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Review

Effective electronic waste management and recycling process involving formal and non-formal sectors

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Electronics waste is becoming a crisis for the society. Huge accumulation of e-waste and their recycling through primitive means for extraction of precious metals is real concern in the developing countries as e-waste contains hazardous materials. Recycling of e-waste through proper technologies is, however, considered to be a profitable business in developed countries due to the presence of precious metals (including gold, silver etc.) in printed circuit boards (PCBs). The present recycling cost is, however, not viable and thereby huge volume of e-waste is being exported to the developing countries like India, China, Brazil etc., where manpower is in-expensive and enforcement of environmental laws is not so stringent. This article is proposing an outsourcing model where equal participation of the formal and non-formal sector is ensured to make the e-waste management business a profitable one. The main motivation for non-formal operators is to extract precious metals (gold, silver) from printed circuit board (PCB) using unscientific and unhygienic methods, which are harmful to the workers and the environment. This practice needs to be discouraged by providing appropriate price to the non-formal operators for the materials they collected. In the proposed approach, non-formal operators will concentrate on collection, disassembly, segregation of e-waste, whereas, formal sector will concentrate on processing the PCBs to extract precious metals. The 95-97% of the e-waste by weight contains metal, glass and plastics, which can easily be dissembled and segregated manually without damaging environment; whereas, the rest 3-5% by weight of e-waste actually consists of PCBs/connectors, need environmentally friendly recycling techniques to manage. The major segregated materials from e-waste, including metals, glass and plastic parts can be recycled through the conventional recycling practices used in municipality waste management by organized smelters and re-processors. The segregated PCB and connectors will be pulverized by professional agency to make homogenous powder and assessment of assay content of the powder will be done to know the worth of the PCBs. Once the right price is decided, non-formal sector can sell the PCBs to the formal recyclers for further process. This approach will allow the formal recyclers to concentrate only on processing PCBs, which requires technologies, specialized skills and expertise. The said approach will eradicate the unhygienic practice prevailing in non-formal units in developing countries and thereby will stop polluting environment, soil, water, and will also protect the health of the worker. Once the outsourced model is established, the recycling of e-waste business will again be viable. It will also ensure the higher yield of metal recovery from e-waste as well as minimum landfill.

Key words: Management, India, e-waste, PCBs.

INTRODUCTION

Electronics waste (E-waste) is the fastest growing waste stream in the industrialized and urbanized world. Few decades back, the amount of waste generated was considered small enough to be diluted in the environment. With massive growth of electronics and hardware sector, the demand of the electronics products has been

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enhanced manifold. Faster change of features in the electronics devices and availability of the improved products forcing the consumers to dispose the electronics products rapidly. This has caused generation of e-waste alarmingly. The major source of e-waste is the disposal of the hardware and electronic items from Government offices, public and private sectors, academic and research institutes. Household consumers are also contributing significant volume of end-of-life electronics products. Apart from domestic generation in India, the imported e-waste volume is also growing substantially, though, import is prohibited in India.

Like other parts of the world, India is also facing serious crisis due to growing generation of e-waste. The main challenge in India is to create awareness of the environmental, social and economic aspects of e-waste among the public, consumers, producers, institutions, policy makers and legislators. The situation is not so grim in the developed countries, as the laws are adequate to take care of the stocking, disposal and land-filling of the end-of life electronics products. Moreover, availability of skilled recyclers and adequate technologies in those countries make the e-waste recycling a profitable business.

It is observed in recent years that large volume of e-waste is being exported from western countries to Asian countries like China, India, etc. for disposal. It seems the recycling business in western countries is becoming economically non-viable due to rising cost of manpower and availability of input materials for running the plant in full capacity. The western countries are, therefore, compelled to find out alternative destinations for disposal, where the labour cost is comparatively low and the environmental laws are not enforced so strictly.

The imported materials are thus reaching through illegal routes in India, China for recycling at small-scale units in non-formal sector. These units use primitive, non-scientific, and non-environment-friendly methods. E-waste is hazardous in nature due to presence of toxic substances like Pb, Cr_6, Hg, Cd and flame retardants (polybrominated biphenyls and polybrominated diphenyl-ethers etc.). E-waste disposal mixed with solid municipal waste is posing a greater threat for environmental degradation in the developing countries, where formal recycling technology is not available and non-formal operators are extracting precious metals through crude means for easy money. The extraction of metals in non-formal units is carried out by dipping printed circuit board (PCBs) in the acidic/alkaline solutions and heating/ burning of PCB. These processes are harmful to the workers and to the environment, which are the major concern of e-waste management in developing countries.

Non-formal units are not registered and their operations are also considered illegal in India as per the existing laws on industry, labour and hazardous substances. Despite, non-formal business is flourishing in India through the network involving collectors, traders and unorganized recyclers. It is felt that just enacting laws and routine vigilance, the growing business of non-formal sector cannot be stopped. It is appropriate to provide alternative source of income to nearly half million people, involved in this profession.

The e-waste recycling, however, can be made a profitable business if it is managed professionally. E-waste contains valuable materials including metal, plastics and glass, which are of the 95% of the total e-waste by weight. The populated PCBs/ connectors are of 3 - 5% of the total e-waste (Gao et al., 2004; http://www.ewasteindia.in/environment.asp) contain valuable metals like gold, silver, copper, and other precious metals like palladium, tantalum etc. In developed countries, well established processes are available for processing PCBs to extract the precious metals with highest yields (Gao et al., 2004; Xuefeng et al., 2005; Mou et al., 2004; Hanapi and Tang, 2006; Hyunmyung and Yong-Chul 2006). These processes are automated and minimal involvement of manpower is required. In contrast, the e-waste processing technologies in developing countries are not yet matured and the recycling is still being carried out in non-formal units by primitive ways. It is estimated that 95% of the e-waste recycling in India has been carried out in non-formal units (Report on “E-waste Inventorisation in India”, MAIT-GTZ Study, 2007). Therefore, a substantial amount of valuable materials are being lost due to unskilled operation. The recycling units is developed countries, on the other hand, are also facing shortage of materials and thereby the operation becomes economical non-viable.

An attempt has thus been made to bridge the formal and non-formal sectors in holistic manner to provide a profitable business model. In the proposed approach, non-formal units will carry out activities including collection, dismantling, disassembly and segregating of the e-waste. The segregated materials like metals (iron, aluminium and copper), glass and plastic parts will be sold to the respective smelters, re-processors etc. for recycling through the conventional practices, which are already prevailed for other materials recovered from municipality waste.

The segregated item like PCB and connectors which are most valuable due to presence of gold, silver, and copper, palladium, tantalum and traces of other precious metals will be converted into powder by a professional agency. The metal assay content of the powder will be assessed by the recognized laboratory. The non-formal will bear the cost of the process as well as the assay testing. The worth of the powder will then be decided based on the metal assay content. Non-formal sector can sell the PCB powder to the established recyclers at the right market price. This will prevent them from carrying out the hazardous extraction route of precious metals. The non-formal sector will be responsible from the collection of the e-waste till the selling of the PCB powder.

The process of PCB powder to recover metals (copper, lead, gold, silver) and precious metals (palladium, tantalum etc.) will be carried out by the formal units in the developed countries, where the maximum yield of recovery will be achieved and loss of value metals to the landfill can be minimized. The e-waste recycling and management will be profitable proposition in near future, once the outsource model is established in the society.

INVENTORY OF E-WASTE IN INDIA

A study carried out by MAIT/GTZ in 2007 estimates the total quantities of generated, recyclable and recycled e-waste are 3,32,979, 000 Kg, 1,44,43 000 Kg and 19,000 000 Kg respectively. The e-waste processed in 2007 consisted of 12000 000 Kg of computers and 7000 000 Kg of televisions. The 2.2 million computers had become obsolete in 2007. India had about 20 million computers in 2007, which would grow to 75 million by 2010. Around 14 million mobile handsets had been replaced in 2007 as per another study (MAIT-GTZ Study, 2007).

Reports on inventory of e-waste are based on models of obsolescence and not based on actual physical inventories in India. The statistics of production, exports and sales of each product and their average life have been considered in these studies. The average life of a personal computer (PC) was assumed to be 5 and 7 years and television (TV) to be 15 and 17 years (http://www.e-wasteproject.org/docs/del_amitjain.pdf. It was also assumed that 100% of electronic units sold in one particular year would become obsolete at the end of the average life. These perceptions of life of e-waste are based on urban conditions; the conditions are far from it considering the rural scenario.

Moreover, apart from the domestic generation of e-waste, the imported electronics waste has also contributed a significant impact in the total inventory of the material. India is becoming a big market for imported e-waste. A study indicates that PCs imported to Delhi in 2003 was nearly 3,600, 000Kg/year (The Hindustan Times, 2007). Another study predicts that the nearly 50,000 to 70,000 tons of e-waste is being imported annually to India (http://www.industelegraph.com/story/2005/9/2/33438/17285*).* Most developed countries, find it financially pro-fitable to send e-waste for re-use /recycling in developing countries. The cost of recycling of a single computer in the United States is $ 20 while the same could be recycled in India for only US $ 2, a gross saving of US $ 18 if the computer is exported to India (ELCINA, 2009).

NON-FORMAL UNITS IN INDIA

Authenticated data on the scale of the non-formal business and number of employed manpower are not available. It is estimated that more than 2000 non-formal recyclers are involved in the recycling business (http://toxicslink.org/dn.php?section=1&id=37&atn=0 http://www.toxicslink.org/dn.php?section=1&id=171&atn=0)
. Over 10,000 numbers of unskilled workers are involved in non-formal sector alone in Delhi (http://toxicslink.org/dn.php?section=1&id=37&atn=0 http://www.toxicslink.org/dn.php?section=1&id=171&atn=0).

Due to substantial profit margin, many small-scale units are being attracted in the recycling business. There are about some 270 medium and big scrap dealers in the country. The non-formal recycling business and the secondary market of refurbished old electronics products are growing steadily due to substantial demand in rural consumers. One study shows that after spending typical US$ 12.5-19 per piece for a single computer with colour monitor, a trader can earn around US$ 50-60 by selling its disassembled components, modules to different recyclers or reusers and by recovering precious metals and other valuables (http://toxicslink.org/dn.php?section=1&id=37&atn=0).

Non-formal units employ child and women labour from poor section of the society at low wages. The labours are neither paid their due wages as prescribed by government, nor, any compensation like medical/ transport/ etc. are offered. Labours are also not aware of their rights (like working hours/social security benefits etc.) and their occupational requirements (like hygiene, safety etc. No legal punitive action can be taken by Governmental agencies against these units, as they are not registered. A study has estimated that 95% of e-waste in India is processed by non-formal sectors units[7].

MOTIVATION OF NON-FORMAL SECTOR FOR METAL RECOVERY

The reasons of attraction of the non-formal sector into the recycling business can be understood if one sees the quantities and qualities of the materials recovered from e-waste and their market value. The data collected from one of the organised sector has been produced in this context (http://www.ewasteindia.in/environment.asp).

The amount of ferrous and non-ferrous metals, cable

Table 1. Recovered material from 1000 kg of PC

Plastics	% by Weight			Weight in Kg		
	23			230		
Metals		Cables	5		Cables	50
		Non-ferrous metals	29		Non-ferrous metals	290
	57	Ferrous metals	20	570	Ferrous metals	200
		PCBs	4		PCBs	40

NB: After recycling process of all items 99% was recovered and only 1% was sent for secured landfill.

Table 2. Saleable material recovered from 1000 kg assorted E-waste *(*containing PC, TV, Mobile Phone etc.)

Material	% Composition (by weight)
Mild steel	23
Stainless steel	8
Glass	27
Plastics	27
Copper	3
Aluminium	3
Other materials	8
Hazardous materials	1

NB: E-Waste also contains precious metals like gold, silver, palladium, platinum etc.

Table 3. Market value of the metal recovered from 1000Kg of PCBs

Recovered metal	Weight	Approximate cost (in US$)
Gold	279.93 g	6115 (@685.00 per 31 g)
Precious metals (Pt, Pd, In)	93.31 g	3852 (@ 1284.00 per 31 g)
Copper	190.512 Kg	1470 (@ 3.50 per 453.59 g)
Aluminium	145.152 Kg	448 .00 (@ 1.28 per 453.59 g)
Lead and Tin (Pb/Sn)	30.844 Kg	144.16 (@2.12 per 453.59 g)
Silver	450 g	213.15 (@ 14.70 per 31 g)

NB: Data generated on average recovery of one ton of populated PCBs and value is taken from the prevailing rate at that point of time. These are only to give a perception of value from the metal recovery from e-waste.

and PCBs recovered from one ton (1000 kg) of computers is indicated at Table 1. The 1000 kg assorted e-waste contains a substantial amount of saleable materials like mild steel, stainless steel, glass, plastic, copper, aluminium etc (Table 2). The volume and cost of the metals recovered from PCBs are indicated at Table 3. In another study, it is estimated that the 1000 kg of populated PCB of computer as e-waste yields 284 gram of gold (Gao et al., 2004).

In spite of awareness of the harmful effect of extracting metals by primitive methods, recycling of discarded electronic products is being carried out in non-formal sector. The non-formal business is growing steadily due to demand and the market value of recoverable materials.

This value chain mainly motivates the non formal recyclers to flourish.

E-WASTE MANAGEMENT IN NON-FORMAL SECTOR

Non-formal sector units in India include *kawaries* (rag-pickers), scrap dealers, whole sellers, recyclers etc. The e-waste management in non-formal sector has following major operations:

Collection

Kawaries, small scrap dealers collect the e-waste from consumer with suitable compensatory price. The consumers are also encouraged in putting the e-waste in recycling chain instead of storing the e-waste or throwing away in municipality garbage. *Kawaries* are one of the most efficient collectors of e-waste and also reduce the load of civil agencies responsible for waste collection. Thus all the collected wastes are put back to effective use. E-waste is collected in bulk quantity by large scrap dealers from government offices, public sector agencies, school, universities and other corporate houses etc. The importers of scrap also collect discarded electronics products in bulk quantity from various developed countries.

Segregation

Collected e-waste from diversified sources is segregated in various categories such as components, modules, metals, glass and plastics depending on the saleability for highest economic returns.

Disassembly

The disassembly methods would be of two types, non–destructive and destructive. Non–destructive recovers the certain disassembled parts for reuse while the destructive disassembly separates each material type for recycling processes. Non–destructive method is not feasible as designs of the products are changing very fast, new functionalities are being added. The composition of various electronic components has also gone a significant change in last few decades, which makes majority of de-soldered components obsolete for re-use.

The disassembly can be realised in the following ways. The dissembled items are broadly classified into following categories:

i) Small & large structural metal parts, heat sinks.
ii) Small & large structural plastic parts.
iii) Printed circuit boards with IC Chips, electronic components and connectors.
iv) Ferrite and ceramic components.
v) Cables and wires.
vi) Glass components.

For example, cathode ray tube (CRT) based television and computer monitors consists of:

i) Enclosures made of plastics (can be sold to plastic reprocesses).
ii) Cables/ wires (power cords, CRT HV cable etc) of the system (can be stripped off insulator materials and copper wire thus recovered).
iii) iron/ steel fittings and screws (can be sold to iron smelters).
iv) Lead rich glass present in the colour picture tube and computer monitors (CRTs can be mechanically separated), however, the glasses have to be separated as high lead content and low lead or of lead free composition The cullet of glasses can be sold to glass parts (panels, funnels) manufacturing units, after segregating glass culets of panel and funnel separately.
v) Deflection yoke is further dismantled into ferrite part. The small populated PCB attached to cathode ray tube and present in tuners are sent for further processing along with other populated PCBs.

Similarly desktop computer consists of

i) Metal/plastic enclosure.
ii) Switch mode power supply unit.
iii) Cooling fan.
iv) Main mother board.
v) Auxiliary cards.
vi) Hard disc drives.
vii) CD/DVD read/write devices.
viii) Main Power cable, inter connecting cable for connection with printer, monitor, modems, scanner.

Typical contents of Television, Desktop Computer and Refrigerator (http://www.industelegraph.com/story/2005/9/2/33438/17285) are shown in Figure 1.

Reuse of recovered materials

The *Kawaries* and the scrape dealers sell all the dismantled and segregated parts of metal, glass and plastics to metal/glass smelters and plastic re-processor who specialize in converting these scrap of coppers, aluminium, iron, glass and plastics. Non-formal units have lack of knowledge of the processes of smelting/ reprocessing and, therefore, prefer to sell such scrap. Thus, they play an important role in proper recycling a

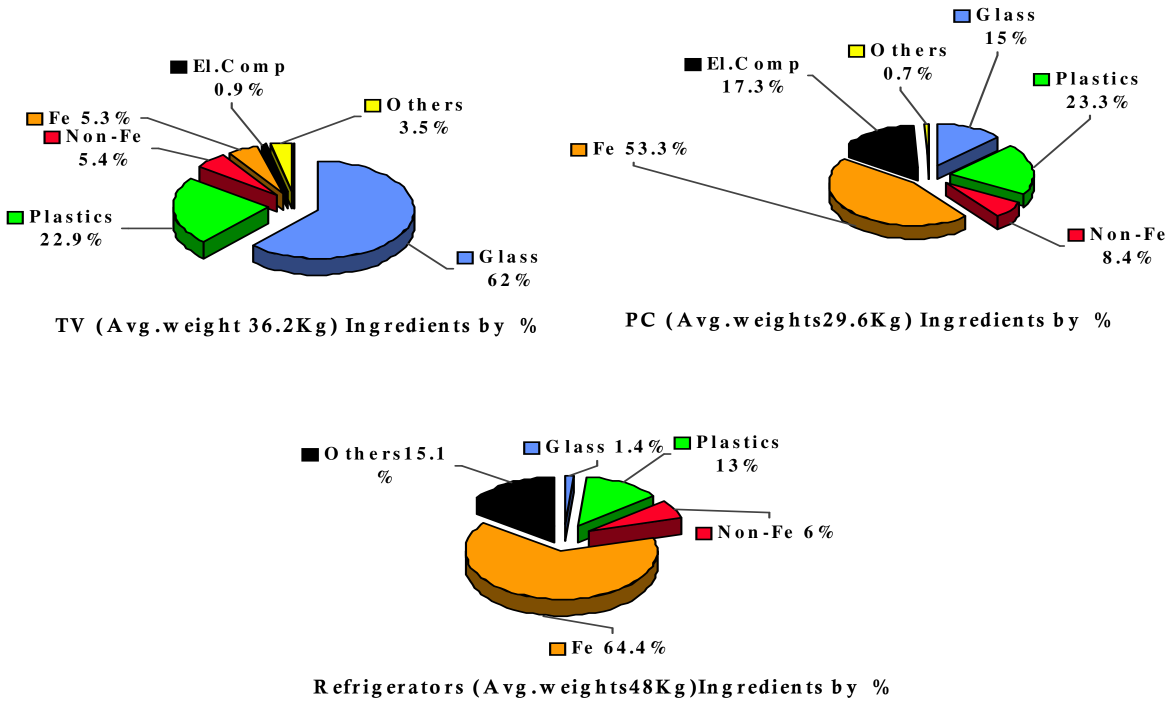

Figure 1. Contents of materials recovered from TV, PC, refrigerators.

large quantum (~ > 95% by weight) of e-waste in reuse chain without harming environment. Therefore, out of the present inventory of total e-waste, 3, 30, 000, 000 Kg, the 3,13,500 000 kg (95%) of e-waste can easily be managed by the non-formal sector without polluting the environment. The rest 16,500 000 kg (5% by weight) of e-waste actually consists of PCBs/Connectors, which need environmentally friendly recycling means to manage.

Recycling of printed circuit boards (PCBs)

The populated PCBs, constituting 3 to 5% by weight of total e-waste, have rich value of metals such as silver, gold, palladium, platinum, tantalum and other metal in traces level. Their recovery requires professional skill and high cost equipments. The lack of knowledge, affordable logistics and greed for quick money motivates non-formal sector to employ unhygienic and un-scientific methods for recovery of valuable metals such as Cu, Ag, and Au etc.

The typical methods employed by non-formal units are focussed to recover gold from the integrated circuits (ICs), gold plated terminals of connectors/PCBs and other components etc. These gold rich components are removed by loosening of the lead solder by surface heating, which, however, causes air pollution. The stripped PCBs are subjected to open burning to recover copper. The boards are heated to extract the thin layer of copper foils in the PCBs. In the acid bath process, the circuit boards are dipped in acid for few hours for de-soldering. Then the used chemical solutions are drained to the ground causing soil pollution. The lead sludge that collects in the bottom during the process is recovered and sold. After a water bath the de-soldered PCBs are boiled with a caustic soda solution and manual scrubbing is done to remove the paint. The PCBs are again dipped in an acid solution for few hours, which results in copper sulphate formation. Iron wires are added to the solution and the sludge contained copper settles in the bottom. The acid solution is drained out to recover the sludge, which is dried, grounded to power and sold in the market. This is one of the most hazardous processes in e-waste recycling. It creates occupational as well as environmental hazards.

E-WASTE MANAGEMENT IN FORMAL SECTOR

Disassembly/Segregation

Units in formal sector use all types of methods to disassemble and segregate the e-waste materials. These methods are varied from manual or semi-automated or automated techniques. These methods are environmenttal friendly and take care of the safety of the health of the operators. Disassembly involves the removal of hazardous components such as batteries and other high and low grade including component, part, group of parts or a sub-assembly from a product (partial disassembly) or the separation of a product into all of its component parts (complete disassembly). The recovery of valuable materials such as printed circuit boards, cables and engineering plastics is simplified by such approach.

Recycling of printed circuit boards (PCBs)

The segregated populated PCBs are processed for the recovery of copper, gold, and other precious metals. The PCBs are grounded to powder of desired size through various mechanical processes including physical impaction, shredding/fragmentation and granulation, etc. Shredding breaks down the PCBs into pieces via ripping or tearing which may then be sorted into material streams having dissimilar subsequent processing demands. The mechanical process, granulation is used to make PCBs scrap into fine particles.

Precious metal particles are further concentrated by means of various separation techniques. Magnetic separation technique is used to separate magnetic materials (iron, nickel and cobalt) from the PCB powder and the aluminium particles are being separated by eddy current separation technique. The metal rich power is then separated from plastic rich particles by electrostatic separation technique. The processes are elaborately discussed in the reported articles (Gao et al., 2004; Xuefeng et al., 2005; Mou et al., 2004; Hanapi and Tang, 2006; Hyunmyung and Yong-Chul, 2006).

The metal recovery involves various thermal and chemical treatments depending on their merits and demerits. Thermal treatment avoids the liquid effluent disposal problems associated with wet chemical extraction methods. Thermal incineration combined with pyrometallurgical treatments is in commercial use for metal recovery from PCBs.

The hydrometallurgical methods are also used to recover metals from PCBs. Electro-refining is generally used alter thermal processing for the purification of copper with the separation of precious metals. Selective recovery of pure metal products directly from waste streams is key advantage of these methods. The cyanide solution is generally used for gold recovery from the PCBs powder. The metal recovery is discussed in details in the articles (Hanapi and Tang, 2006; John et al., 2006; Recovery of high purity precious metals from printed circuit boards, 2009). An indicative tentative process flow chart for recovery of metals/precious metals from the populated PCBs is shown is Figure 2.

PRESENT SCENARIO OF E-WASTE RECYCLING IN DEVELOPED COUNTRIES

The electronic waste recycling was considered to be profitable business in the western countries till the recent past. Appropriate technologies as well as adequate infrastructures are available in developed countries to process the end-of-life electronic products to extract precious metals to the best possible yields. The consumers support financially to the recycling activity in western countries the form of EPR (Extended Producers Responsibility). Though, it is observed that the e-waste recycling is becoming non-viable in the developed countries due to following reasons:

i) The profitability of the e-waste recycling business depends on the recovery percentage of the precious metals including gold, silver, palladium, tantalum, platinum, etc., which are present in very low percentages or in traces. While recycling is done through automated methods, the precious metals are often lost in the bulk of other less valuable metal dust and plastics particles. The automated disassembly and segregation methods may not be appropriate to recover all these precious metals from the waste stream of PCB powder. The prior knowledge of the electronic components and their composition will guide recyclers to identify the origin of precious metals in PCBs. These identified components will preferably need segregation at early stage and process separately for better recovery yield. Therefore, in order to enhance the yield of recovery of precious metals, the manual disassembly and segregation are inevitable for the recycling process. The high manpower cost in the developed countries, however, does not allow the recyclers to encourage any manual operations.

ii) Electronics devices are being continuously modified, improvised and miniaturized through technological developments and advancement of materials research. The design of the PCBs is also being modified and sizes are also drastically reduced. The precious metals contain in the PCBs are thereby reducing with these modernization and miniaturisations.

iii) The advancement of material research is also replacing conventional usages of gold, silver, copper and other precious metals (tantalum, palladium, platinum etc.) without compromising the functionality. This reduces the cost of the products drastically. The recovery of precious metals from PCBs of modern electronics devices are reducing compare to the historical PCBs. These reduce the profit margin of the recycling business and thereby recycling business is being shifted to the countries like China, India and Brazil.

iv) In order to move up in the ladder of the technology value chain, the developed countries prefer to transfer the manufacturing or processing technology to the deve-

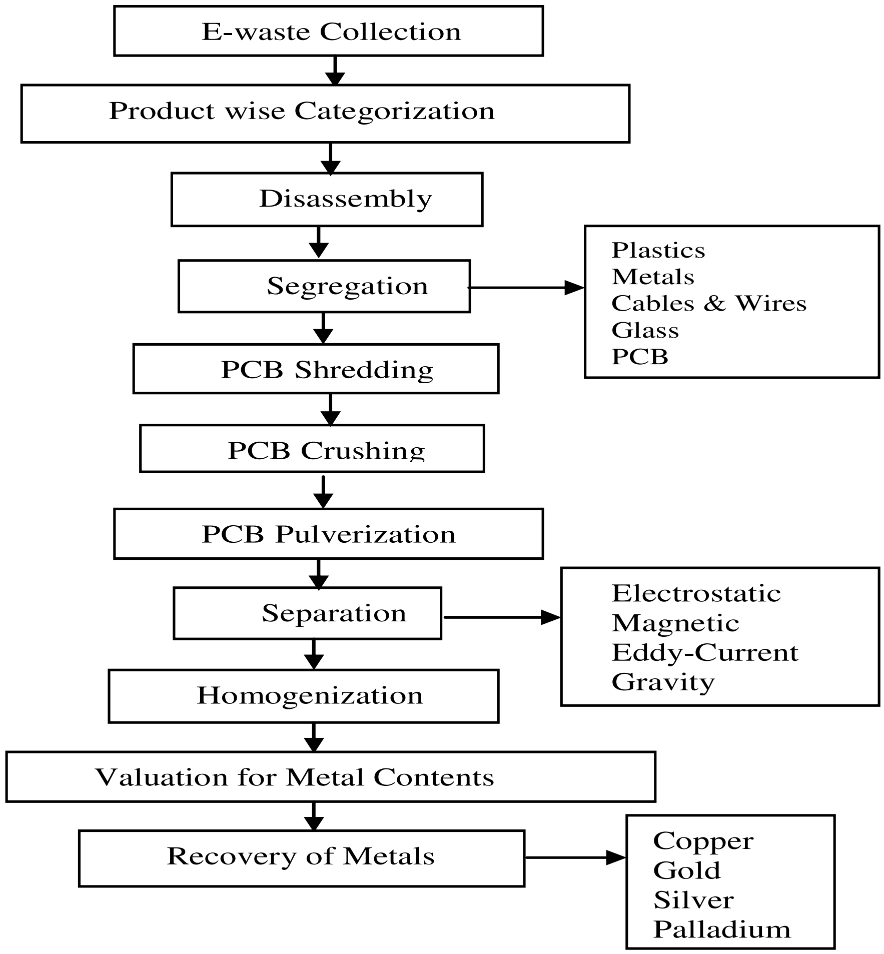

Figure 2. Process flow chart for recovery of saleable materials e-waste.

loping countries. Those technologies are often transferred, which are comparably established and needs no further innovation. In contrast, developed countries could concentrate on the value added technology. The e-waste recycling technology is no longer a high end technology where further innovation is required. The trend is therefore to shift the operation is the low cost destinations like China, India and Brazil.

PROPOSED MODEL FOR E-WASTE RECYCLING

The major reason for the domination by non-formal units is economics of metal recovery in the e-waste recycling business and abundance of low cost labour. The present situation does not appeal to the non-formal sector to divert waste materials to professional recyclers due to obvious economic reasons. They are compelled to extract precious metals (copper and gold) through unhygienic practices. Due to their lack of knowledge, the recovery yield of the precious metals is very poor and, thereby, substantial percentage of the metals like copper, gold, silver, and other precious metals (palladium, tantalum, platinum, etc.) are lost. The authors feel that if suitable prices for the precious metal present in PCBs/connectors are paid to non-formal units, they can be discouraged from extracting metal from scrape PCBs/connector by themselves through primitive means. In the proposed approach, non formal units will concentrate on collection, disassembly, and segregations. The segregation of metals, glass and plastics from e-waste by non-destructive methods and channelizing them for further processing by professional smelters can be safely carried out by non-formal sectors as these will not damage the environments. Metal recovery from PCBs and connectors require innovative approach for environment friendly disposal approach. In this article, a novel methodology involving non-formal sectors has been devised so that ill effects on the environment can be eliminated. The proposed approach will have following steps.

Step: 1

Collection, disassembly and segregation

E-wastes will be collected from various consumers from home, offices, industry and corporate houses, private and public organizations etc. It is proposed to bring the e-waste collectors (Kawaries) in co-operative domain and provide remunerative returns for their collection. The collected e-waste should be segregated in to various categories, dissembled and segregated to separate populated PCBs and connectors. E-waste consists of huge variety of electronic/electrical (WEEE) products and their market values also vary widely depending on their demand. PCBs and connectors are most valuable parts as it contains gold, silver copper and other precious metals. It is proposed to pulverise the concentrated e-waste that is, populated PCBs and connectors.

The concentrated e-waste is created by manually removing items such as glass components, metal fittings, screws, connectors etc., cables, heat sinks, plastic enclosures, fans, transformers, batteries etc. The populated PCB containing connectors and other components is rich in valuable metals such as copper, silver, gold, palladium, tantalum etc.

Step: 2

Shredding, crushing and pulverization

These processes are carried out to make homogeneous mixture of populated PCBs to primarily assess the quantity of various saleable metals present in wide variety of populated PCBs. The pulverization is also carried out to separate particles with different types of metal contents but also to liberate metals from plastic part of individual components and laminate of PCBs. The particle size of pulverized PCBs needs to be further processed by suitable method to improve the homogenized e-waste. The idea of pulverization is also to maximize separation of metal particles from plastic to which it is normally adhered.

The PCBs populated with whole range of passive, active, electro mechanical and inductive components in both leaded and surface mount configuration are shredded in a mechanical shearing machine down to a size of about 3 x 3 mm. Finally, these shredded pieces were subjected to dry grinding in a ball mill to a top size of 1.0 mm. The shredded materials are then pulverized less than 1.0 mm size for liberation of metal and plastic by physical beneficiation techniques (Gao et al., 2004; Xuefeng et al., 2005).

As an alternative method, the material for large scale operation can be carried out by simultaneously shredding and pulverizing operation. In this method, the PCBs are crushed to suitable particle sizes in two-stages of shredding operation. A double-toothed roll shear and a hammer crusher are used to liberate of metals from other components contained in the PCBs. The PCBs are crushed to less than 1 mm by compression and shear with specially designed double toothed roll crusher. A hammer mill was used as the secondary crusher, which essentially consists of rotating hammers and a perforated screen that controls the product size. Fine shredding is required to liberate metals from the cladding materials or composite laminates such as resin, fibreglass and plastics. The degree of liberation of metal increases with its particle sizes and ideal liberation particle size is found to be 0.5 mm (Gao et al., 2004; Xuefeng et al., 2005)

Before assay analysis, acceptable industrial standards of pulverization will be used to ensure the standardization of the powder with respect to their particle size distribution, homogenization, sampling procedure and sample collection.

Step: 3

Valuation methods for PCBs: assay metal contents

The metal rich powders are subjected to essay content by professional agencies having adequate instrumental facilities. It is essential as different metals in PCBs are very unevenly distributed. The standardised method of sampling and assay analysis of metal content in PCBs and subsequent certification from professional (private/ public) agencies would be done to motivate non-formal recyclers to know the presence various metals in transparent manner.

The exact quantitative data on the metal composition of PCBs (in pulverized form) can be obtained by using atomic absorption spectroscopy (AAS) or inductively coupled plasma/atomic emission spectroscopy (ICP/ AES). This process includes acid or caustic leaching of the powdered material with, HCL, HF, in appropriate proportion and sequence. All of the metals can be extracted and determined by AAS or ICP/AES, using atomization by either flame or hydride system or graphite furnace. Although AAS can analyze a number of elements in the range of ppm or ppb concentration, it is more time and cost intensive. The standard sampling from homogenized pulverized powder is important for valuation method.

The proper worth of the PCBs, segregated by non-formal sector will be decided from the assay analysis report, and the market value of the metal. The price of such powders can be ascertained in a transparent manner and suitable money can be paid to the collector. The confidence of e-waste collector can be earned in a progressive manner, thereby, encourage them to sell the collected populated PCBs to agencies for processing them in environment friendly manner.

Step: 4

Metals extraction

The pulverized PCB powder will then be sold to the professional authorised smelters who have the adequate knowledge and facilities to extract metals like lead, copper, gold, silver, palladium, platinum etc. The powder can be segregated into various groups containing rich copper rich, iron rich, aluminium rich, lead rich and other mixed metal rich. The magnetic separation is used for separating iron, nickel and cobalt metal and aluminium will be separated by eddy current separation. The electrostatic separation is used for separating plastic and metals and various embedded plastic and metal clusters are separated by gravity separation methods.

The extraction of the precious metal will be carried out by the well-established techniques, which are discussed in details at various articles (Xuefeng et al., 2005; Mou et al., 2004; Hanapi and Tang, 2006; Hyunmyung and Yong-Chul, 2006; John et al., 2006; Recovery of high purity precious metals from printed circuit boards, 2009)

METHODOLOGY FOR THE PROPOSED APPROACH

In the proposed recycling process, non-formal sector will collect the e-waste from various stakeholders by paying suitable prices (~1US$/ kg). The collected e-waste will be categorized and usable modules will be separated out. The disassembly, segregation of e-waste will be carried out to recover the metals, plastics and glass. These manual processes will incur further cost to the non-formal sector as labour (~1US$/ kg). The usable modules (modules, batteries etc.), metals (copper, iron, steel etc.), plastics (casing, bobbins, etc.), glass will be sold to the respective smelters and re-processors for further use of these materials. Non-formal will recover some money (~0.5 US$/ kg on average) by selling these usable materials.

The non-formal sectors will use professional mining firms to covert the connectors, switches and PCBs in homogenous powder. The process will involve the shredding, crushing, pulverizing and homogenization. The professional firms will charge appropriate prices (approximately ~0.2 US$/ kg) to the non-formal sectors for converting the PCBs to homogenous powder.

The non-formal sectors will take help of the authorized laboratory to assess the assay content of the homogenous powder and obtain the appropriate certificate by the by paying nominal charges (approximately ~0.01 US$/ kg).

The non-formal sector will then sell the PCB powder to the formal sector/ authorized recyclers based on their appropriate market prices. The price will depend upon the presence of the precious metals (assay content) in the PCB powder. The non-formal sector may earn approximately 20 US$/ kg from formal sector. The prices estimated in the above proposal are indicative and based on the market prices of various materials in India. The indication of the price structure is only to give a perception of the value recovered from various stages of the recycling process. The actual money flow and profitability of both non-formal and formal sector can only be obtained by actual market survey. The detailed process flow chart of the recommended recovery of metals/ precious metals from the populated PCBs, responsible stakeholders and the money flow is described as in Figure 3.

Conclusions

The e-waste recycling is becoming non-viable business in western countries due to high cost of labour, transportation, electric power etc. The decreasing percentage of precious metal content in the modern electronics devices is the other concern for the viability of the business. The volume of e-waste is, however, enhancing alarmingly in the world. Due to presence of the toxic elements, it is all the more dangerous for the society to stock them without carrying out appropriate disposal. It is also observed that the growth of consumption of the electronics products and subsequent disposal are increasing in the developing countries, whereas, the consumption rate in the developed countries are getting saturated. The volume of the e-waste is thus increasing alarmingly in the developing countries due to their own as well as imported disposable electronics hardware products.

It is therefore appropriate to devise a holistic approach to manage and recycle the e-waste in self-sustained manner to save the environment and the human health. The developed countries have technology and infrastructure, whereas, the cost of labour, transporting, processing etc. are cheaper in the developing countries. It is, therefore, proposed in this article to manage the e-waste involving non-formal sectors at developing countries and formal sectors in the developed countries.

In the proposed approach, non-formal units will be involved in collection, disassembly and segregation of e-

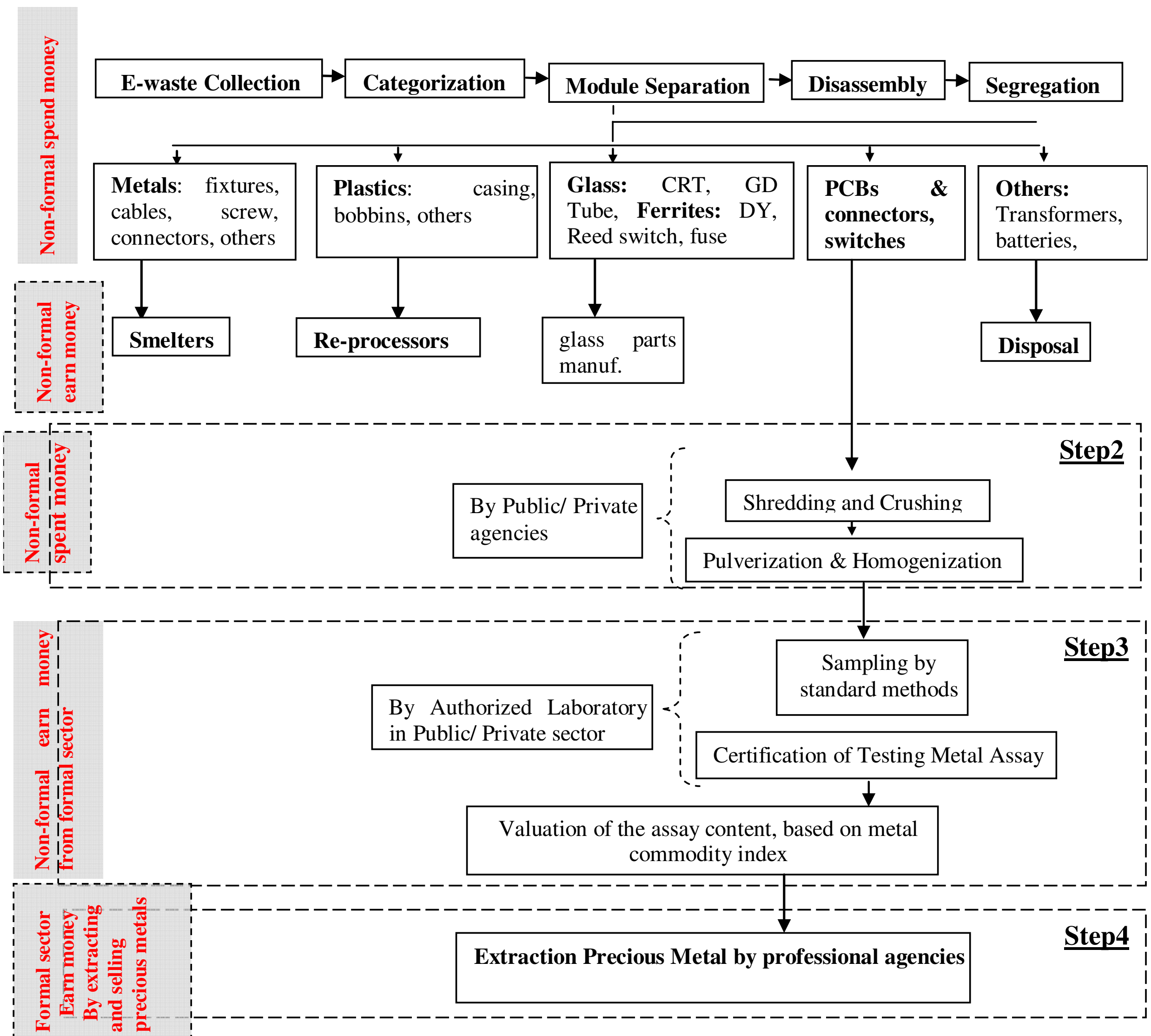

Figure 3. Process flow chart for e-waste management.

waste and earn appropriate incentive for their efforts. The non-formal sector will also be responsible for preparing the homogenous powder of the PCB, assessing their precious metal content as well as obtaining certificate for attracting formal sector to buy their powder in the best market price. It will encourage e-waste collector to earn maximum without indulging in extracting gold, silver etc. through burning and chemically exposing processes. The harmful impact on environment and to human being will be reduced. This is an outsource model of e-waste recycling, where formal sector will only concentrate on the core activity of PCB recycling. The cost of the initial phase of the processes can be saved and the profitability will enhance. Enough PCBs materials will be available for the established recyclers at developed countries. It would thus address the shortage of materials for the formal units. The zero/minimum waste disposal to landfills will be achieved through this model. The proposed approach would bring mutual trust between non-formal and authorised metal extractors.

Since the non-formal recyclers are dealing major amount of e-waste in India, the said approach will impact on the majority of the e-waste management value chain. Moreover, nearly 95% of e-waste by weight will be segregated and then managed/ recycled by the conventional municipality waste management techniques. The said approach is, therefore, will be impacted major recycling management mechanism. Since the primitive

Table 4. Approximate intrinsic value of typical medium graded PCBs waste

Component	Weight (by %)	Value (by Kg)	Intrinsic value	
			(pound per Kg)	%
Gold	0.025	6500.0	1.625	57.48
Palladium	0.010	8000.0	0.8	28.30
Silver	0.100	70.0	0.07	2.48
Copper	16.00	0.8	0.128	4.53
Tin	3.000	3.0	0.09	3.18
Lead	2.000	0.3	0.006	0.21
Nickel	1.000	5.0	0.05	1.77
Aluminium	5.000	0.9	0.045	1.59
Iron	5.000	0.1	0.005	0.18
Zinc	1.000	0.8	0.008	0.28
Total	33.135	-	2.827	100.00

Note: Metal values are based on June 2002 London Metal Exchange Levels.
(Source: Xuefeng et. al. China University of mining Technology, Xuzhou University)

Table 5. Approximate sellable metal in e-waste

Items	Weight	Wt. (by %)
E-waste	3,30, 000,000 Kg	100
PCBs	16, 500, 000 Kg	5
Precious Metal content in PCB (33% of the weight)	2, 72,250 Kg	1.65

methods are avoided, the recovery percentage of the precious metals will also be improved to a significant level. The metals (palladium, platinum, tantalum etc.) those are present in the trace level will also be recovered. At present these metals are lost due to lack skill level. The employment of the manpower involved in the non-formal sector will also remain.

The present inventory of total e-waste has projected as 3, 30, 000,000 Kg. The 95% of the total weight of e-waste (that is, 3, 13,500 000 Kg) can easily be managed by the non-formal units without polluting the environment. The projected volume of the e-waste generation and its associated concerns in the society will be drastically reduced. The rest 5% of the weight (that is, 16, 500,000 Kg) of e-waste actually consists of PCBs/ connectors, which needs environmentally friendly recycling techniques to manage.

In another table (Table 4) it is indicated that the approximate intrinsic value of metals recovered typically from medium graded PCBs scrap and non-metal[3]. It may also be noted from the table, that 33% of typical medium graded PCBs has saleable metal contents whereas 67% consist of combusable material like epoxy resins and fabric etc.

Table 5 further indicates that the 5% of the PCB in e-waste needs to be processed by the formal sector in the processed process and 1.65% of the metal content of the total volume of the e-waste (that is, 2, 72,250 Kg in Indian perspective) needs an environmental friendly, skilled process. This volume is sizable enough to be tackled by the society by authorised metals extractors at the developed countries.

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