Market potential of innovative e-waste recycling technologies in developing countries

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Abstract

The United Nations Environment Programme (UNEP) identified e-waste as one of their most relevant topics with regard to their Resource Efficiency and Sustainable Consumption and Production initiatives. As a result the study "Recycling – from E-waste to Resources" was commissioned to an expert consortium around the "Solving the e-Waste Problem" StEP initiative. This paper presents one of the key outcomes of this study - the analysis of the market potential of innovative technologies for the e-waste recycling sector in selected developing countries. Criteria to compare and select innovative technologies are grouped along the elements of sustainability. The analysis rated a few technologies to have an innovation potential for developing countries. This includes the pre-processing technologies "manual dismantling/ sorting of fractions", "de-gassing CFC, HCFC" and "semi-automatic CRT cut and cleaning", as well as the end-processing technologies integrated smelter for non-ferrous material and aluminium remelter/refiner. Based on a selection of developing countries in Africa, Asia and Latin America, the study suggests that all countries would have a potential for the adaptation of the mentioned pre-processing technologies. Due to the large volumes and high investments needed to establish state-of-the-art end-processing facilities, a mid-term medium potential for integrated smelters could only be identified in larger emerging economies, whereas aluminium remelter / refiner have a potential in most countries. Informal collection and manual dismantling activities do not necessarily need to be transformed to formalized processes and often have advantages over the introduction of new technologies from a sustainability point of view. However, all other informal activities such as wet-chemical leaching bear great adverse environmental and social impacts and are also often less attractive from an economical point of view.

Keywords: e-waste, innovative & sustainable recycling technology, UNEP resource panel, StEP

1 Introduction

Sustainable innovation, understood as the shift of sustainable technologies, products and services to the market, requires a market creation concept and one common global agenda. The challenge is to raise awareness among all actors of the different sectors in order to realize the innovation potential and to shift to eco-innovations that lead to sustainable consumption and production patterns. With regard to their sustainability impacts and the greatest promise for successful innovations that would lead to a reduction in these impacts, UNEP made a selection of the most relevant topics. The need for a study on "Recycling – from E-waste to Resources" was identified and commissioned to an expert consortium around the "Solving the e-Waste Problem" StEP initiative (Schluep et al. 2009). The results of the study feed into the work of the UNEP Resource Panel, the preparation of the 10-year Framework of Programmes on Sustainable Consumption and Production (Marrakech Process), and hence into the '2010/2011 cycle' of the United Nations Commission on Sustainable Development.

In order to achieve the call 'from e-Waste to Resources', an integrated waste policy and management plan, which addresses environmental impacts along the whole life-cycle of products, materials and processes, is crucial. As an element of the 3R Principle – Reduce, Reuse, Recycle - recycling reduces waste going to final disposal, decreases consumption of natural resources and improves energy efficiency. It is, in this respect, a key process, which can be improved through innovative and more effective processes and technologies. Although the focus of this study is on recycling, an emphasis on reuse as an important part in the 3R hierarchy is necessary by underlining the needs of appropriate collection, careful dismantling and creation of output qualities suitable for reuse. However, reused products or components thereof eventually will have to be recycled in an environmentally sound way, as reuse is not an alternative to recycling but an extension of lifetime before a product is recycled.

The key objectives of the study presented in this paper are:

- Analysis of the market potential of innovative technologies for the e-waste recycling sector in selected developing countries.
- Classification of countries according to their current market situations and framework conditions for e-waste recycling technologies.

In order to achieve these objectives the presented analysis concentrates:

- on a consistent set of different types of metals (ferrous and non-ferrous metals) such as iron (Fe), aluminium (Al), copper (Cu), palladium (Pd) and gold (Au)
- on the e-waste streams (1) cooling and freezing appliances (C&F), (2) information and communication technology (ICT) appliances and (3) cathode ray tubes (CRTs)
- on technologies which according to Hillebrand et al. (1994) encompass (a) the specific configuration of techniques ("technical hardware"), (b) the scientific and technical knowledge, formal qualifications and experienced-based knowledge ("know-how"), (c) the management methods used to link technical hardware and know-how ("organization") and (d) the physical good or service emerging from the production process ("product").
- on the following selection of developing countries and countries in transition: South Africa, Kenya, Uganda, Morocco, Senegal, Peru, Colombia, Mexico, Brazil, India and China.

2 Technology assessment methodology

In order to understand the procedure of selecting innovative e-waste recycling technologies in the context of developing countries, 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 recycling
- General structure and main steps of the recycling chain
- Overall objectives for e-waste recycling
- Sustainability criteria for the evaluation of technologies

2.1 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. EEE is a major driver for the development of demand and prices for a number of metals as shown in table 1. Consequently inappropriate disposal of e-waste not only leads to significant environmental problems but also to a systematic loss of secondary materials (Hagelüken and Meskers 2008). Hence the appropriate handling of e-waste can both prevent serious environmental damage and also recover valuable materials, especially metals.

Metal	Primary production*	Byproduct 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 US Geological Survey (2007), GFMS (2007), Johnson Matthey 2008)
** Using the average price in 2007.

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

2.2 General structure and main steps of the recycling chain

The recycling chain for e-waste is classified into three main subsequent steps: (i) collection, (ii) sorting/dismantling and pre-processing (including sorting, dismantling and mechanical treatment) and (iii) end-processing. All three steps should operate and interact in a holistic manner to achieve the overall recycling objectives.

2.3 Overall objectives for e-waste recycling

The overall objectives to achieve are:

- Take care of hazardous/toxic substances contained in e-waste in an environmentally sound manner while preventing secondary and tertiary emissions,
- Recover valuable materials as effectively as possible,
- Create economically and environmentally sustainable businesses (optimize eco-efficiency),
- Consider the social implications and the local context of operations (e.g. employment opportunities, available skills and education etc.).

Taking the above objectives into consideration, the identification of innovative technologies needs to be based upon an evaluation to what extent a specific technology contributes to achieving these objectives as a whole, also taking into account the regional context and the step in the recycling chain it addresses. A technology cannot be considered sufficiently innovative when it is very clean with respect to emissions, but inefficient in recovering valuable materials or too costly to be applicable in practice, for example. The same applies if a process (chain) would recover valuable substances at attractive costs but fails to prove that hazardous emissions do not occur. And finally, innovative technologies have to take the regional context into account. What could be a highly effective technology/solution in e.g. a Western European (highly industrialized) context can be a completely misguided approach in Africa or Asia (developing, industrializing context) – and vice versa. Implementing a high-tech, capital intensive recycling process will not be suitable in every country or region, and hence cannot be regarded as innovative per se. In another region/country with the required (framework) conditions, the same technology would be very suitable and can be regarded as highly innovative. In this respect an innovative approach goes beyond the technology aspect but must include a most appropriate combination of processes in a recycling chain. This combination of processes is not limited to a single country/region, but should be seen from an international/global perspective. In this manner the most suitable technologies for the different stages in the recycling chain can be combined in an optimum way, while utilizing specific framework conditions in each location.

2.4 Sustainability criteria for the evaluation of technologies

Criteria to compare the innovation of technologies can be grouped along the elements of sustainability. The sustainability attributes used as innovation criteria were adapted according to Zumbühl (2006) and Streicher Porte et al. (2009) and are given in table 2. The term "technology" summarizes all technical installations, skills, processes and combinations thereof as defined in the introduction of this paper.

Attributes	**Indicators involved**
Economic attributes	
Low net costs	Costs for transport, processing and labour vs. revenues
Low capital costs	Investment costs for additional plants and technologies used in a scenario
Increased potential for local economic growth	Additional industries and services involved by implementing a scenario
Environmental attributes	
Low use of electricity	Savings of electricity but also energy in general by implementing a scenario
Low fuel use for transport	Fuel used by shipping and road transport
Low use of freshwater	Freshwater consumption of a recycling scenario
Little (toxic) emissions	Caused vs. prevented emissions according to the savings of raw materials calculated with eco-indicator '99 (or other appropriate tools)
High metal recovery rates	Range and yields of metals contained in the waste, which can be recovered and used as secondary raw material. In case of technical conflicts prioritization by economic and environmental value ("footprint") of the recovered substances.
Social attributes	
Creation of jobs for the previously unemployed	Working hours for low-skilled and semi-skilled workers generated
Creation of highly skilled jobs	Working hours for highly skilled workers generated
Creation of jobs outside the target country	Working hours generated outside the target country
Low health and safety impacts	Impacts of a scenario on health and safety of the employees engaged in a scenario

Table 2: Sustainability attributes used as innovation criteria and to compare current and innovative technologies

These attributes in principal are valid for all the different steps in the recycling chain. Nevertheless, there are points for attention when making the evaluation. When looking at a recycling chain only different technologies within the same stage of the chain can be compared to each other, as the objectives for the technologies are then the same.

Furthermore, the attributes are not independent parameters. They are partly connected to each other, as it is impossible to achieve the maximum value for each single attribute. Instead a compromise has to be found where for the entire system the optimum value is obtained. For example, a high metal recovery and/or low toxic emissions from complex materials cannot be achieved at the lowest operating level or with the lowest capital costs. This also leads to a quantitative interpretation of “high”, “low” etc. as stated in the table. Practically, there might be a useful value for “low”, but this is relative and depends on the process looked upon. For example, low capital costs for end-processing will often still seem high compared to the capital cost for pre-processing.

3 Innovative e-waste recycling technologies

Pre-processing and end-processing technologies were 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. Table 3 summarizes these findings and presents a 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 non-ferrous (pyrometallurgical methods)	Non-ferrous (including printed wiring 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	Captial 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

Table 3: Selection of recycling technologies with the most promise to help create a more sustainable recycling sector in developing countries

Regarding pre-processing technologies for all waste streams positive benefits exist in manual disassembly and sorting, as well as for the introduction of semi-automatic technologies aiming at fulfilling specific and environmentally relevant activities (De-gassing of chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC); CRT cut & cleaning). Notwithstanding different approaches and levels of innovativeness in technologies, boundary conditions and in particular social attributes (e.g. job creation), or economic ones (e.g. like capital intensiveness) will play the most crucial role and could hamper the effectiveness of any technology or approach. Fully automated technologies are less innovative and suitable for developing countries for pre-processing activities, especially when considering the inter-linkages with end-processing technologies as well as the global recycling chain and material flows.

Environmentally sound end-processing technologies require high investment cost compared to pre-processing technologies, as well as a considerable tonnage to operate such processes economically and a medium to high level of education of the workers. Therefore, it is most feasible to use existing facilities where possible. The environmental performance of these facilities has to be quantitatively evaluated in order to assess if state-of-the-art efficiencies, environment health and safety regulations and emission standards are met. Locally or regionally available facilities can be used in the case of steel, aluminium and other non-ferrous materials, or globally available facilities when considering treatment of printed wiring boards. This division of labour and changing the local recycling chain into an international recycling chain uses the strengths available in each location to create and support environmentally and economical sustainable businesses and recycling chains.

4 Market potential

Estimations of generated e-waste volumes for 2020 in selected countries in Asia, Africa and Latin America (see Müller et al. 2009) suggest that all countries would have a potential for the adaptation of pre-processing technologies. Whereas manual dismantling and sorting technologies are already applied in some of the countries, there is no indication that other more advanced technologies are applied. Competition for the adaptation of manual dismantling and sorting technologies originate from a large informal sector in China and India (Wang 2008, Streicher-Porte and Yang 2007, Rochat et al. 2008) and from a formal sector in South Africa (Finlay and Liechti 2008, Schluep 2009). Because e-waste recycling is only beginning to appear in all other countries, there is a lack of competition for the adaptation of innovative pre-processing technologies.

Due to the large volumes and high investments needed to establish state-of-the-art end-processing facilities, a mid-term medium potential for integrated smelters could only be identified in larger emerging economies such as China, India, South Africa, Brazil and Mexico, whereas aluminium remelter / refiner have a medium to high potential in most countries.

Informal collection and manual dismantling activities do not necessarily need to be transformed to formalized processes and often have advantages over the introduction of new technologies from a sustainability point of view (Rochat et al. 2008). The informal collection system is rather efficient in countries like India and China because the daily informal collectors are penetrating into each community of the city to collect e-waste from house to house. Moreover, deep-level manual dismantling in formal or informal environments is preferred over semi-automatic processes due to the abundant workforce and low labour costs (Gmuender 2007, Wang 2008). However, all other informal activities such as wet-chemical leaching bear great adverse environmental and social impacts (Sepúlveda et al. 2009) and are also often less attractive from an economical point of view than innovative technologies as identified above.

5 Classification of countries

The selected countries were analyzed qualitatively considering their formal and informal sectors in order to classify them according to their current market situations and framework conditions for a possible transfer of innovative e-waste recycling technologies (figure 1)

Figure 1 is divided into four quadrants representing different shares of the recycling market between the informal and the formal sector. Normally, a sustainable recycling system should grow towards the upper right corner of the graph, where most of the established recycling schemes in Europe are located now, where the informal sector only exists as an exceptional case, if at all. However, this should not prejudice informal recycling activities being unsustainable per se. Depending on the socio-economic and cultural context of a country, a sustainable recycling system could include an organized informal collection system and the first steps of informal pre-processing as well (see previous chapter).

None of the selected countries features an established informal recycling sector while not having an established formal recycling sector at the same time. It is thought that in emerging and large economies like India and China both sectors depend on each other, while it is also known that both sectors in these countries mainly operate in an unsustainable way (Sepúlveda et al. 2009).

The countries could be classified into three groups:

- Group A is classified as promising for the introduction of pre-processing technologies with a strong support in capacity building (Kenya, Uganda, Senegal, Peru);
- Group B is classified as having a significant potential for the introduction of pre- and end-processing technologies with a strong support in capacity building in the informal sector (India, China);
- Group C is classified as having a significant potential to adapt pre- and to some extent end-processing technologies to their own needs, following a technology and knowledge exchange (South Africa, Morocco, Colombia, Mexico, Brazil).

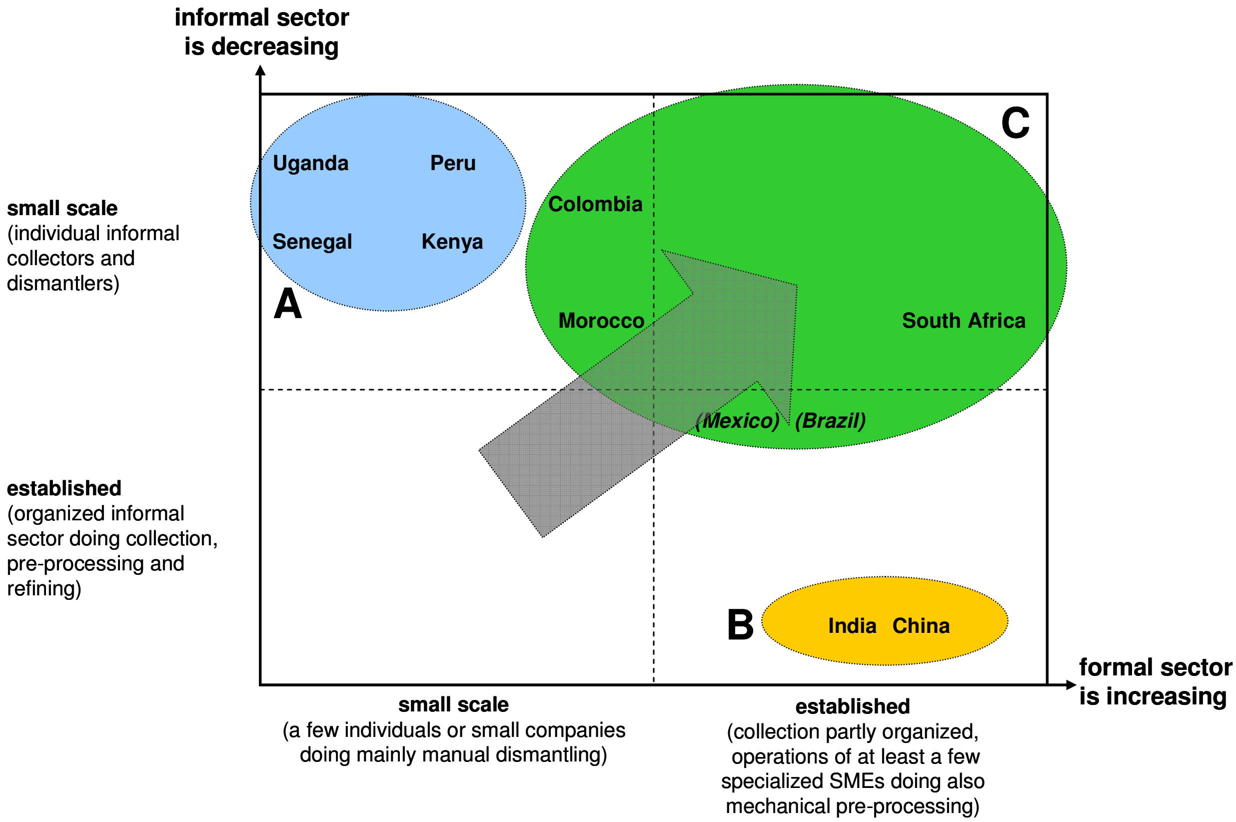

Figure 1: Comparative analysis of selected developing countries regarding the dimension of the formal and informal e-waste recycling sector

Acknowledgement

The authors of the study acknowledge the support by UNEP and the European Union who initiated and enabled this research, and thank all the members of the StEP family who increased the quality of the results by their valuable review.

References

Finlay A. and Liechti D. (2008). e-Waste Assessment South Africa. E-Waste Association of South Africa, Johannesburg, South Africa.

GFMS (2007). Platinum and palladium survey 2007. London.

Gmuender S. (2007). Recycling - from waste to resource: assessment of optimal manual dismantling depth of a desktop PC in China based on eco-efficiency calculations. Master Thesis EPFL / Empa, Lausanne / St.Gallen, Switzerland.

Hagelüken C. and Meskers C.E.M. (2008). Mining our computers- opportunities and challenges to recover scarce and valuable metals from end-of-Life electronic devices. In: Reichl H., Nissen N.F., et al. (eds): Electronics Goes Green 2008+. Stuttgart: Fraunhofer IRB Verlag, 2008, pp. 623-628.

Hilllebrand W. et al. (1994) Strengthening Technological Capability in Developing Countries - Lessons from the German Technical Cooperation, Berlin, Germany.

Johnson M. (2008). Platinum 2008. London.

Mueller E., Schluep M. et al. (2009). Assessment of e-waste flows: a probabilistic approach to quantify e-waste based on world ICT and development indicators. R'09 Twin World Congress, 14-16 September 2009, Davos, Switzerland.

Rochat D., Rodrigues W., et al. (2008) India: Including the Existing Informal Sector in a Clean e-Waste Channel. In: Proceedings of the Waste Management Conference (WasteCon2008), Durban, South Africa.

Schluep M. (2009). E-waste management in Africa - Rising up the political agenda. Recycling International, April 09, 56-61.

Schluep M., Hagelüken C., et al. (2009). Recycling – from e-waste to resources. Sustainable innovation & technology transfer industrial sector studies. Final report, United Nations Environment Programme (UNEP), StEP – Solving the e-Waste Problem, Paris / France and Bonn / Germany.

Sepúlveda, A., M. Schluep, et al. (2009) A review of environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. Environmental Impact Assessment Review, in press.

Streicher-Porte M., Marthaler C., et al. (2009). One laptop per child, local refurbishment or overseas donations? Sustainability assessment of computer supply scenarios for schools in Colombia. Journal of Environmental Management, in press.

Streicher-Porte M. Yang J. (2007). WEEE recycling in China, present situation and main obstacles for improvement. IEEE International Symposium on Electronics and Environment, Orlando, USA.

US Geological Survey (2007). Minerals Commodities Summary 2007. Washington.

Wang, F. (2008). Economic conditions for developing large scale WEEE recycling infrastructure based on manual dismantling in China - the learning experience from the setup of a pilot plant. Master Thesis, Universiteit Leiden, Delft University of Technology, The Netherlands.

Zumbühl D. (2006). Mass flow assessment (MFA) and assessment of recycling strategies for cathode ray tubes (CRTs) for the Cape Metropolian Area (CMA), South Africa. Zürich / St. Gallen: ETH Zurich / Empa.