery. Technology plays a crucial role especially in the second and third steps and, in particular, in pre-processing and end-processing. After the collection phase end-of-life appliances are treated in order to obtain components (to be reused or refurbished) or materials fractions (to be recycled and reused as raw materials). Components or material fractions that are not reused or recycled (due to their intrinsic hazardous content or lack of secondary markets) are sent to a suitable disposal site. Notwithstanding different approaches and methods the aim of second and third step of the recycling chain is mainly to:

· Take care of hazardous components and fractions in an environmentally sound manner,

· Economically recover components and material fractions.

The two dimensions are inter-linked by means of eco-efficiency, intended as the effort of obtaining attractive economic results (revenues and costs) without compromising the environment. Any approach has furthermore different social implications so that a full, indepth assessment needs to be carried out before the optimal solution in different contexts can be identified. Depending on 1) the type of equipment and treatment technologies available, 2) the socio-economic boundary conditions and 3) the legislative requirements to be fulfilled, different options that can ensure the full treatment of e-waste exist. In the following sections technologies available for dismantling and pre-processing of ewaste are presented, according to the different end-of-life device streams:

· C&F appliances,

· ICT equipment,

· Monitors and TVs.

While collection, dismantling and pre-processing can differ across different e-waste streams, depending on the constituent components or materials as well as on the technologies available, end-processing technologies have been developed with a focus on the material streams, regardless of the e-waste device stream they come from.

End-processing technologies are described in the following according to those main fractions streams, having (i) environmental (toxic control, resource conservation, energy saving) or (ii) economical relevance or (iii) a relevant mass percentage on the total weight of appliances, as extensively detailed in the UNU study supporting the 2008 Review of the WEEE Directive:

· PWBs and small electronic devices: due to the environmental and economic value connected with special and precious metals used in such devices,

· Metallic fractions with precious metals: for the reasons above,

· Metallic fractions without precious metals: for the economic value and the mass relevance of such fractions in some e-waste categories, like C&F appliances, · Aluminium: Both for economical reasons as well as environmental ones, mainly connected with the energy usage to make primary aluminium, Ferrous metals: For economic reasons and for the mass relevance in Cooling and freezing appliances, as well as environmental aspects connected with the

production of the primary ones, in particular the CO2 production, · Glass (specifically CRT glass): For environmental reasons, mainly connected to the use of lead.

APPLICATION OF A "TECHNOLOGY TRANSFER & Framework" For Selected Recycling Technologies

METHODOLOGY

the "Framework for Analysis: Technology Transfer to address Climate Change" and aims to formulate the first step of a strategic technology transfer programme for sustainable e-waste recycling technologies in developing countries by:

· Selecting e-waste recycling technologies with the most promise to help create a more sustainable recycling sector.

· Identifying two possible target countries which would be promising for the introduction of sustainable e-waste recycling technologies, by applying the UNEP technology transfer framework.

· Identifying potential barriers and possible interventions (proposed course of action) in support of a successful transfer of sustainable recycling technologies is pivotal.

SUSTAINABLE E-WASTE RECYCLING TECHNOLOGIES

E-waste recycling technologies have been described in and subsequently rated into (a) innovative technologies for the development of a sustainable recycling sector and (b) technologies not suited to support sustainable recycling in developing countries.

Following Table summarizes these findings and presents our selection of recycling technologies with the most promise to help create a more sustainable recycling sector in developing countries.

	Waste streams	**Economic attributes**	**Environmental attributes**	**Social attributes**
Manual dismantling/ sorting of fractions	All	Low capital cost,sorting of valuable fractions/ components	Efficient sorting of fractions	Labour intensive, Job creation
De-gassing CFC, HCFC	C&F	Mandatory requirement having low cost	Fundamental step to ensure control over hazardous substances having huge GWP potential	
Semi-automatic CRT cut and cleaning	CRT	Low capital and net cost	Low energy consumption	Labour intensive
Integrated smelter for nonferrous (pyrometallurgical methods)	Non-ferrous (including printed circuit boards) like Cu, Pb, Zn, Sn or mix	Capital cost high Low net (unit) costs due to economies of scale Local growth potential high	No toxic emissions Low water use Transport: internationally Little waste products Recovery rates >> 90%	Automated process control so less jobs created Highly skilled workforce EHS*

Aluminium remelter/refiner	Aluminium	Capital cost medium –high Net cost low Economies of scale	No toxic emissions Salt slag has to be treated or disposed Env. sound Transport within region or country Water use: low - medium	Job creation: yes Mix of low skilled and high skilled jobs EHS low risks

Selection of recycling technologies with the most promise to help create a more sustainable recycling sector in developing countries

INNOVATION HUBS AND KNOWLEDGE CENTRES OF EXCELLENCE IN EMERGING ECONOMIES

Due to the early stage of awareness for e-waste recycling in emerging economies, innovation hubs and centres of excellence have not been established yet. However, some organizations are currently establishing their e-waste competence and have a great potential to develop into innovation hubs. Multilateral institutions, mainly National Cleaner Production Centres and Basel Convention Regional Centres develop into knowledge hubs for e-waste management in some countries. The current situation in China, India and South Africa indicate that smaller and less complex economies such as South Africa's improve faster in awareness and competence.

Crucial instruments and framework conditions for the development of innovation hubs include the possibility to participate in international knowledge partnerships programmes. It also has been observed that without clear legal framework and active participation of the government, the development of innovative technologies is hampered. The future success of technological innovation in environments with strong informal participation strongly depends on alternative business models with financial incentives, which allow the informal sector to still participate with "safe" recycling processes, while hazardous operations are transferred to state-of-the-art formal recyclers. The development of innovation hubs also demand for a fair competitive environment with common rules, clearly favouring the development and application of innovative technologies.