ANALYSIS OF ELECTRONIC WASTE RECYCLING IN THE UNITED STATES AND POTENTIAL APPLICATION IN CHINA

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EXECUTIVE SUMMARY

With increasing consumption of electrical and electronic products worldwide, the generation of electronic waste (e-waste) is growing rapidly, both in developed and developing countries. It is reported that in 2012 the generated amount in the U.S. was about 9.4 million tons and in China 7.3 million tons, just next to the U.S. The global e-waste generation amount in the same year was estimated at 49 million tons. Some measures have been taken to address this problem in developed countries, such as various electronic waste recycling programs carried out by municipalities, companies, and non-profit organizations. At the same time, technologies for electronic waste recycling are being developed for recovering valuable materials from e-waste and treating hazardous materials properly. However, these activities are at an initial stage, since the estimated fraction of electronic waste actually recycled is still less than 30% in the U.S.. Another problem is the illegal export of electronic waste by recyclers from developed countries to less developed countries, such as China. China, as the largest acceptor and the second largest producer of electronic waste, has become the major sink of the world's electronic waste.

This study analyzed the electronic waste recycling system in the U.S. as an example of established such systems in developed countries. Then, the present collecting and disposing situation of electronic waste in China was examined in detail, including e-waste collection and recycling in both formal and informal chains. The potential of applying the western electronic waste recycling systems into China was then further explored as well as the environmental and social benefits that could be hopefully achieved through this.

China is now taking care of 20% of electronic waste generated globally. About 38% of this e-waste is recycled by informal recyclers who use primitive recycling methods to recover valuable materials, leading to serious environmental pollution. Ironically, due to the existence of informal recyclers, the amount of electronic waste available to formal recyclers, who conduct environmentally responsible recycling, is just around 18% of the total, far from sufficient to

support the capital investment in processing technologies and costly air pollution control systems and much of the existing facilities for e-waste recycling are idle.

The problem should be tackled from the perspectives of both regulation and technology. Regulation support is the most critical issue in solving the electronic waste problem in China and should be provided in order to prohibit illegal import of e-waste and promote responsible recycling of the e-waste generated within the country. To prohibit illegal import, Chinese government should improve existing regulations to avoid loopholes allowing electronic waste import and at the same time strengthen the inspection to enforce the implementation. To promote responsible electronic recycling, well-defined Extended Producer Responsibility should also be established and fully implemented.

From a technology perspective, a combination of existing manual dismantling pre-processing in China and more advanced western end-processing technology was proposed by a Chinese researcher in 2012, which was further calculated in this thesis. Annually, about 75 million tons of raw materials could be conserved and 0.22 million tons of hazardous materials could be avoided by adopting the proposed recycling chain. Also, a large amount of non-renewable energy and associated greenhouse gas emissions could be avoided, due to the energy consumption difference between using virgin or recycled material, which may lead to price reduction of electrical and electronic products in the future.

The industrialization and regulation of each sector (collection, second-hand market, refurbishment, remanufacturing, recycling) in electronic waste recycling system is recommended for China. However, because of the existence of informal sectors in China, it could hardly be lucrative for formal industries in current situation. Therefore, the Chinese government can play a critical role in encompassing in this effort, as much as possible, the people engaged in the informal sectors. It is suggested that, at the beginning, the industrialization of e-waste recycling and processing be a state-owned enterprise. After it is well developed under the guidance and investment of the government, it can then be privatized and driven by the market.

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Shumeng Liu, New York City, December 4th, 2014

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATION AND ACRONYMS

ANSI: American National Standards Institute

ASQ: American Society for Quality

ARF: Advanced Recycling Fee

BFR: Brominated Flame Retardant

BAN: Basel Action Network

CCFL: Cold Cathode Fluorescent Lamp

CRT: Cathode Ray Tube

DEQ: Department of Environmental Quality

EPA: Environmental Protection Agency

E.U.: European Union

EEE: Electrical and Electronic Equipment

GHG: Green House Gas

LCD: Liquid-Crystal Display

E-waste: Electronic Waste

RIOS: Recycling Industry Operating Standard

OHSAS: Occupational Health and Safety Management System

ISO: International Organization for Standardization

NAID: National Association for Information Destruction

WEEE: Waste Electrical and Electronic Equipment

SMM: Sustainable Materials Management

MSW: Municipal Solid Waste

NGO: Non-Governmental Organization

PGM: Platinum Group Metals

PDP: Plasma Display Panel

PCB: Printed Circuit Board

R2: Responsible Recycling

StEP: Solving the E-waste Problem

USD: US Dollar

EPR: Extended Producer Responsibility

ELI: eCycling Leadership Initiative

FGC: Federal Green Challenge

WEC: WasteWise Electronics Challenge

LED: Light Emitting Diode

ANALYSIS OF ELECTRONIC WASTE RECYCLING IN THE UNITED STATES AND POTENTIAL APPLICATION IN CHINA

1 Introduction

1.1 Definition of electronic waste

Electronic waste (E-waste) describes discarded electrical or electronic equipment. The definition of e-waste varies among different countries. In European Union, it is divided into ten categories in the new Waste Electrical and Electronic Equipment (WEEE Directive) 2012/19/EU[1] as Table 1. For details, please refer to APPENDIX A.

Table 1 E-waste category pursuant to the EU Directive 2012/19

1	Large household appliances
2	Small household appliances
3	IT and telecommunications equipment
4	Consumer equipment and photovoltaic panels
5	Lighting equipment
6	Electrical and electric tools
7	Toys, leisure and sports equipment
8	Medical devices
9	Monitoring and control instruments
10	Automatic dispensers

Table 1 shows that the definition of e-waste in the European Union (EU) includes everything that has a power cord or battery. The e-waste definition[2] of China is the same as the EU directive but five home appliances: air conditioner, refrigerator, washing machine, TV and computer are mainly regulated. As the consumption of mobile phones grows dramatically these years, the obsolete amount of mobile phones[3] has also been included now.

In the United States, e-waste is not clearly defined. The term "e-waste" mainly refers to consumer electronics that are near or at the end of its useful life[4]. Consumer electronics[5] consist of video and audio equipment and information products, such as television, computer and mobile phones.

1.2 E-waste generation in different countries

E-waste is the fastest growing sector in the municipal solid waste (MSW) stream. It is estimated that about 49 million tons of e-waste are produced worldwide in 2012[6]. The European Union (E.U.) contributed 9.9 million tons. The U.S., the world leader in waste generation discarded 9.4 million tons, while China, who produced 7.3 million tons, was just next to the U.S.. Since all these data are measured by Solving the E-waste Problem (StEP), an international initiative, this thesis will follow the e-waste definition of StEP: "*All types of electrical and electronic equipment (EEE) that enters the waste stream. This includes TVs, computers, mobile phones, white goods (e.g. fridges, washing machines, dryer etc.), home entertainment and stereo systems, toys, toasters, kettles-almost any household or business item with circuitry or electrical components with power or battery supply*."

Figure 1 shows the generation of e-waste in various countries[6]. Since the population of each region is different, the average e-waste generated per capita is of importance. As shown in Figure 2, the generation of e-waste per capita varies proportionally to purchasing power (USD per inhabitant, StEP)[6]. Apparently, the U.S. has the highest the e-waste generation amount both in total and per inhabitant (29.8 kg per capita). Even though China is second to the U.S. in total e-waste generation, its generation per capita is only 5.4 kg per year.

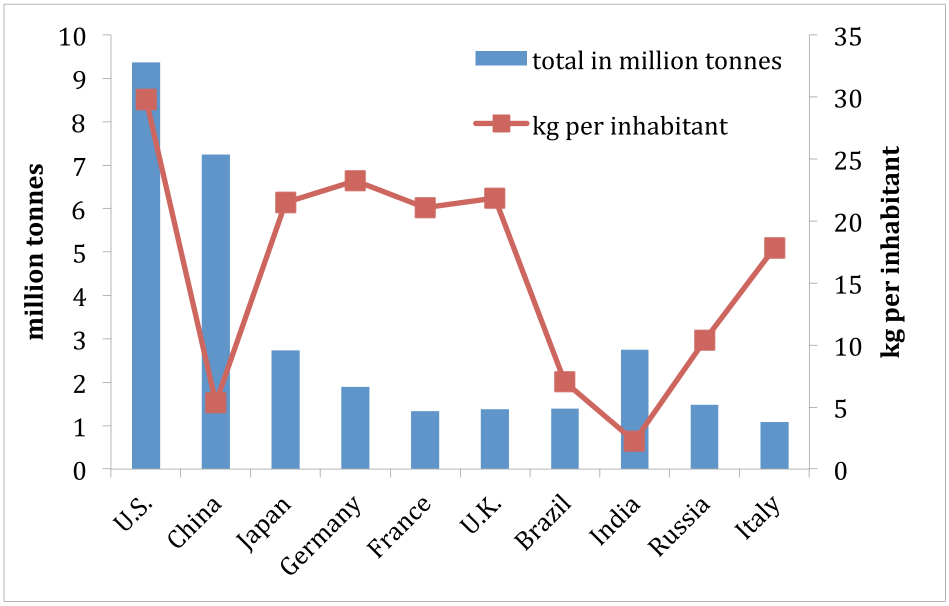

Figure 1 E-waste generation in typical countries (2012, StEP) [6]

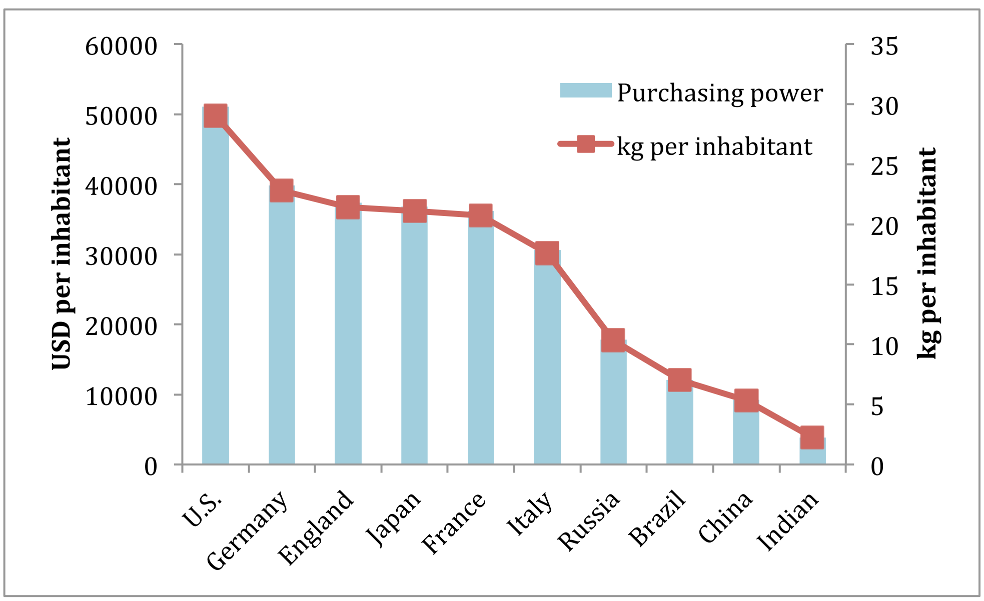

Figure 2 Relationship between e-waste generation and purchasing power (2012, StEP) [6]

1.3 Composition of e-waste

E-waste usually consists of plastics, glass, various metals, and several elements of the periodic table. With the rise in the price of raw materials, the market for these valuable materials, especially metals, is the economic driver for the e-waste recycling industry. Also, most e-waste at the end of its life is considered to be hazardous, due to the contained heavy metals, such as mercury and lead.

1.3.1 Material composition and metal content of typical end-of-life e-waste

Table 2 shows the material composition of selected typical e-waste[7]. The desktop computer in this table does not include its monitor. Usually, computer monitors can be divided into cathode-ray-tube (CRT) display and liquid-crystal display (LCD). Similarly, televisions can be divided into CRT TV, LCD TV and plasma display panel (PDP) TV. Printed circuit board (PCB) is used to support and connect electronic components in EEE. PCBs are used in all but the simplest EEE, where wire wrap or point-to-point construction will be applied instead. Table 3 shows the concentration of selected common metals in PCBs of various types of EEE[7].

Table 2 Material composition of typical end-of-life e-waste[7]

Equipment type	Weight fraction of materials (%)							
						CRT glass		
	Fe	Al	Cu	Plastic	PCB	Panel glass	Funnel glass	Battery
Refrigerator	47.6	1.3	3.4	43.7	0.5	-	-	-
Washing machine	51.7	2.0	3.1	35.3	1.7	-	-	-
Air conditioner	45.9	9.3	17.8	17.7	2.7	-	-	-
CRT TV	12.7	0.1	3.9	17.9	8.7	22.9	12.9	-
PDP TV	33.6	15.1	1.2	10.1	7.8	-	-	-
LCD TV	43.0	3.8	0.8	31.8	11.6	-	-	-
Desktop	47.2	-	0.9	2.8	9.4	-	-	-
Laptop	19.5	2.4	1.0	25.8	13.7	-	-	14.4
Mobile phone	0.8	-	0.3	37.6	30.3	-	-	20.4

Note: "-" means unavailable. It is the same for all subsequent tables.

Table 3 Metal content in PCB of typical end-of-life e-waste[7]

Equipment type	Metal content of PCB (mg/kg)								
	Common metal						Precious metal		
	Al	Cu	Fe	Pb	Sn	Zn	Ag	Au	Pd
Refrigerator	16,000	170,000	21,000	21,000	83,000	17,000	42	44	–
Washing machine	1,000	70,000	95,000	2,200	9,100	2,400	51	17	–
Air conditioner	6,900	75,000	20,000	5800	19,000	4,900	58	15	–
CRT TV	62,000	72,000	34,000	14,000	18,000	5,300	120	5	20
PDP TV	38,000	210,000	20,000	7,100	15,000	12,000	400	300	–
LCD TV	63,000	180,000	49,000	17,000	29,000	20,000	600	200	–
Desktop	18,000	200,000	13,000	23,000	18,000	2,700	570	240	150
Laptop	18,000	190,000	37,000	9,800	16,000	16,000	1,100	630	200
Mobile phone	15,000	330,000	18,000	13,000	35,000	5,000	3,800	1,500	300

1.3.2 Hazardous materials in e-waste

As mentioned earlier, e-waste contains some heavy metals. In the U.S., even though the mass of e-waste accounts for less than 2% of the landfilled MSW, it contributes to 70% of the heavy metals disposed in landfills[8]. In addition to metals, some plastics may form toxic dioxins and furans when incinerated under uncontrolled conditions. Table 4 lists the principal hazardous substances in e-waste[9,10].

Table 4 Principal hazardous substances in e-waste[9,10]

Hazardous substances	Electronic components	Public health risk
Lead	CRT and solder	Damaging the nervous system and causing brain disorders
Mercury	Television and computer display	Causing sensory impairment, disturbed sensation and a lack of coordination.
Cadmium	PCB and semiconductor	Liver and kidney problem
Brominated flame retardant (BFR)	PCB, cable and case	Generating brominated dioxin/furan

1.3.3 Urban mining potential

Urban mining is to reclaim materials from waste, buildings and products; the term is commonly used to describe the process of recovering metals from e-waste instead of ores. The concentration of metals in e-waste is usually much higher than in related ores as shown in Table 5. Extracting minerals from ore is extremely energy-intensive, accounting for up to 40% of the final product cost[11]. Urban mining provides us with an opportunity to lower the cost and preserve the natural resources. Besides, as shown in Table 6, copper and precious metals are the most valuable parts within e-waste.

Table 5 Metal content in different raw materials

Metal	Primary Mining	Urban Mining[12]
Cu	0.5-1.0%[13]	3.0-21%
Al	3-5%[14]	1.0-19.0%
Ag	850ppm[15]	6-2000ppm
Au	1-5ppm[16]	10-1000ppm

Table 6 Value-share of metals in electronics[17]

Value-share	Fe	Al	Cu	Precious Metals
TV-board	4%	10%	50%	36%
PC-board	0%	1%	18%	81%
Mobile phones	0%	0%	9%	91%
Portable audio	2%	0%	82%	15%
DVD-player	13%	3%	42%	42%

2 E-waste Management System in the United States

2.1 E-waste management regulations

2.1.1 Federal legislations

There is no federal legislation set especially for e-waste management. The Resource Conservation and Recovery Act (RCRA)[18] is the main federal law governing solid waste, which is used to govern the disposal of solid waste and hazardous waste. As to e-waste, it only covers CRT. State regulations are usually more detailed deserving more of our attention.

2.1.2 State legislations

The United States consists of 50 states and the federal District of Columbia (DC). So far, statewide e-waste recycling legislation has been passed in 25 states[19]. Some states are considering e-waste recycling laws or improving existing laws. There are mainly three types of state laws regarding e-waste management.

- *Extended Producer Responsibility*

Manufacturers are assigned the responsibility by Extended Producer Responsibility (EPR) to take care of end-of-life management of consumer products. EPR is defined as "an environmental protection strategy to reach an environmental objective of a decreased total environmental impact of a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling and final disposal."[20] Product design, which determines the toxicity and waste of the product at the end of life, is under the greatest control of manufacturers. The management of end-of-life products can be expensive and time consuming. To some extent, EPR serves as financial incentives to promote environmental-friendly designing of products. If the manufacturers design the products in a way easy for end-of-life treatment, they will actually save both time and money during products' end-of-life treatment stage.

- *Manufacturer Education*[21]

Before putting a certain consumer electronic into market in the state, manufactures are required to report to the Department of Environmental Quality (DEQ) and then DEQ will further report to higher level committee. This law actually authorizes the local government's participation in electronics recycling. Besides, manufacturers should establish and implement a public education program to inform consumers about their recycling programs.

- *Advance Recycling Fee*

The Advanced Recycling Fee (ARF) is a fee used for recycling while paid at the point of purchase. The amount of ARF relies on the size and type of the electronics. It is a front-end financing system that charge consumers a fee when selling certain electronic products. The money collected is then used for e-waste collection and recycling.

As mentioned above, 25 states have legislations related to e-waste recycling. 23 of them use EPR approach[19]. California is the only one applying ARF (consumer fee), while Utah is the only state using Manufacturer Education. It can be better illustrated in Figure 3 the Map of States with Legislations.

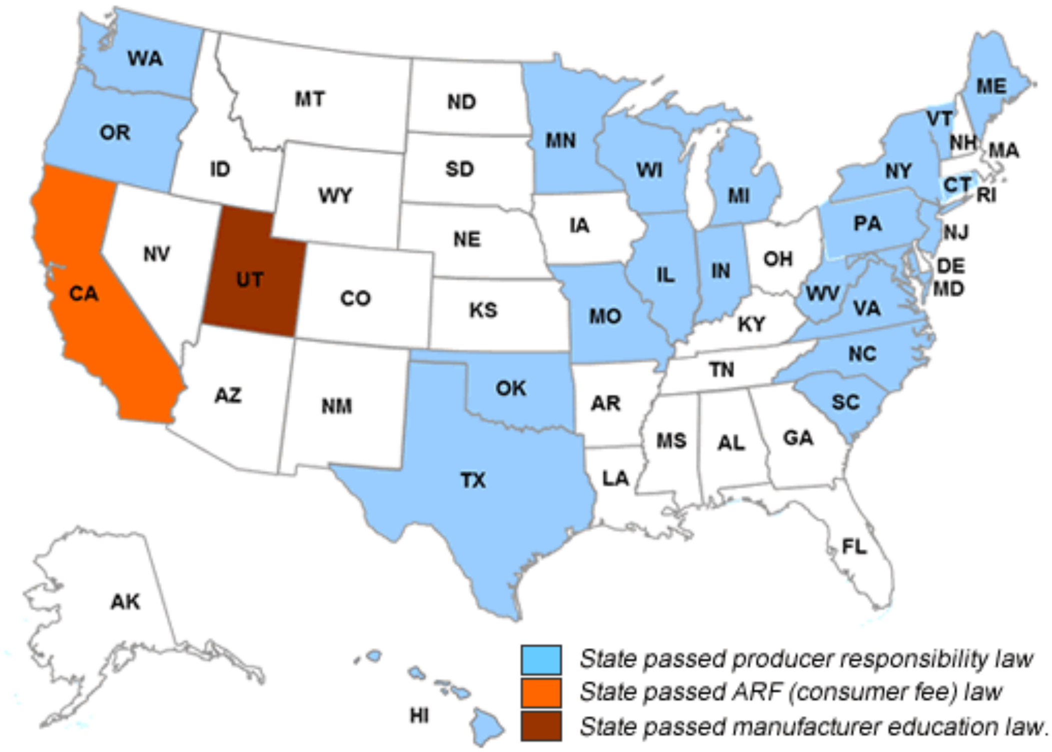

Figure 3 The Map of States with Legislations[19]

2.2 E-waste recycling initiatives and recycling programs in the U.S.

2.2.1 E-waste recycling initiatives

To better develop e-waste recycling within the country, related initiatives have been formed to help and guide recycling entities. In this way, e-waste can be recycled in a more environmentally friendly manner.

• StEP Initiative

StEP is an international initiative, launched in 2007 by United Nations to solve the issues relating to WEEE worldwide. Together with eminent members from Non-Governmental Organizations (NGOs), international organizations, industry, governments, and academic entity, StEP initiates and promotes sustainable solution for e-waste all over the world. The StEP initiative is not in favor of any specific product and seeks instead to provide science-based and applicable recommendation to solve the e-waste issue.

• Consumer Electronic Association's eCycling Leadership Initiative

The Consumer Electronics Association (CEA) is a standards and trade organization for the consumer electronics industry in the U.S.. CEA is an authoritative association on consumer surveys, engineering standards, market research and forecasts, legislative and regulatory news, training resources and so on. As of 2013, more than 2,000 companies have joined this association. Leaded by CEA[22], the eCycling Leadership Initiative (ELI) acts as collaboration between consumer electronics manufacturers, retailers, collectors, recyclers, NGOs and governments at all levels.

• EPA's Sustainable Materials Management Electronics Challenge

The definition of Sustainable Materials Management (SMM) is "an approach to serving human needs by using/reusing resources most productively and sustainably throughout their life cycles, from the point of resource extraction through material disposal"[23]. This approach is meant to minimize materials consumption in an environmental friendly and economical manner. There are three challenges in this program: Food Recovery Challenge, Electronics Challenge and Federal Green Challenge. Apparently, Electronics Challenge is the one most related to e-waste recycling.

Electronics Challenge is joined by original electronic products manufacturers and retailers who are promoting responsible e-waste recycling. EPA provides technical assistance, resources and recognition to those recycling entities. In this way, the recycling programs can be better guided and developed. This challenge has a tired structure (Bronze, Silver and Gold) that contains increasingly comprehensive requirements.

• EPA's Sustainable Materials Management Federal Green Challenge-Electronics

Same as Electronic Challenge, Federal Green Challenge (FGC) is under the EPA's Sustainable

Materials Management Program. It challenges federal agencies in the U.S. including EPA itself to lead the society by example in reducing the Federal Government's environmental impact.

• EPA's WasteWise Electronics Challenge

The WasteWise Electronics Challenge (WEC) challenges its partners to set goals for reducing electronics waste. All US business, local governments, and non-profit organizations can participate in WasteWise. There exist endorsers in this program, who are responsible for recruiting organizations to become WasteWise partners and providing WasteWiase partners with ongoing information.

2.2.2 E-waste recycling programs

Under those electronics recycling initiatives, participants are developing their own recycling programs to realize the goal of reduction, reuse and recycling of e-waste. There are many recycling programs run by different entities: retailers and manufacturers, recyclers, municipal collection, non-profit and profit organizations.

(1) Recycling programs run by manufacturers and retailers of electronics

Some manufacturers of electronic products, such as cellphones, computers and televisions, are running recycling programs to take obsolete equipment back for both environmental and economic concern. Most of them are only responsible for recycling their own brand products. The manufacturers distinguished in their recycling performance are APPLE, SAMSUNG, DELL and HP, who were recognized as the top performers with regard to efforts to address the electronic recycling issue. As mentioned before, 23 states in the U.S. require manufacturers to be responsible for getting their own products recycled. They must provide free and convenient electronics recycling to most consumers in the state, like New York.

Similar to manufacturers, many electronic products retailers are offering several options to donate or recycle electronics. For example, the retailers under EPA's Electronics Challenge: Best Buy, Sprint and Staples. Also, some carriers are selling phones and running mobile phone recycling programs, such as AT&T, T-Mobile and Verizon Wireless.

The general process of recycling program is illustrated as Figure 4.

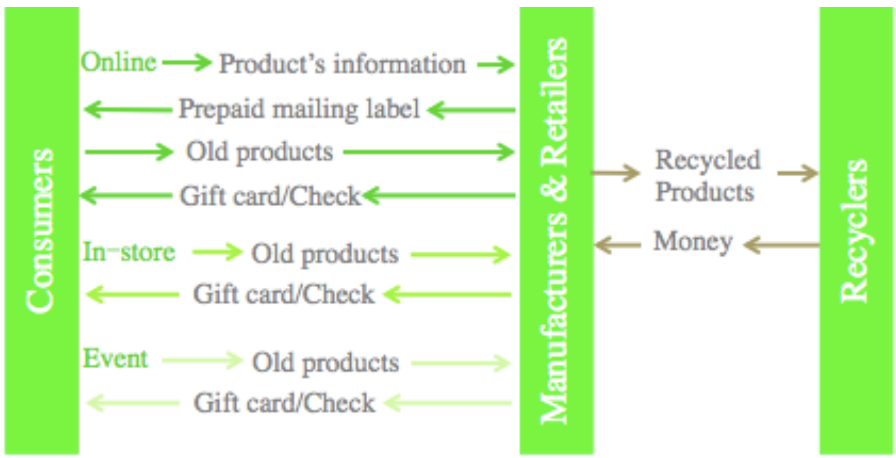

Figure 4 Process of Electronics Recycling Program

From Figure 4 we can see, usually there are three ways to get our obsolete products recycled: online recycling, in-store recycling and recycling events. Through in-store recycling and recycling events, electronics can be recycled directly if covered. During online recycling process, things get more complicated. First, consumers can use online estimator to get an estimate of what the item may be worth. Add the item to Trade-in cart and then print a prepaid mailing label. Mail the item to Trade-in Center. Receive a mail back with a check or gift card. Finally, the collected electronics will be sent to recyclers to get reused, refurbished/remanufactured or recycled. The recyclers will give those collectors (manufacturers and retailers) a share of money as a return.

(2) Recycling programs run by electronics recyclers

Apart from taking the recycled products from collectors (e.g. manufacturers and retailers), some recyclers have their own recycling programs. For example, the WMPaystoRecycle.com is a service of WM Product Recovery Services, L.L.C., a Waste Management company.

Similar to the programs run by manufactures and retailers, consumers can get free quote on the website for their products and then they will receive a pre-paid label. Once their pre-paid shipments are received, they can receive a quick and convenient payment through PayPal account based on the products' condition. Even though those recyclers do not have their own stores to get products recycled, they have convenient drop-off locations for local residents. Some recyclers will charge the consumer for recycling fee based on the size and weight of electronics while some will not, subject to the state law. Same as manufacturers, they may hold recycling events to get electronics recycled.

(3) Programs run by municipal collection center

Municipal collection can be carried out through two possible means. One is through assigned electronics collection center in each area. Another one is municipal recycling program. For example, in New York City, there is an innovative program named e-cycleNYC. Under this program, residents can pick up and recycle unwanted electronics conveniently. This program is set up for apartment buildings. Depending on the size and type of building, apartment buildings in New York City can be eligible for the following service options by signing up an online application form.

In this way, residents can recycle their electronics more conveniently since they may hardly transport televisions and other large electronics to drop-off events or locations and take-back programs.

(4) Programs run by businesses, institutions and government

Some businesses, institutions and federal governments have their own recycling programs. For businesses, the recycling rate within the company can sometimes be an advertisement for them. As to governments, like those under FGC program, they serve as a model in electronics recycling for their citizens.

(5) Programs run by non-profit organization

Goodwill and The Salvation Army are the most successful non-profit organizations holding electronics recycling programs. Goodwill serves as both the collector and recycler in the recycling process while The Salvation Army is just the collector. They all have charity shop for receiving donations and reselling the recycled products. Besides, those non-profit organizations are sponsoring some electronics recycling events also.

2.3 Advanced recycling technologies in the United States

2.3.1 Certification programs for electronics recyclers

If under no control, electronics recycling process may lead to great environmental problems. Since it is hard to guarantee all the electronics recycling entities are doing the right things, EPA has carried out some certification programs for recyclers to encourage them to get products recycled in a more responsible manner. Current three accredited certification standards exist: the Responsible Recycling Practice (R2), R2/RIOS and the e-Stewards standards. To get certified, recyclers need to find a certifying body, which is an independent third-party auditor. And win a certification from this third-party auditor demonstrating that they do recycle end-of-life electronics in a responsible manner as required. And those certifying bodies also need to be accredited by ANSI-ASQ National Accreditation Board (ANAB) before they can certify electronic recyclers.

- R2[24]

The R2 Practices standard was developed by a multi-stakeholder group that included US EPA and industry representatives. Establishing a voluntary, market-based mechanism to facilitate best electronics recycling practices in e-waste recycling industry is the goal of this standard. Now it is maintained and promoted by R2 Solutions, a non-profit organization, which is responsible for educating the industry about the R2 Standard, informing the public of this standard and supporting the R2 Governing Council to update the standard. Since R2 is the first certification program for electronic recyclers in the U.S., it is not as strict as those later. Under special circumstances, land disposal, incineration and energy recovery of e-waste could be possible. There is no prohibition on exporting hazardous e-waste to developing countries. Also, the use of prison recycling operations is allowed.

- R2/RIOS[25]

The Recycling Industry Operating Standard (RIOS) is a comprehensive quality, environment, and health & safety (QEH&S) integrated management system standard. It is an ANSI accredited standard that includes all of the attributes and processes from ISO:9001 (Quality), ISO:14001 (Environmental), and OHSAS:18001(Safety). As mentioned above, R2 is best practices standard specifically for the electronics industry and e-waste. R2/RIOS is a combination of the two standards, which means your electronics asset disposition partner has an audited management system in place.

- E-Stewards Certification[26]

For the first 2.5 years of the R2 Practices standard, the Electronics TakeBack Coalition and the Basel Action Network (BAN) actively participated in the standard. BAN then withdrew from the cooperation, because they thought some aspects of R2 violated the basis of their work. Although the document of R2 was modified accordingly after their departure, BAN was asked to develop anther standard. Then e-Stewards came out in the late 2008, after the R2 was completed.

E-Stewards requires all the certification bodies must be company-wide not just facility by facility. R2 asks for a robust management system but does not have specific requirements. E-Stewards requires recyclers to be incorporated into International Organization for Standardization (ISO)

14001, with most elements of Occupational Health and Safety Management System (OHSAS) 18001. Additionally, e-Stewards standard totally forbids the export of hazardous e-waste to less developed countries, landfill or incineration plant and the use of prison labor.

2.3.2 Recycling technologies

After being collected via various channels, e-waste is then shipped to recycling entities for recycling, recyclers need to test their functionality first to determine whether they could be reused, refurbished/remanufactured or recycled as illustrated in Figure 5. When the products have been designated as reusable, after cleaning and come tests, they can be sold in some charity or thrift shops, like Goodwill and The Salvation Army.

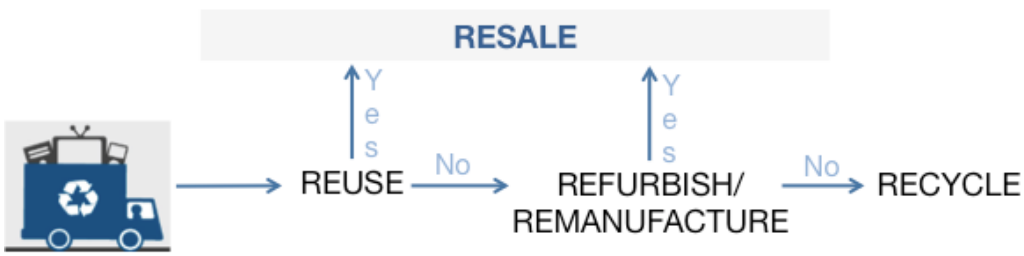

Figure 5 Recycling process of recyclers

Usually, people would care much about their private information within their equipment. Therefore, recyclers should take the responsibility of data destruction. In some special cases, fully trained technicians should go to their office location to provide hard drive destruction services, since some customers would require all the data in their obsolete products to be totally destructed before leaving their facilities. This is very common with consumers working in health care facilities, banks and other financial institutions, government agencies, and other organizations whose data security is very important and subject to regulatory compliance. After electronics have been shipped to recyclers' place, all the data is wiped or destroyed permanently before being resold. Also, if the equipment is dismantled and shredded for recycling, data is damaged at the same time. There is one certification related to data destruction process: National Association for Information Destruction (NAID) certification. NAID certification program is a voluntary program and used to certify NAID member companies meeting the standards set for a secure destruction process.

If unfortunately the equipment cannot be resold by any means, it will be put into recycling processing line where the different materials will be recycled separately. Usually, pre-processing is used to prepare separated materials stream for further materials recycling (also materials recovery) by downstream industries. Pre-processing for regular materials and CRT are illustrated below.

- **Pre-processing technologies**

Regular materials pre-processing[27]

It will be dismantled and shredded to optimal size first, and then advanced sorting techniques are applied to separate the materials into glass, plastic, base metals and precious metals. The recycling process may change a little bit depending on the company. Technologies adopted by *Sims Recycling Solution* are introduced here as an example.

To be specific, prior to mechanized processing, hand sorting of electronics occurs to extract materials such as batteries, plastics, copper wire and PCB for quality control process. Then comes initial size reduction process to reduce materials to approximately 100mm in size. Large-sized particles make it easier for hand pickers to sort large pieces of plastics and glasses out. It also ensures secure destruction of equipment with sensitive materials such as hard drive. The following it the secondary size reduction process. Next, overhead electro-magnets are applied above conveyer to remove ferrous metals from the waste stream. Ferrous metals are collected in large storage containers for sale as recycled steel. Left materials are further separated by eddy currents. Eddy currents works by time-varying magnetic fields. Materials can be separated due to their different accelerations in the same magnetic field. Basically, the acceleration is determined by conductivity of the materials. Therefore, in this way, materials with low or non-metallic content (PCB, plastic and wire) can be effectively separated from left non-ferrous metals, such as aluminum and copper. Also, in some more precise facilities, even the materials with similar conductivity can be further separated by the difference in conductivity divided by density. Aluminum scrap, as conductive lighter alloys can be separated via eddy currents from heavier alloys, like copper scrap[28]. Or, copper and aluminum can be further separated using certain solution based on their density difference. Last, a process of water separation or sensor technology is used to separate non-metallic content, such as plastics and glass, from low-metallic content (PCB and copper wire). The printed circuit boards, steel, aluminum and copper content are collected and sold as recycled commodities. Those recycled materials can be further manufactured into new products. Figure 6 is the flow diagram of the overall recycling process.

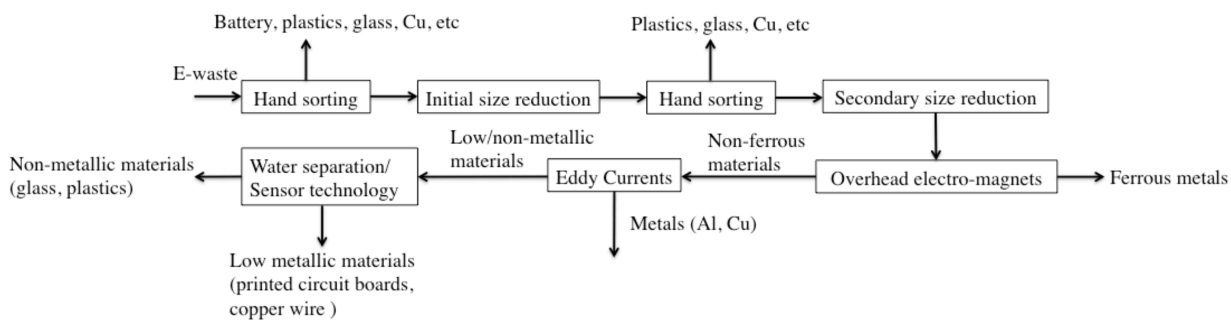

Figure 6 Regular Materials Recycling Process

CRT pre-processing[29]

Since CRT contains high content of lead, it is regulated as hazardous waste and disposed separately from regular e-wastes recycling process. The distribution of lead is shown in Figure 7. Glass panel is regarded as unleaded glass as its low lead content while glass funnel is leaded. To achieve the maximum recycling rate, unleaded and leaded glasses should be separated. Same as above, the CRT recycling process used by *Sims Recycling Solution* is illustrated here.

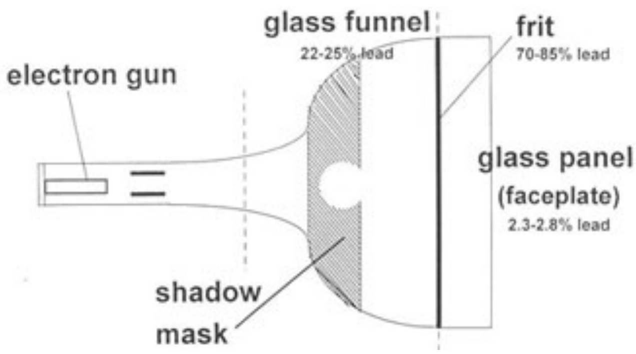

Figure 7 Composition of CRT[30]

The first stage of recycling process involves a controlled size reduction process. Through this process, screen and the complete tube are shredded down into smaller pieces facilitating the separation of leaded from unleaded glass ready for sorting. Dust produced during this stage includes phosphorous material from the tube and screen plus a small number of glass powders. Then the waste stream will go through electro-magnets and eddy currents to get ferrous materials and non-ferrous metals out of glass material. Then the mixed leaded and unleaded glass enters the wash stage. This stage cleans the glass of iron oxides and phosphors that coat the inside of CRT. It also separate our any glass dust produced in the sizing process. The phosphors, oxide and dust are then sent for sound environmental disposal, while the glass is sent to the sorting stage. At the last stage, glass-sensing technology recognizes different properties between leaded and unleaded glass. The speed of the conveyer for waste stream is known and so a computer knows when leaded glass reaches the end of the conveyer. Momentum carries unleaded glass over a separator while leaded glass is re-directed. Then the two glasses are bulked up to sale to CRT manufacturers, where they are used to make new CRTs in a closed loop recycling solution. Figure 8 is the flow diagram of the overall CRT recycling process.

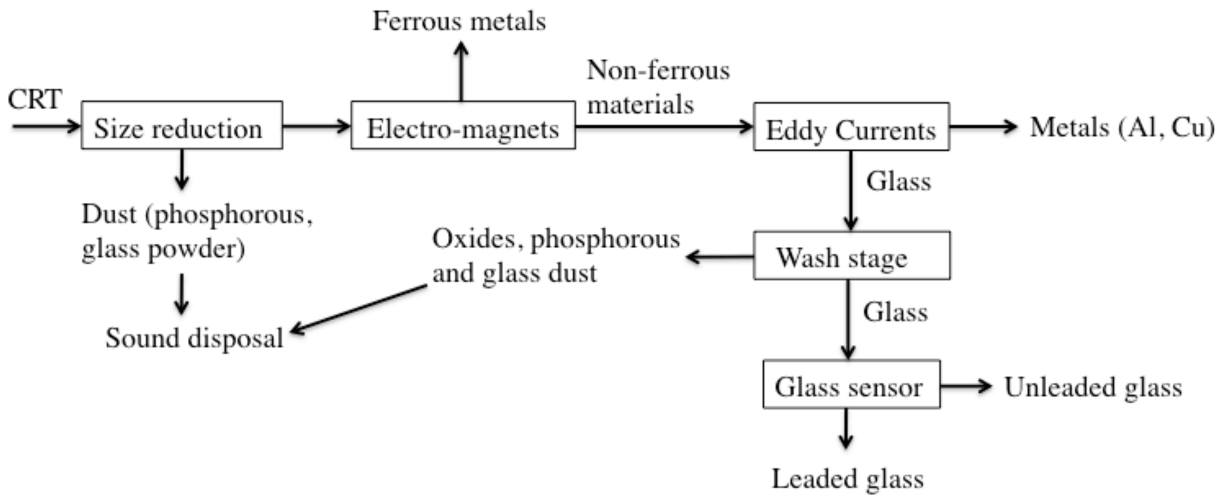

Figure 8 CRT Recycling Process

However, since the market for CRT technology has shrunken in recent years because of the advent of flat panel technology, the leaded glass now is usually heated to a molten state to get lead extracted out[31] during the following materials recycling process and cleaned glass is then recycled as regular glass, instead of making new CRTs.

- **End-processing technologies (materials recovery)**

Glass

As mentioned earlier, the glass of e-waste can be categorized into leaded glass and unleaded glass. There are two mature technologies for both kinds of glass. Glass-to-glass is for unleaded glass while glass-to-lead is for leaded glass. After being separated from leaded glass, unleaded glass can be put into glass-to-glass recycling process, where those recycled unleaded glass is sent to glass smelter to produce new glass and for new applications. Since those recycled glass does not need to go through raw materials acquisition process, much energy will be saved and emission will be reduced by using them to produce new glass. Actually, leaded glass used to be recycled to make new tubes for CRT televisions or monitors. But, as mentioned, in recent years, with the development of flat-screen technology, the market demand for CRT television or monitor has almost dried up in developed countries. Therefore, glass-to-lead technology comes out. Leaded glass can be put into secondary lead production furnace to extract lead out and silica can be used as flux during the process.

However, Nulife Glass Processing Ltd has designed a better technology to deal with leaded glass instead of previous glass-to-lead technology and it has already been applied in many developed countries including the U.S.[61]. The process is similar to the secondary lead smelting process, during which lead is extracted out of molten leaded glass[31]. After being extracted, the lead can be further utilized while clean glass can be treated like those unleaded glass mentioned above to make new glass products. In this way, all the materials put into furnace can be converted to clean glass and lead.

Plastics

Plastics will be sent to plastics recyclers. Those recyclers will further sort the plastics based on weight, color or resin code and shredded for reuse applications. There are more than 15 types of resins among plastic e-waste. The most common ones[32] are:

- Acrylonitrile Butadiene Styrene (ABS)
- High-impact Polystyrene (HIPS)
- Polyphenylene Oxide Blends (PPO)
- Polycarbonate (PC)

They are all recyclable plastics. However, unlike other recycled materials, usually plastics will lose quality through the recycling process. This is because plastics are actually polymers. Polymers are processed by melting at high temperature and then injected into mold to create the finished product. During recycling process, the plastic is again exposed to high heat, which could probably change its properties if it is contaminated by another polymer. Then we call this material is downcycled[33]. Downcycling means the recycled material has lost quality or functionality. But the end product can still be used. That is why plastic is rarely recycled into same product that it was originally. Recycled plastics are often not recyclable again. The way to avoid downcycling is achieving the highest purity when sorting the plastics.

Because the sorting process of plastics is extremely tricky, the contamination during recycling process sometimes is inevitable. Therefore, instead of recycling, some plastics served as fuel materials due to their high heating values, while in this case the dioxin issue should be carefully addressed.

Metals

- Aluminum & Iron

As illustrated before, ferrous materials are separated from other materials using overhead electro-magnets, while aluminum is separated from other metals using eddy currents or typical solution according to their density differences. And then separated aluminum and ferrous scraps will be sent to their corresponding smelting plants to get recovered.

- Copper & Precious metals

From Table 6, we can see that copper and precious metals are the most valuable part in e-waste. Copper and precious metals are usually recovered together in integrated copper smelters/refiners in developed countries, where copper get refined first while precious metals are collected under the anode and then get further refined successively. Precious metals are mainly contained in PCB. Therefore, PCB is usually collected together with copper. During the dismantling process, PCB had better be separated out from e-waste stream. This is because precious metals are usually closely tied up with plastics and non-ferrous metals in PCB. If shredded and separated into different kinds of materials, the amount of precious metals that could be recovered from PCB will decrease.

Copper content in e-waste is approximately 10-50 times[34] higher than copper ore (0.5-2.0%

Cu)[13]. The copper content in PCB alone is 10-30% Cu[35]. Considering the huge demand in the market and resource shortage, e-waste could serve as valuable copper scrap for secondary copper production. Actually, there are two typical technologies for copper production: pyrometallurgy and hydrometallurgy. Usually, pyrometallurgy is more commonly used than the other. This is because of the advancement of pyrometallurgical process as well as low cost compared to hydrometallurgical process[9]. The processing steps are as follows. The part of copper smelting and refining are also illustrated in Figure 9.

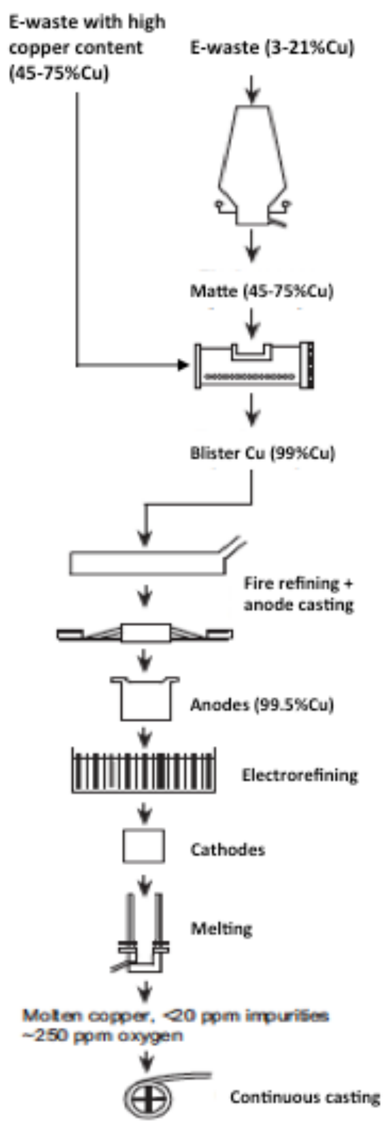

Figure 9 Process of Copper Recovery Using Integrated Smelters/Refiners

Step 1: Matte smelting. Shredded e-waste scrap is sent to integrated smelter. The objective of smelting is to oxidize other mixed metals like lead, cadmium, zinc and some aluminum/iron leftovers. The molten matte contains most of the copper in the scrap (45-75% Cu)[13], while the left slag that is a mixture of various metal oxides will further react with SiO_2 flux to form molten slag. Precious metals are contained within the matte.

Step 2: Converting stage. The molten matte is then moved into converter to get further oxidized with air or oxygen-enriched air. Left impurities are oxidized and crude (99%Cu)[13] blister copper is produced. E-waste scrap with high copper content (45-75%Cu)[13] can be sent directly into converter without going through smelting process.

Step 3: Fire refining and anode casting. Electrorefining requires strong, flat thin anodes, but the blister copper coming out from converter is liquid. So, the molten blister copper will be fire-refined and casted into anode shape molds (99.5%Cu)[13].

Step 4: Electrorefining. The corresponding cathodes are made of stainless steel (occasionally copper). Copper gets refined through two steps: a) electrochemically dissolving copper from impure copper anodes into electrolyte (usually $CuSO_4$-H_2SO_4-H_2O)[13], and b) electrochemically plating pure copper onto cathodes. The deposited copper will remain on the cathodes for one to two weeks and then get removed from the cell to get reused.

Step 5: Precious metal refinery. Many anode impurities are insoluble in the electrolyte. Usually they are precious metals, like Au, Ag, Pd and sometimes heavy metal Pb. They are collected in the form of slime and treated for further recovery. First, the anode slimes are leached by oxidizing sulfuric solution to remove residual copper. The residue from leaching is smelted to get impurities oxidized and then casted to form bullion with silver, gold and platinum group metals (PGM, e.g. Pd, Pt) concentrated. At last, those precious metals are further recovered through a series of electrorefining processes[36].

Actually, there is no integrated smelter/refiner in the U.S.. Pre-processed e-waste scraps containing copper and precious metals will be sent overseas to Canada or Western Europe for end-processing[9].

- Heavy metals

The most common heavy metals are mercury, lead and cadmium. The amount of those heavy metals is very small. But even a little amount of those heavy metals can be extremely toxic to human beings and the environment.

Mercury (Hg)

Mercury is fed in gaseous form to cold cathode fluorescent lamps (CCFL) tubes in the backlights of LCD monitors, LCD television and laptop. In service the electronically ionized mercury yields ultraviolet (UV) rays, which are transformed into visible light by the fluorescent layer. If shredded together with other e-waste, the CCFL backlights will be broken and inside vaporous mercury will escape. So, the best way to prevent mercury pollution is to dismantle the products manually into LCD panel and CCFL backlight. In this way, the mercury inside CCFL backlight can be captured while the LCD panel will be put back into regular e-waste recycling process to get shredded.

Lead (Pb)

Lead is another dominant toxic material in e-waste. Apart from those within CRT tubes, there are still huge lead content in e-waste, especially solders that are used to connect components together. This part of lead content will be mixed with metal scrap and sent to integrated smelters/refiners to recover the copper first. As mentioned in the recovery process of copper, some lead would get oxidized during smelting stage and stay in slag. But the distribution of lead is not just in the slag, lead may also be captured in the dusts from converting and slag cleaning. The left part of lead will go with copper until the electrorefining stage. During this stage, lead is found mostly within the anode slimes as insoluble $PbSO_4$[13]. Those Pb-rich waste residues are then sent to get Pb recovered or disposed safely. The distribution of lead and other related impurities during Noranda smelting is listed in Table 7.

Table 7 Impurity distributions during Noranda smelting[13]

Element	% to matte	% to slag	% to offgas
Ni	77	22	1
Pb	13	13	74
Sb	15	31	54
Zn	6	84	10

From Table 7, we can see the majority of lead should be contained within captured dust. This is because the temperature within reactors is usually higher than 1200°C[12,13], while the melting point and boiling point of lead oxide are 888°C and 1477°C respectively. Lead oxide is the most common lead compound under high temperature. During heat treatment, most of lead compound will convert into lead oxide, expect lead chloride and lead sulfide.

Cadmium (Cd)

Cadmium is usually contained in PCB and semiconductors. The melting point and boiling point of cadmium oxide are 900-1000°C and 1559°C respectively. Similar to lead, the distribution of cadmium should be mainly contained in dust, which is usually collected and disposed safely.

2.4 Export of e-waste from the United States

From those annual reports of recycling programs run by manufacturers or retailers, we do see remarkable achievements, but the amount of e-waste exported overseas is still significant. It is obvious that it could be economically beneficial to the U.S. to dump e-waste to less developed countries. In this way, they can exchange those waste for money instead of disposing them by themselves and polluting their own environment. Even though we can almost guarantee all the e-waste sent to those responsible collectors will be sent to downstream responsible certified recyclers as they promised. There are also some uncertified entities, which may be more reachable to customers. They also claim responsible recycling and even condemn what they are exactly doing: shipping and selling e-waste in developing countries secretly to avoid disposal costs and make some money out of it. US EPA estimates about 50%~80% of e-waste were exported in the name of responsible recycling[37]. According to the data of United States International Trade Commission in 2011, the trading volume of the import of e-waste from the U.S. into China reached 11.54 billion US dollars, accounting for 11.1% of China's total imports from the U.S.[38]. Not only the U.S., other developed countries, like E.U., are also exporting their generated e-waste to developing countries. Only 19% of e-waste in E.U. is recycled, which means 81% of these resources escape from being reintroduced in the production system in Europe. Actually, more than 50% of the e-waste in E.U. goes into unofficial collection routes, sometimes leading to illegal export and improper treatment[39]. The export routes of e-waste from western Europe and north America are shown in Figure 10.

Figure 10 Export of e-waste from Western Europe and North America[39]

The Basel Convention is an international treaty used to limit the transportation of hazardous waste among nations, especially from developed to developing countries. For those countries ratifying the Basel Convention, hazardous cannot be exported without a permit, unless proof can be provided showing wastes will be managed responsibly in the waste-importing country[40]. It has significantly decreased the exportation and importation activities of wastes. As of September 2014, there are 181 parties to the Convention, including the E.U.. The U.S. and Haiti have signed but not ratified the Convention. Since e-waste contains many hazardous materials, e-waste drew parties' attention at the most recent conference hold from Nov 27th to Dec 1st 2006. However, even in counties party to the Convention, illegal export of e-waste still exists due to loopholes in regulations and lax inspection, let alone non-parties. For non-parties to the Convention, like the U.S., it has yet to ratify the Basel Convention and has a number of agreements that do not take away from the Basel Convention, justifying the shipping of e-waste to other countries.

Governments in those developed countries should strengthen the supervision of uncertified recyclers, encourage them to get certified and educate residents to send their obsolete products to right places to avoid those uncertified entities. Most importantly, they should join Basel Convention and develop a comprehensive e-waste management system without loopholes and then strengthen the inspection over the whole system.

3 Electronic Waste Issues in China

3.1 The e-waste sink of the world: China

Figure 10 shows that most of the exported e-waste is shipped to developing countries, like China, India, Vietnam, and Pakistan. Among these countries, China is the largest sink of e-waste. It was widely reported that about 70% of e-waste produced globally ended up in China[41]. However, this conclusion was drawn by the United Nations in 2003 and has been quoted over the years without further verification. However, it is not proper to use this data after more than 10 years, because China has put in place some important regulations during this long period. The annual imported e-waste in 2010 was estimated to be around 2.6 million tons by a researcher in Netherlands[42]. Assuming that the import volume remains constant in recent years and adding the domestic e-waste generation in China (i.e. 7.3 million tons), the overall e-waste ending up in China annually is estimated at about 9.9 million tons.

3.2 Channels for importing e-waste to China

Actually, China has explicitly banned the import of e-waste in *Catalogue for Managing the Import of Wastes (Latest edition: MEP, MOC, NDRC, GAC, AQSIQ, 2009, No.36),* which is effective since Feb 2000[43]. However, e-waste can still find its way to get into them. As mentioned earlier, China, which is a party of Basel Convention, is now still taking care of about 20% of global e-waste (China: 9.9 million tons, global: 49 million tons). The following could be possible channels for trans-boundary shipments of e-waste into China:

a) Direct shipments to Chinese ports

Since China has already ratified the Basel Convention, it is almost impossible now to directly ship full containers of e-waste into Chinese ports[44]. To ship them into mainland China, there must be some less visible and less direct ways.

b) Mixed shipments with bulk mixed metal scraps

The import of mixed metal scraps for recycling is legal, though the import of e-waste is not allowed in China. Some dealers and smugglers today may blend e-waste with cables and mixed metal scraps together[45]. Usually, e-waste only accounts for around 10% of the total and it is very difficult to distinguish e-waste from other scraps because the fractions are too small. Therefore, the legality of a shipment of e-waste mixed with metal scraps can be hardly identified.

c) Transport through Hong Kong

Even though Hong Kong is part of China, the legislative system is a little bit different from mainland China. E-waste cannot enter mainland China but the import of e-waste is allowed for licensed importers at Hong Kong[46]. Once the shipment has entered Hong Kong, it can then be easily re-exported to any other regions or countries, including mainland China[47]. As shown in Figure 10, Hong Kong is the main gate for e-waste into China.

d) Transport through Vietnam

Another channel is a circuitous path of exporting e-waste through Vietnam into mainland China. E-waste exported from Japan and the U.S. is transported to Haiphong in Vietnam where exists the international port. As shown in Figure 11 that Mong Cai and Dongxin are border cities of Vietnam and China respectively. Therefore, if e-waste is transported to the Mong Cai, then it can easily cross the border into China through Dongxin at night in small boats[48].

Figure 11 Smuggling map through Vietnam into Mainland China

3.3 Collection of e-waste in China

E-waste is collected either informally or formally in China. The central government has not explicitly banned informal collectors because just the collection itself does not have much negative environmental impact and in fact reduces the need for landfilling space. The flowchart below shows the fate of collected e-waste. Because of the valuable content in e-waste and existence of informal collectors, the amount of e-waste mixed with MSW to landfill or incineration plant is trivial in China, except for those landfilled residues after informal recycling, as illustrated in Figure 12 below.

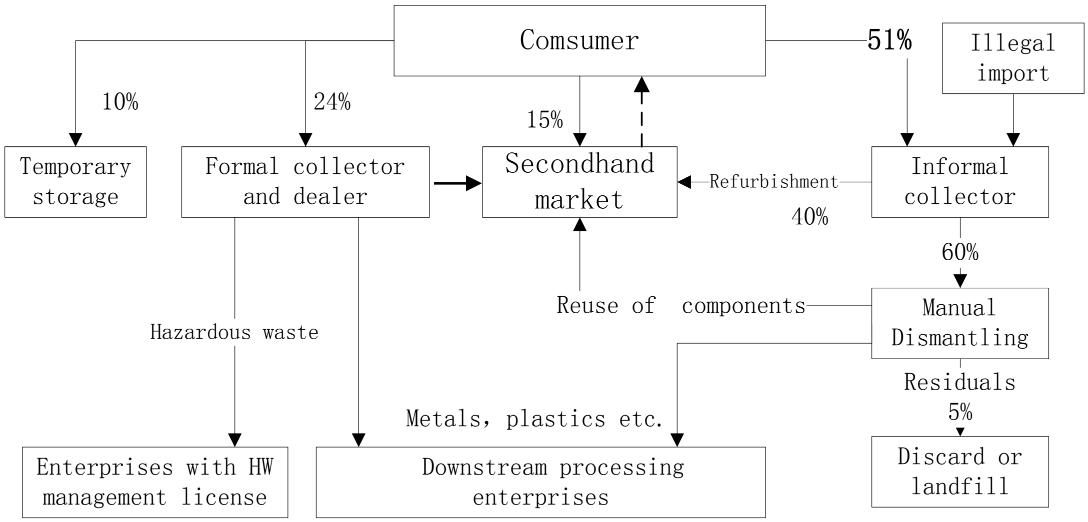

Figure 12 E-waste collection flow in China[49]

3.3.1 Informal collection

Informal self-employed collectors, usually from rural areas, show up in urban areas. Because most electronic products were introduced into rural areas in the recent years, there is not much e-waste in rural areas. In the cities, informal collectors are collecting e-waste in following ways: door-to-door collection, temporary dumpsite scavengers, landfill scavengers, street waste pickers, and collectors for import waste. They are using cash to exchange for household waste items, not just e-waste, also plastic, paper and metal scraps. The collected e-waste is then sold to local second-hand market, repairers, recyclers or downstream scrap dealers according to products condition. "Cherry picking" is another name of this informal collection process since, in this way, only the waste with significant value is collected[50]. Because the value within e-waste is relatively high, the collection rate is usually high.

Actually informal collection system can be very effective compared with formal one, since individual collectors are able to reach every waste source. Also, citizens usually are willing to sell their obsolete products for money and may not bother to send their electronic products to designated recycling stations. The group of informal collectors is estimated to include 440,000 people[51,52] in China.

3.3.2 Formal collection

Formal collection is organized by municipalities and the collected e-waste is directed to designated environmentally responsible recyclers. Since the recycling process is under better control in formal recycling process, the cost is higher than informal recycling process. So, when collecting e-waste, they will charge more than the "cherry picker" collectors. There is no doubt residents are therefore more willing to sell their products to informal collectors.

The national "Home Appliance Old for New Rebate Program" was launched by the Chinese government from 2009 to 2011, in order to stimulate the formal recycling of old appliances as well as the purchase of new home appliances. Those home appliances include air conditioners, refrigerators, televisions, washing machines and computers, which accounts for more than 50%[53] of the total e-waste amount. Authorized participants in this rebate program are supermarkets, home appliance retailers, chain stores, logistics companies and waste collection companies. Actually, Chinese government subsidized them to participate in this program. In this case, they could pay consumers at a higher price than informal collectors, which put them in a favorable position during competition. It was first launched on June 1st 2009 in nine pilot cities distributed in different areas of China. Because of the huge success it achieved, the program was then expanded nationwide since June 1st 2010. Figure 13 shows how exactly this program was run.

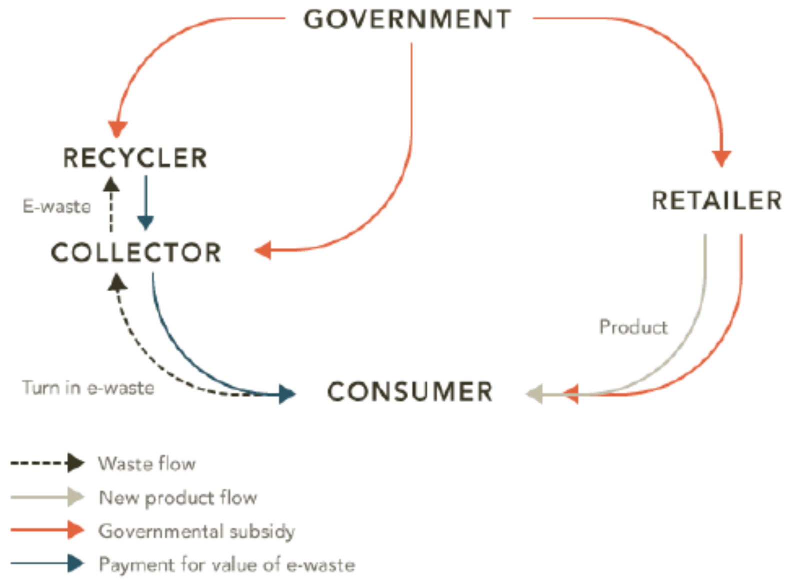

Figure 13 "Home Appliance Old for New Rebate Program" flow chart[3]

However, since this program totally relied on the subsidies from the government, with the end of this program on Dec 31st 2011, the advantage of formal sectors over informal sectors vanished at the same time. Figure 14 shows the recycling amounts and rate of the five home appliances before, during and after the program. In Figure 14, we can see an obvious increased recycling rate as the implementation of this program and also a slump after its termination. The term "theoretical" means that the amount is not tracked but estimated. Such a successful program still had to be terminated because all the subsidies demanded to support this national program imposed a huge financial burden on Chinese government.

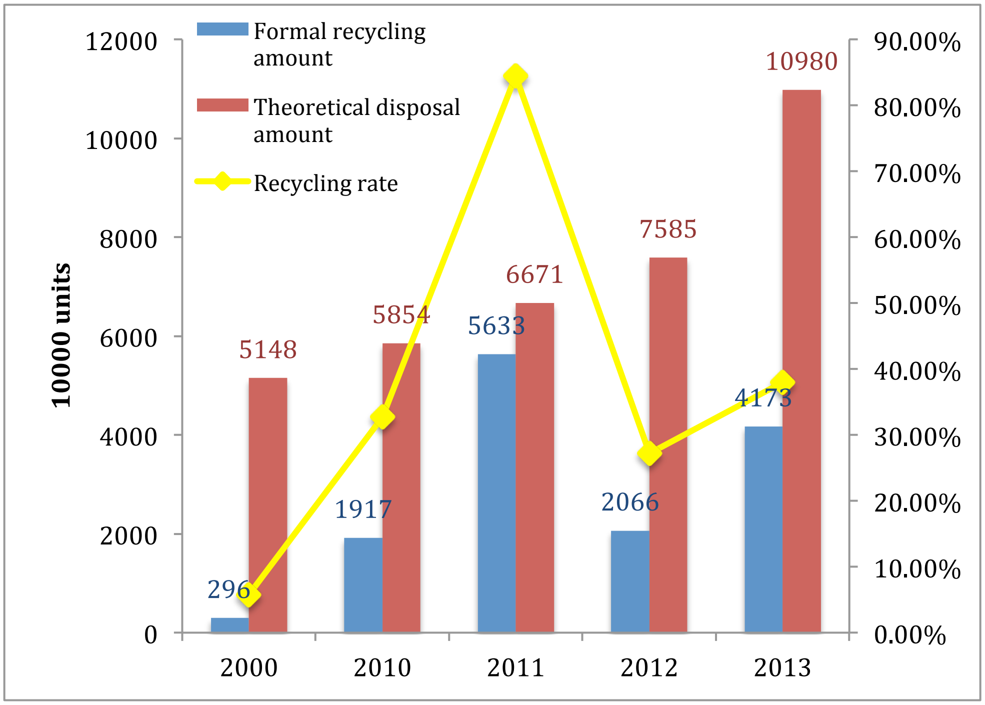

Figure 14 Formal recycling and theoretical disposal of obsolete home appliance[54]

3.4 Environmental issues associated with e-waste treatment in China

There are three options for end-of-life processing of e-waste after being collected: refurbishment, remanufacturing and recycling[55]. Both refurbished and remanufactured products are supposed to be reused. Refurbishment is using technical approach to restore electronic products to reusable status. And then those refurbished products could be resold in second-hand market. However, both the refurbishment industry and the second-hand markets are not well regulated in China. The quality and safety of refurbished products can hardly be guaranteed. Different from refurbishment, remanufacturing is the process of disassembly and recovery at the module level, and eventually at the product level. Usually, remanufacturing is a mass production process while refurbishment is small-scale. The quality of remanufactured product could be even higher than new product. Remanufacturing of electronics in China mainly focuses on cartridges, copiers, information technology servers and printers, which contain high-value parts and are durable[55]. If the products have no chance to get reused, they will be sent for materials recycling. For now, after being collected, individual informal collectors will sell those waste products either to refurbishing workshops or informal e-waste recyclers (later referred to as informal recycling chain), while those collected formally will be recycled formally (later referred to as formal recycling chain).

According to Figure 12, about 24% of the domestic e-waste goes to formal collectors while 51% goes to informal ones[49]. An estimated 60% of the e-waste from informal collectors will be sent for end-of-life treatment[49]. Therefore, at present in China, about 24% of domestic e-waste is sent for formal recycling while 30.6% is sent for informal recycling. As to imported e-waste, 40% is refurbished and then used while the remaining 60% goes to informal recycling. The estimated e-waste flow in this case is shown in Figure 15 below. About 38% of e-waste ends up in informal recycling entities and only 18% for formal recyclers. A large amount ends up in second-hand markets.

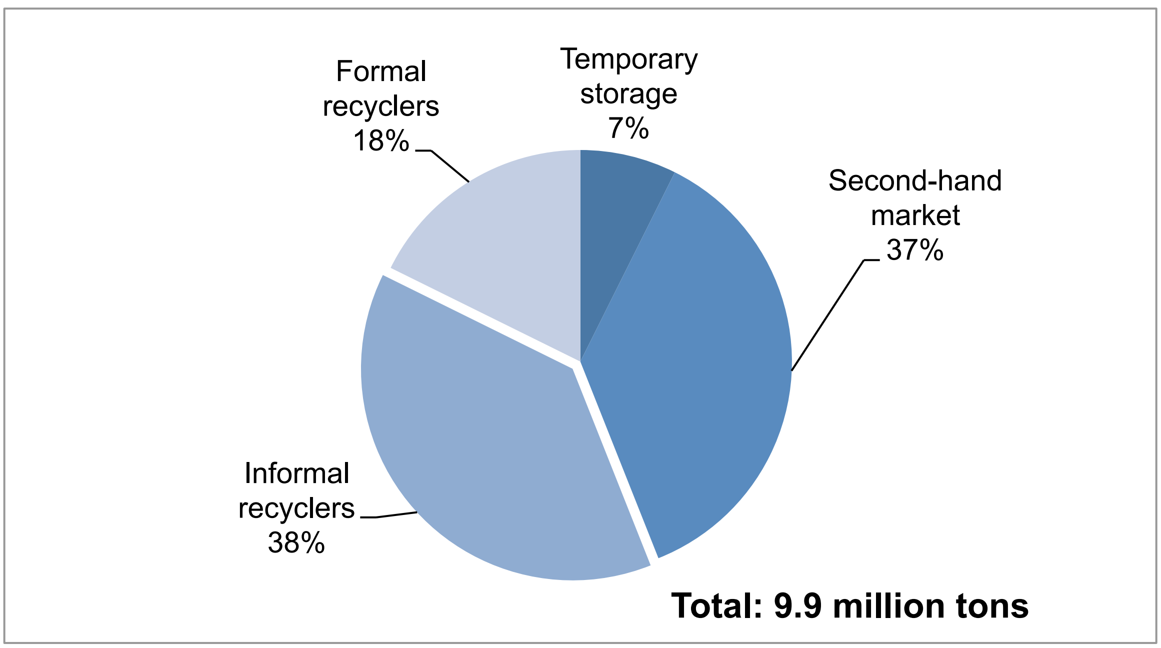

Figure 15 Estimated e-waste flow in China (2012)[42,49]

The electronic waste generated domestically and globally exposed Chinese people to great environmental pollution, which may even be life-threatening. Even if they are sent to formal e-waste recycling facilities, the formal recyclers will recycle it in a more responsible manner but still with some remaining environmental issues. Associated environmental concerns with both informal and formal recycling ways will be discussed separately below. It is worth mentioning that both informal and formal recycling refer to materials recovery process. Therefore, informal and formal recyclers refer to the entities conducting informal or formal materials recovery process correspondingly.

3.4.1 Informal recycling

Recycling can help reserve the raw materials for products, while the hazardous chemicals released during recycling process can harm workers as well as neighboring communities and environment when under uncontrolled conditions. This uncontrolled recycling process is named as informal recycling. Workers in informal e-waste recycling industry are estimated to be around 250,000 people[51] in China. Photos below were taken from informal e-waste recycling facilities in China.

Figure 16 Informal e-waste recycling situation in China

Usually reusable materials (e.g. copper, aluminum, ferrous scraps, plastic and glass) are picked out manually and sell to raw material suppliers and manufactures. And the parts with precious metals (e.g. PCB) will be further smelted and acid-washed. The most typical processes are *plastic recycling* and *circuit board recycling*. For details about possible hazards associated with e-waste processing, please refer to APPENDIX B.

- *Plastic recycling*

To get plastics recycled, they must be sorted well. However, there are too many kinds of chemical engineering plastics. The method used to distinguish between similar plastics is extremely primitive. They just ignite them, let them burn and then observe their color, drawing strength. The main method is to judge the characteristics and quality by smelling the odor. As we all known, open burning of plastics is the biggest contributor to dioxin emission nowadays, which is the most toxic substances on earth. The toxic of 21^{st} century is now managed under the environment of 19^{th} century.

- *Printed circuit board recycling*

The first process is called “Burning Board”. The components within electronic products are usually connected by tin, which has low melting point. By burning the connecting tin, the circuit board can be easily got out of the product. Collect a certain number of circuit board and then send them together to the local furnace to get metal ingots out, which contain gold, silver, palladium, copper and aluminum. At last, they will sell the ingots on the basis of the proportion of precious metals content. Another popular term is “Gold Washing”. In this process, after the plastic cases are burned, the left metals will be recovered using different acids. The metals get recovered through this process are usually copper and precious metals. The final precipitates should be gold. Their gold production accounts for 1/20 of the total gold output in China, even influencing the international gold prices[56].

The biggest informal recycling area in China is Guiyu, Guangdong Province, which is now deemed as the most toxic place in the world. There exit 3,200 recycling companies in this 52 km^2

area. About 60,000 residents are occupied in recycling work. The annual e-waste treatment amount is about 1.9 million tons. Annual gold output is 15 tons[3]. Many local residents escaped from their hometown after they have earned enough money by recycling e-waste. It was reported that more than 90% children have elevated lead levels. Also, Guiyu was reported to have the highest exposure to cancer-causing dioxins in the world and a high rate (six times the average level) of miscarriages. Actually, they know what they are doing is bad for their health and next generation, but they keep doing so for the sake of money.

3.4.2 Formal recycling

Formal recyclers refer to those authorized enterprises on the E-waste Dismantling Enterprise List with a treatment license in China. Even though all formal recyclers strictly stick to environmental requirements, not all formal recyclers are adopting exactly the same recycling process. Generally speaking, there are four typical types of formal recycling process in China. They are different in their way of processing PCB. As of now, all the formal entities are still conducting manual pre-processing in China[54]. Not all of them will further recycle PCB, most of formal recycling processes just stop after manual dismantling and then sell separated metal scraps (copper, aluminum and iron), glass and plastics to raw material suppliers and manufactures. At the same time, hazardous materials (i.e. such as CRT funnel glass, LCD backlights and PCB) will be sent to hazardous waste treatment center. CRT and PCB are regarded as hazardous because of lead content while LCD backlights contain mercury. A few of them would send PCB for secondary copper production[54]. Those facilities do not start the operation of their machinery even though they have, because it is actually uneconomic for them due to the shortage of e-waste resource. On the contrary, other formal recyclers are responsible for both pre-processing and end-processing of PCB. There are mainly two ways for materials recovery. One is mechanical separation and the other is hydrometallurgical method. CRT funnel glass and LCD backlights will be sent to hazardous waste treatment center also. Figure below shows the end-of-life treatment situation of PCB in China.

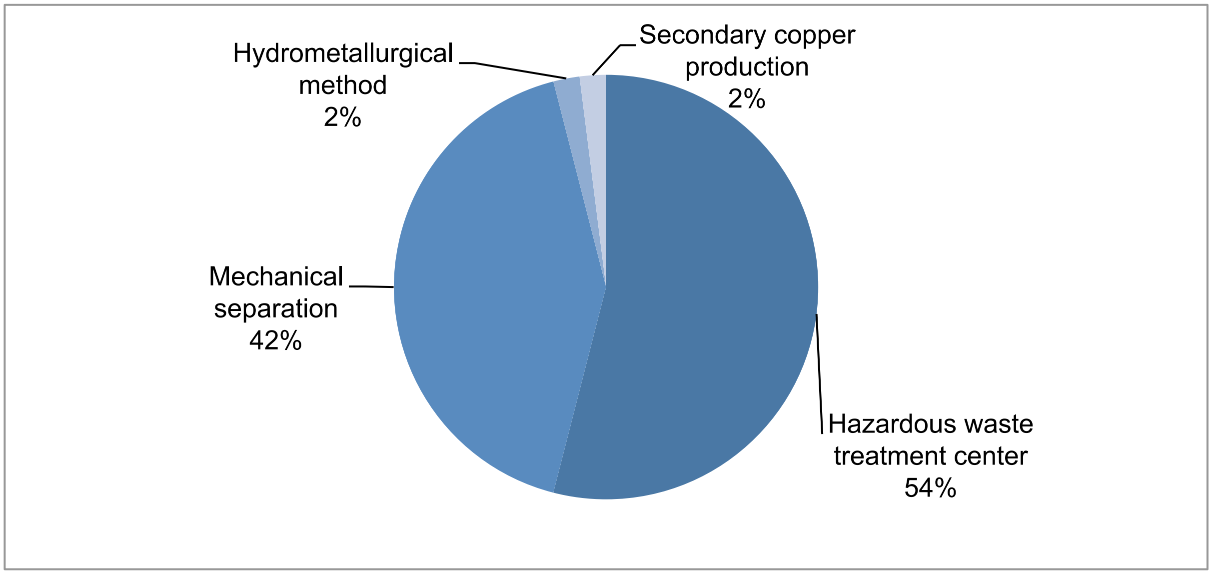

Figure 17 End-of-life treatment situation of PCB in China[54]

Obviously, mechanical separation is the most common methods for metals recovery from PCB in China. Mechanical separation is based on the differences in physical properties (e.g. density, conductibility, magnetic property, etc.) of different metals. However, the separating efficiency is restricted by similar physical properties. The recovery efficiency of aluminum is reported to be about 90%[57]. Hydrometallurgical process is made up of leaching of solid materials, solution concentration and purification and metal recovery. Even though the materials recovery efficiency of hydrometallurgical method is higher than mechanical separation, the large amount of caustic and dangerous leachant (e.g. cyanide) poses great health risks to both the inhabitants and environment. Table 8 lists the leaching agents used to leach precious metals out of e-waste products.

Table 8 Leaching agents in hydrometallurgical process

Metal	Leaching Agent
Palladium	Hydrochloric and Sodium Chlorate
Base Metals	Nitric Acid
Gold and Silver	Thiourea or Cyanide
Copper	Sulphuric Acid or Aqua Regia

4 Potential Application of Advanced E-waste Management System in China

Even though western countries set a good example for us about how to get e-waste recycled responsibly, China cannot directly copy it but incorporate it creatively to better fit into its unique society. As the biggest electronic manufacturer in the world, China is in need of sufficient raw materials. So not only the environmental issues, the recovery rate also means a lot to recyclers in China. To be specific, informal collectors is much more effective than formal collectors, since individual collectors can reach almost every waste source. Besides, the effectiveness of informal manual dismantling is significantly higher than formal mechanical shredding, which makes part of informal recycling valuable. Therefore, it would be better if we could find a way combining the benefits in both informal and formal chains. In other words, efficient informal collection and dismantling part was proposed to be linked with efficient, safe and environmental friendly formal materials recycling to form a better recycling chain[37].

4.1 Technology support

4.1.1 Proposed e-waste recycling chain

In collection part, we can continue to let those self-employed collectors to collect e-waste and then send to formal collection center. The collection center then decides whether the collected products have the potential to be resold. If yes, they would be sent to refurbishing shops or remanufacturers to get refurbished or remanufactured. Even though some products would be repaired before entering second-hand market now, this field is loosely regulated in China. Therefore the quality and safety of refurbished products can hardly be guaranteed. Also, there is no professional industry especially responsible for electrical and electronic products remanufacturing now in China. Actually, no country has recognized remanufacturing officially as a distinct industrial activity yet, even developed countries, like the U.S.[58]. For those products, which can be neither refurbished nor remanufactured, they would be sent for end-of-life processing to get valuable materials recovered.

In pre-processing part, formal recycling entities could hire those previous informal recyclers to help conduct manual dismantling and sorting. To guarantee those untrained informal recyclers to dismantle e-waste in an environmental-friendly manner, there should be professional recyclers to lead them in the workshop and transform them into formal recyclers. After pre-processing, aluminum scraps, copper scraps, ferrous fractions, glass (leaded and unleaded) and plastics are separately collected. PCB should be collected together with copper scraps.

In end-processing, the technology adopted now in the formal e-waste recycling in China for precious metal recovery is hydrometallurgical process while integrated smelting and refining facilities (pyrometallurgical process) are the most successful technology right now in e-waste recycling in western countries[9]. The recycling efficiency of precious metals of both methods is almost the same. But integrated copper smelter is more economical[9] compared to hydrometallurgical process and avoid the large amount of caustic and dangerous leachant, which may lead to serious environmental concern. Plastics, aluminum and iron scraps will be sent to related secondary production factory as usual, while leaded glass can be cleaned first and then sent to glass factory together with unleaded glass.

The overall proposed treatment chain is illustrated in Figure 18. The color represents the level of technology support needed.

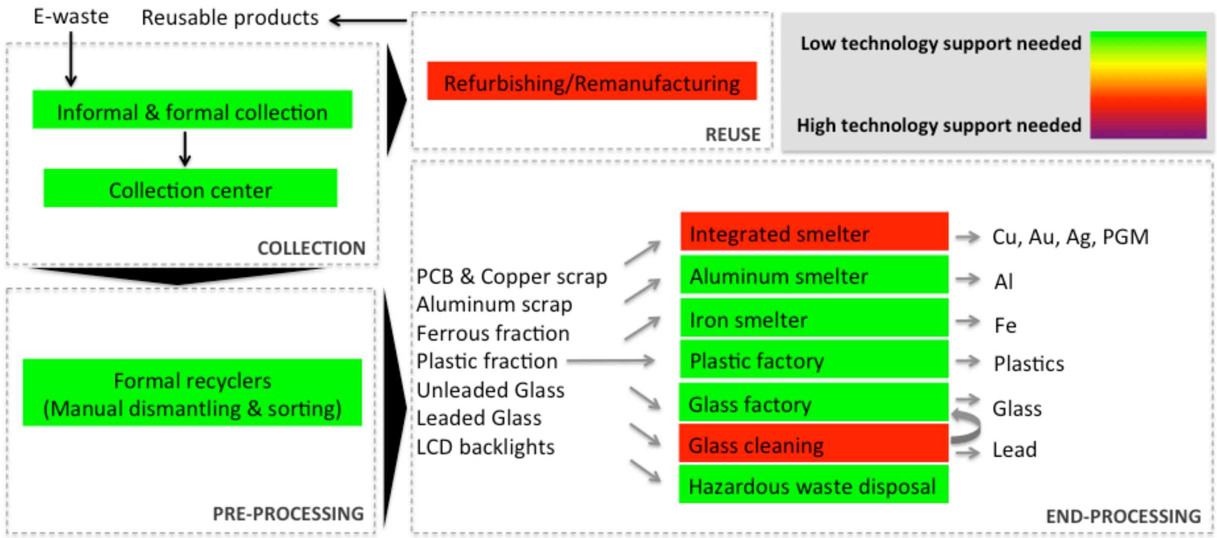

Figure 18 Proposed e-waste recycling chain in China

4.1.2 Technology obstacles and recommendations

The biggest issue associated with remanufacturing is that most of the products were not designed for remanufacturing, which makes the remanufacturing process difficult. So, to solve the problems we should motivate or even require manufacturers to take the remanufacturing possibility into their designs.

As of now, there is no integrated copper smelter in China and to build such state-of-the-art smelters/refiners needs large initial cost. But there do exist several advanced copper smelters for secondary copper production in China, like Kaldo furnace and Ausmelt furnace[59]. Secondary copper refers to all non-primary copper sources, such as e-waste and metallurgical waste. Secondary copper currently contributes about 35% to global copper production according to the International Copper Study Group[60]. The average treatment capacity in each secondary copper production plant in China is about 100,000 tons/year[59]. As to precious metals, even though there are around 150-200 factories recycling precious metals, their overall treatment capacity is low and primitive facilities, outdated technology and low recovery rate lead to a waste of resources and energy. We can add precious metals refinery sector to existing copper smelters to form integrated smelters/refiners as what western countries do. In this way, we can hopefully maximize the output of these existing smelters or even expand them to handle all the e-waste disposed in China.

Besides, glass-to-lead technology is proposed for leaded glass recycling in China but the whole system and facility has not been established yet. Actually, even during glass-to-lead process, at least 85% of the glass will still be toxic and need to be disposed as hazardous waste[61]. Therefore, the Nulife process is a better way out if possible. Since LCD technology is relatively new to China, the amount of LCD TVs and LCD monitors ready for end-of-life treatment is not that much. Therefore, the technology for proper treatment of LCD backlights is not mature right now in China but backlights is required by regulation to be separated out of other e-waste stream and disposed safely.

To solve the gap between the demand for raw materials and urgency for pollution control, Chinese government has to invest on the construction of advanced facilities within the country. However, this cannot be achieved overnight. Before the well establishment of end-processing in China, there is still another way out, which is the so-called "Best-of-2-Words" philosophy (Bo2W)[37]. Bo2W proposes a network for recycling e-waste worldwide. Developing countries, like China, can export those well-sorted materials to international state-of-the-art end-processing facilities to get recovered responsibly before technology issue solved. To some extent, it is not so much as an issue of technology as an issue of money.

Back to pre-processing, the reason why we choose to use manual dismantling and sorting in China while mechanical processing in western countries is that the labor cost is still low in China compared with developed countries. However, as the labor cost increases, the formal recycling sector, which is responsible for pre-processing, will transfer gradually from labor-intensive work to mechanical process.

4.2 Regulation support

As mentioned before, China is a party of Basel Convention, which bans the import of e-waste. Besides, China has various regulations, laws and standards related to e-waste management. Six of the most important regulations and laws are shown in Table 9.

Table 9 Regulations and laws related to e-waste management in China[50]

Regulations/Laws (English)	Regulations/Laws (Chinese)	Major Content	Effective Time
Catalogue for Managing the Import of Wastes *(Latest edition: MEP, MOC, NDRC, GAC, AQSIQ, 2009, No.36)*	进口废物管理目录（环保部，商务部，发改委，海关总署，国家质检总局 公告 2009 年第 36 号）	Bans the import of e-waste	Feb 2000
Technical Policy on Pollution Prevention and Control of WEEE *(SEPA No.115)*	废弃家用电器与电子产品污染防治技术政策 环发 [2006]115 号	•Set principles of '3R' and 'polluter pays principle' •Stipulates eco-design •Makes provisions for environmentally-sound collection, reuse, recycling and disposal of WEEE	Apr 2006
Ordinance on Management of Prevention and Control of Pollution from Electronic and Information Products *(MIIT No.39)*	电子信息产品污染控制管理办法（工信部令第 39 号）	•Requirements for product eco-design •Restrictions on the use of hazardous substances •Requirements for producers to provide information about their products	Mar 2007
Administrative Measures on Pollution Prevention of WEEE *(SEPA No.40);* Technical Specifications of Pollution Control for Processing WEEE	电子废物污染环境防治管理办法（环保总局令第 40 号）；废弃电器电子产品处理污染控制技术规范(HJ527-2010)	•Calls for prevention of pollution caused by the disassembly, recycling and disposal of e-waste •Licensing scheme for managing e-waste recycling companies	Feb 2008
Regulation on Management of the Recycling and	废弃电器电子产品回收处理管理条例	•Makes e-waste recycling mandatory	Jan 2011

Disposal of Waste Electrical and Electronic Equipment *(State Council No.551)*	（国务院令第 551 号）	•Implements Extended Producer Responsibility •Establishes a special fund to subsidize e-waste recycling

To solve the e-waste problem in China, we have to deal with both recycling and import issues. To absolutely ban the import of e-waste from developed countries, we should ban the import of both second-hand EEE and e-waste around the whole country including Hong Kong in any case. The reason why we should ban them together is that it is really hard to distinguish between e-waste and second-hand EEE. Otherwise, we should strengthen supervision and inspection of all the shipments into the ports of China and Hong Kong. China launched its *Green Fence Initiative* from Feb 1st to Nov 30th in 2013 for ten months. The National Customs inspected each shipment carefully to fight against the smuggling of foreign garbage into China. They mainly focused on two categories of garbage: 1) smuggling of solid waste on the inventory of national banned importation; 2) smuggling of solid waste not meeting related environmental control standards[62]. During the operational period, the customs seized and returned 56,400 tons of foreign garbage[63]. The *Green Fence* was just a trial but has promoted even the recycling industry in developed countries, such as the U.S.. The trial has been ended but the vigorous inspection of imported shipments should move towards.

As to the sale of reusable products (directly reusable or refurbished/remanufactured to be reusable), government should take measures to regulate second-hand market. Currently, second-hand market is within grey zone of Chinese regulation system. Many products sold in this market were unqualified. Better-regulated second-market also demands well-established refurbishment and remanufacturing industries.

As to e-waste materials recycling industry, directly banning the informal recycling plants is not a wise choice. It is unfair to deny the opportunity for poor people to sacrifice even their health to earn decent money to make a better life. The government should at least create some safe job opportunities for those people. However, hiring informal recyclers into formal recycling entities is not an easy thing to do. If they can earn more money as self-employed worker, they will not be willing to work for formal entities. To achieve this, government should divert e-waste stream from informal recyclers to formal recyclers. In this way, informal recyclers cannot get enough e-waste to make money out of it and then they will consider the possible job offered by formal entities. How could e-waste be redirected? There must be some economic incentive for customers similar to what the Chinese government did in "Home Appliance Old for New Rebate Program". Guarantee of source of e-waste is not only good for recycling entities but also for refurbishing and especially beneficial to mass production in remanufacturing industries in the future.

However, providing economic incentive could be a huge burden for the government. Manufactures, who are making money by selling EEE, should also assume this responsibility of recycling. Chinese government is now promoting EPR within the country. However, as of now, it is still unclearly defined and the whole system has not been established. Besides, there are some potential difficulties. First, it is really hard to identify the producers because of the prevailing of smuggling and imitation in China. Second, some producers may report more than actual recycled amount[64]. To mitigate these difficulties, Chinese government should strengthen the supervision over and measures against smuggling and imitation. Complete EPR system should be established, which defines not only the responsibility of producers but also retailers, consumers and even government. Various recycling programs will develop along with the fully implementation of EPR in China, which provides more options for consumers to get their obsolete products recycled.

4.3 Industrialization

E-waste recycling can be better developed if it could be industrialized and driven by the market.

However, due to the e-waste management system has not been well established in China. The industrialization of e-waste recycling still has a long way to go. The possible industries related to e-waste recycling could be e-waste collection industry, refurbishment/remanufacturing industry and recycling industry. However, all these industries could hardly be profitable if they are private enterprises and without other subsidies in current situation. So at the initial stage, they had better be state-owned enterprise or at least supported by government. After the whole e-waste recycling system has been further developed in China, those enterprises can be privatized and then only rely on market without government's support.

5 Environmental and Social Benefits Analysis

5.1 Electrical and electronic equipment ready for end-of-life management in China

5.1.1 Domestic generation

Speaking of e-waste, China now mainly focuses on six types of products: mobile phones, computer, television, air conditioner, washing machine and refrigerator. As mentioned earlier, the five main household appliance types, i.e. computer, television, air conditioner, washing machine and refrigerator, already included in non-implemented Chinese legal measures, were assessed to account for more than 50% of the total e-waste[53].

Table 10 is the estimated domestic generation amount of the six types of WEEE in China. The data was obtained from the slides presented on 4th ITU Green Standards Week in Beijing by Basel Convention Regional Centre for Asia and the Pacific in Sep 2014. Figure 19 shows the accumulated generation amount accordingly[65].

Table 10 Domestic generation of e-waste in China (million units)[65]

Year	Refrigerator	Washing machine	Air conditioner	Television	Computer	Mobile phones	Total
2010	8.03	13.41	14.40	32.90	38.57	83.18	190.49
2011	8.53	12.41	16.96	43.65	42.99	114.82	239.36
2012	12.09	13.73	21.67	47.38	47.07	184.93	326.87
2013	14.69	16.03	28.32	43.79	50.79	231.33	384.95
2014	12.32	19.04	35.15	28.33	54.13	241.15	390.12
2015	13.75	20.86	37.52	38.11	57.1	241.12	408.46
2016	18.73	24.17	35.08	42.95	59.7	281.97	462.60
2017	23.29	26.59	40.57	44.55	61.97	306.77	503.74
2018	35.77	29.71	42.9	52.05	63.94	317.55	541.92
2019	42.45	35.94	57.07	56.96	65.63	325.74	583.79
2020	54.47	44.68	71.92	66.70	67.08	332.76	637.61

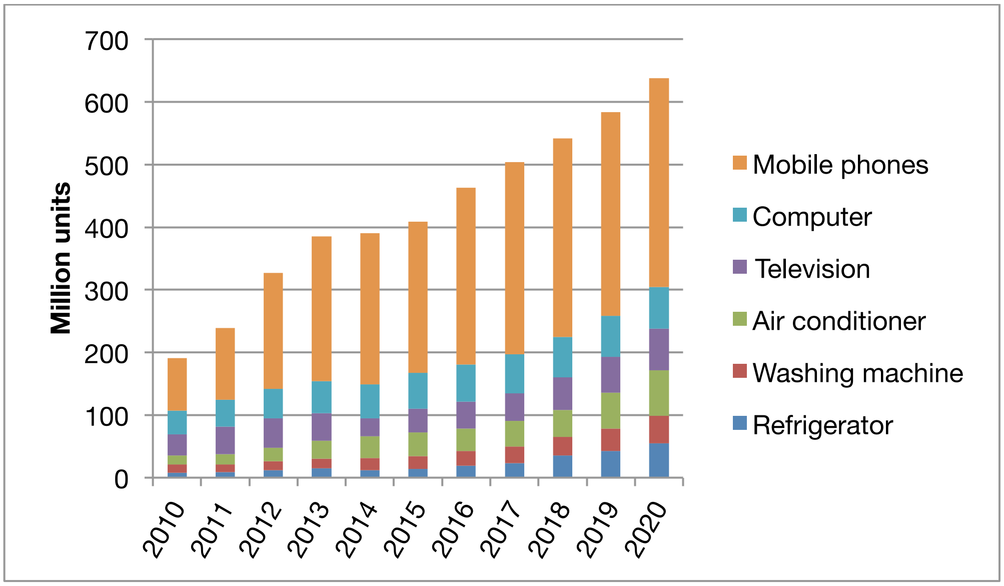

Figure 19 Domestic generation of e-waste in China (million units)[65]

Table 11 lists the average weight of each type of electrical or electronic product in China. The "computer" category includes desktop computer, computer monitor (CRT, LCD) and laptop. The television here includes CRT TV, LCD TV and PDP TV. Since LED technology is quite new compared to other technologies, the number of obsolete light emitting diode (LED) TV and display is very small, which is usually neglected. However, there is no official data available measuring the waste amount of each specific type of electrical or electronic product in China. Based on a diagram in StEP report[3] last year, the estimated average weight of overall television (CRT, LCD and PDP) is about 30 kg, while the estimated average weight of computers (desktops, monitors and laptops) is about 10.7 kg. Table 12 demonstrates the total weight of domestic e-waste in China. Figure 20 shows the accumulated weight accordingly.

Table 11 Average weight of each type of electrical or electronic products[50,66]

E-waste Type		Weight (kg)	
Air conditioner		51	
Refrigerator		45	
Washing machine		80	
Television	PDP	16	30
	LCD	12.52	
	CRT	36.8	

Computer	LCD monitors	6.26	10.7
	CRT monitors	18.4	
	Desktop	12.26	
	Laptop	3.55	
Mobile phones		0.133	

Note: CRT/LCD TV is assumed to have the same composition as CRT/LCD monitor and the size is usually doubled.

Table 12 Weight of domestic e-waste in China (million tons)[50,65,66]

Year	Refrigerator	Washing machine	Air conditioner	Television	Computer	Mobile phones	Total
2010	0.36	1.07	0.73	0.99	0.41	0.01	3.58
2011	0.38	0.99	0.86	1.31	0.46	0.02	4.03
2012	0.54	1.10	1.11	1.43	0.50	0.02	4.70
2013	0.66	1.28	1.44	1.32	0.54	0.03	5.28
2014	0.55	1.52	1.79	0.85	0.58	0.03	5.33
2015	0.62	1.67	1.91	1.15	0.61	0.03	5.99
2016	0.84	1.93	1.79	1.29	0.64	0.04	6.53
2017	1.05	2.13	2.07	1.34	0.66	0.04	7.29
2018	1.61	2.38	2.19	1.57	0.68	0.04	8.47
2019	1.91	2.88	2.91	1.71	0.70	0.04	10.16
2020	2.45	3.57	3.67	2.01	0.72	0.04	12.46

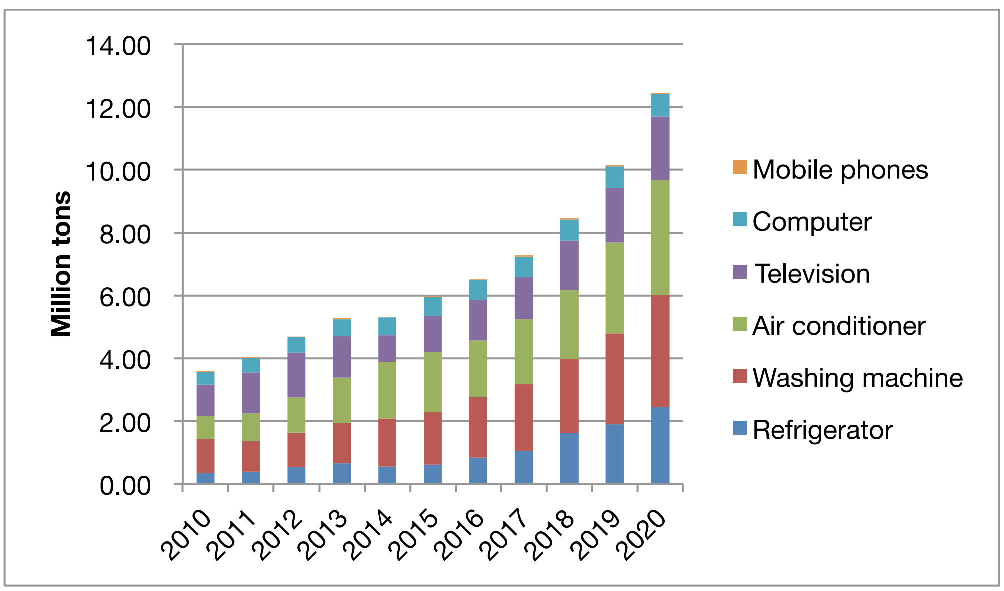

Figure 20 Weight of domestic e-waste in China (million tons)[50,65,66]

Though the majority of data here are estimated, they can still somehow show the trend to some extent. For example, as illustrated in Figure 21, the weight percentages of televisions and computers are shrinking while air conditioners and refrigerators make up more percentage of e-waste amounts in recent years. Besides, the weight percentages of mobile phones and washing machine remain stable over the years. Actually, according to Table 12, the amount of every type of e-waste is going up. The reason why the weight percentages of consumer electronic wastes, like mobile phones, computers and televisions are either stable or going down is that more large home appliances are dropped. This is a sign of better economy to some extent, since many people can afford to buy new large home appliances.

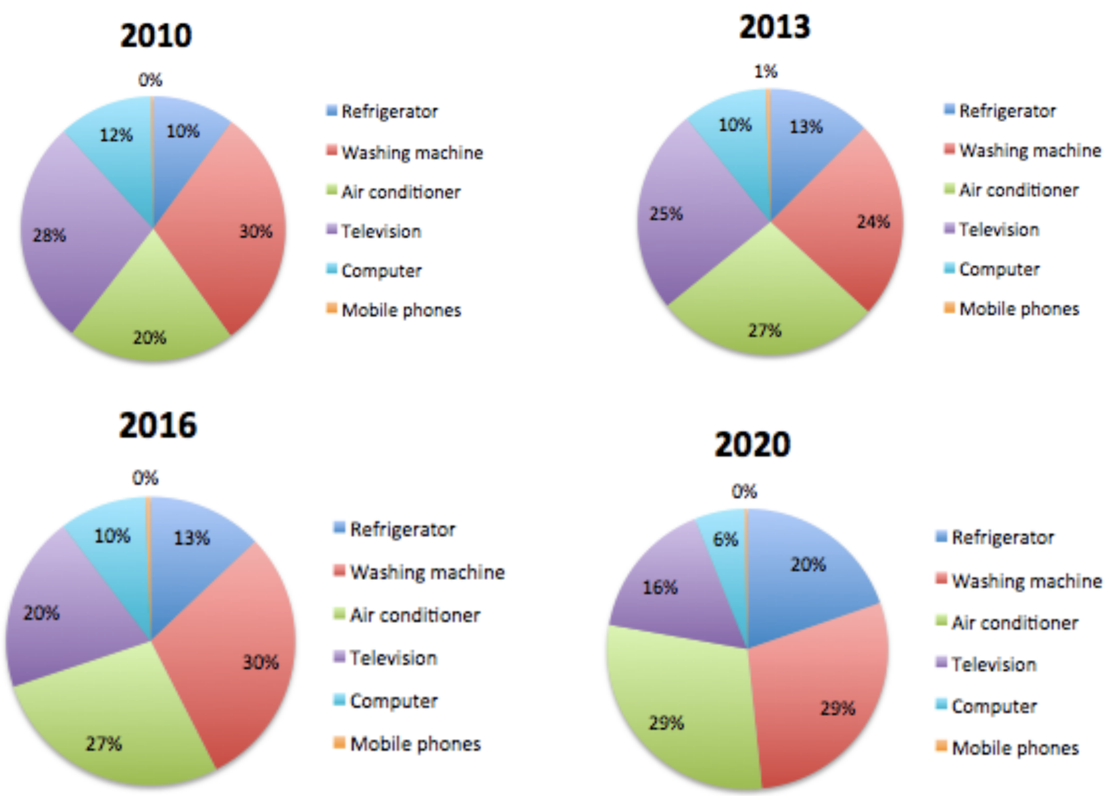

Figure 21 Weight percentages of six types of waste electrical or electronic products in China[50,65,66]

Apart from these six types of waste electrical or electronic products, there are still other types of e-waste in waste stream, like DVD players. As mentioned before, the amount of e-waste generated domestically in China in 2012 is about 7.3 million tons. Therefore, the e-waste composition in 2012 can be illustrated as the pie chart in Figure 22.

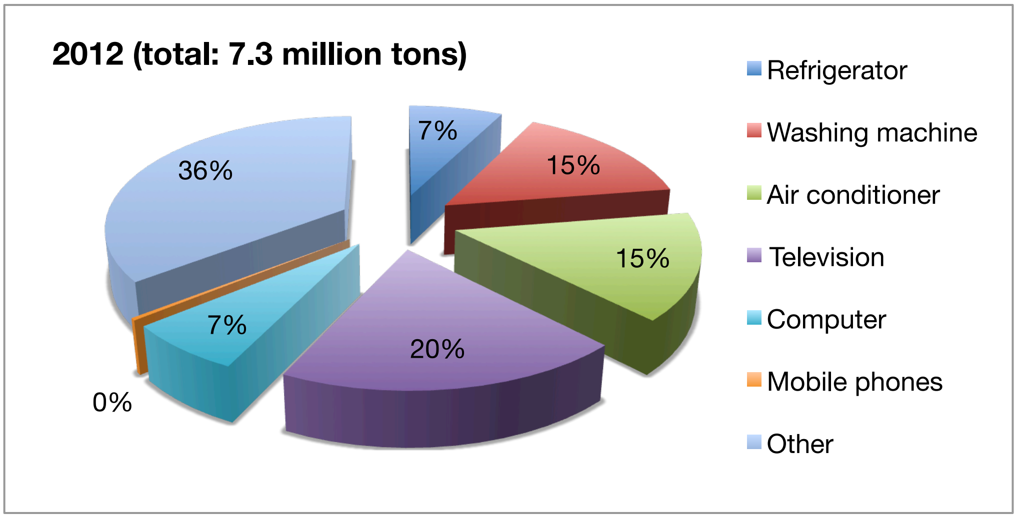

Figure 22 Composition of e-waste in China (2012)

As shown in the figure above, these six types of e-waste account for approximate 64% of the e-waste in 2012 in China.

5.1.2 Imported e-waste

Because this waste stream is illegal, it is impossible to track the amount. However, the average annual amount was estimated to be around 2.6 million tons in 2010[42]. Assume the imported amount does not change in recent years. So we are using this number here to further estimate the composition of imported e-waste in China. According to Figure 10, the imported e-waste is usually from developed countries. Here, we use the composition of imported e-waste from the U.S. to represent overall imported e-waste. Figure 23 shows the weight breakdown by product of export amounts in the U.S.. All the figures about exported e-waste stream from the U.S. are obtained from a MIT report "*Quantitative Characterization of Domestic and Transboundary Flows of Used Electronics*"[67].

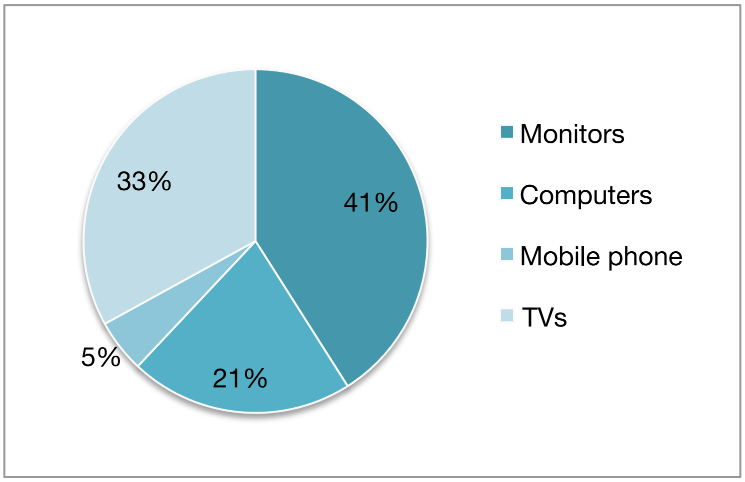

Figure 23 Weight fractions of exported e-waste in the U.S. (2010, MIT)[67]

Those exported e-waste categories can be further categorized as follows:

• TVs (CRT and Flat Panel)

• Mobile Phones

• Computers (Laptops and Desktops)

• Monitors (CRT and Flat Panel)

Actually, the collected data about CRT monitors amount includes some monitors with desktops, video monitors and CRT monitors. To simplify, assume all the CRT monitor units here are just CRT monitors. Flat panel TVs can be divided into LCD TVs and PDP TVs. Flat panel monitors here are assumed to be LCD monitors since the proportion of other flat panel types in the market is still small let alone in waste stream.

According to the data in the MIT report about exported quantity of each e-waste type, the number fraction of different e-waste type in each category can be further calculated as shown in Table 13.

Table 13 Detailed breakdown of different e-waste category (2010, MIT)[67]

E-waste Type		Number Fraction
Televisions	PDP TV	0.43%
	LCD TV	6.71%
	CRT TV	92.86%
Monitors	LCD Monitor	67.90%
	CRT Monitor	32.10%
Mobile Phones		100.00%
Computers	Laptop	72.50%
	Desktop	27.50%

Note: LCD TVs shipments are about 94% of flat panel TVs shipments worldwide while PDP TVs account for 6% in 2012[68]. Even though this is about shipment not exact information about waste, this shipment information is worldwide, which means both developing countries and developed countries are included. Therefore, it can used to estimate the breakdown of waste flat panel TVs in the U.S. to some extent and then calculate the average weight per television unit.

On the basis of Table 11 and Table 13, average weight of each unit in different categories of e-waste stream can be calculated as Table 14.

Table 14 Average weight of each unit in different types of e-waste products[50,66,67]

E-waste Category	Average weight per unit (kg)
Monitors	35.081
Computers	10.157
Mobile phones	0.133
TVs	5.945

Since the average imported e-waste amount is estimated to be 2.6 million tons per year, weight of each e-waste category can be further calculated based on weight fractions shown in Figure 23. According to average weight of each unit in different categories listed in Table 14, the total quantity of each category can be achieved. Then, the quantity of each e-waste type can be further calculated based on related number fraction. All the figures above are listed in Table 15.

Table 15 Annual imported e-waste in China[42,50,66,67]

E-waste Type		Weight (million tons)	Quantity (million units)	
Televisions	PDP TV	0.86	24.46	0.10
	LCD TV			1.64
	CRT TV			22.71
Monitors	LCD Monitor	1.07	104.95	71.27
	CRT Monitor			33.69
Mobile Phones		0.10	0.13	977.44
Computers	Laptop	0.55	91.84	66.58
	Desktop			25.26
Total		**2.60**	**1198.69**	**1198.69**

5.2 Environmental analysis

Environmental benefits can be earned by transferring existing e-waste recycling situation into the proposed recycling chain, which include energy saving, green house gas (GHG) reduction, raw materials conservation and toxic materials saving. However, since there is no record about the related energy consumption in informal recycling chain as well as its associated GHG emissions. Therefore, the energy saving and reduction, which will be calculated in this section, focus on the benefits over zero recycling situation by adopting the proposed e-waste recycling chain. Assume the percentage of each e-waste flow remains same as current situation after adopting the proposed recycling chain and the composition of each e-waste flow is the same. The boundary of environmental analysis in following part is described below:

1) Only the recycling of six types of EEE (air conditioner, refrigerator, washing machine, TV, computer and mobile phone) is discussed here.

2) Batteries and phone chargers are excluded.

3) Only the recycling of metals and glass is included. The recycling of plastics is out of scope since not all types of plastics would be recycled and some plastics would be used as fuel in some cases.

4) Only the benefits gained from end-of-life recycling chain, excluding the benefits from refurbishment or remanufacturing.

5) Exclude transportation difference.

6) The benefits focus on next year (2015).

5.2.1 Raw materials conservation

The overall materials recovery efficiency is determined by both pre-processing efficiency and end-processing efficiency. Usually, during pre-processing, with regard to materials recovery manual dismantling efficiency is almost 100% while mechanical pre-processing is about 70%[37]. As mentioned, pre-processing technique in both formal/informal chains in China is usually just manual dismantling and sorting.

During end-processing, copper, aluminum and ferrous scraps are sent to corresponding smelting plants to recover in both informal and formal chains. Assume the recovery efficiency is similar to US standards: Al (93%)[69], Cu (81%)[70] and Fe (98%)[71]. As to the recovery of precious metals, by informal leaching, the recovery rate is about 68.9% (assume recovery rate of all precious metals is similar to gold) while that of integrated smelters could be as high as 95.3%[37]. As mentioned earlier, the recovery efficiency of aluminum through mechanical separating system is about 90%[57]. Here, assume the recovery efficiency of all the other metals is the same as aluminum. As to formal hydrometallurgical method in China, the recovery efficiency of each kind of precious metal is reported to be 98% for silver, 93% for palladium and 97% for gold[72]. Actually, the recovery efficiency can be various in different reports using different measuring methods. Since the recovery efficiency of formal hydrometallurgical method is similar to that of integrated smelters, there is no need to differentiate between the two. Therefore, it is assumed that both of them can achieve recovery efficiency as high as 95.3%. Also, it is assumed that the glass amount does not change after class cleaning, as claimed by Nulife[61].

The material flow in informal recyclers is illustrated in Figure 24. As mentioned before, PCB recycling process varies in formal recycling entities. Formal recycling material flow is illustrated in Figure 25. Figure 26 is material flow of the proposed E-waste Recycling Process.

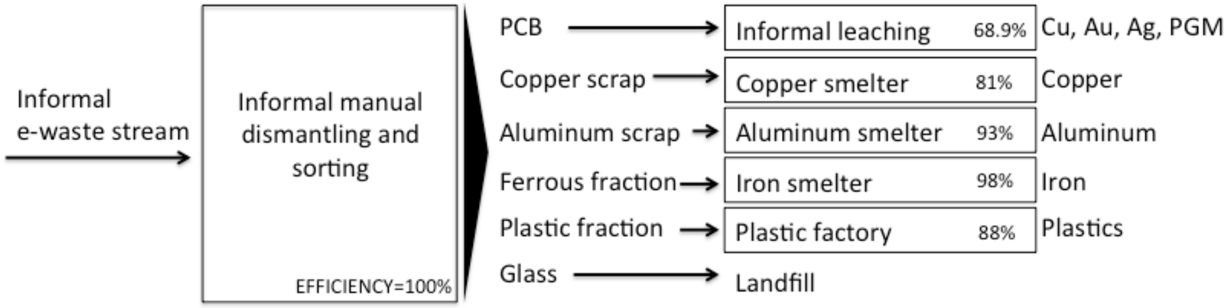

Figure 24 Material flow of informal e-waste recycling process

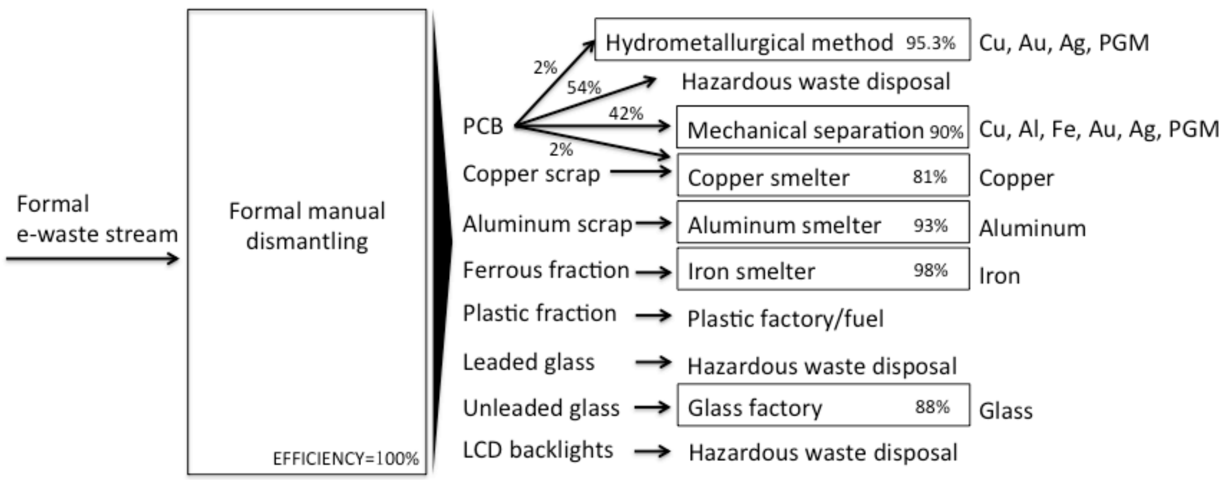

Figure 25 Material flow of formal e-waste recycling process

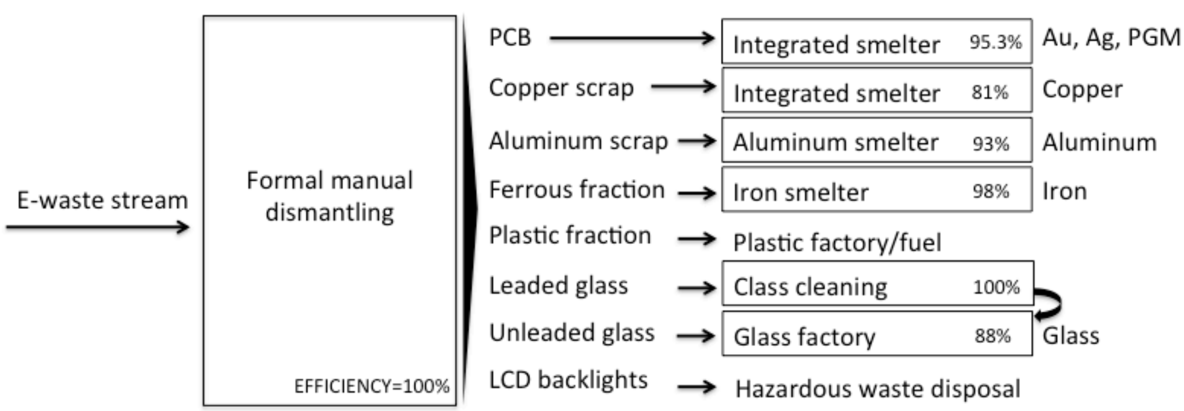

Figure 26 Material flow of proposed e-waste recycling process

As mentioned earlier, raw materials mainly discussed here are base metals, precious metals and glass, which are listed in detail in Table 16. According to Table 2 and Table 3, the raw materials content in each type of e-waste are listed in Table 17.

Table 16 Recycled raw materials

Raw Material	Breakdown
Base Metals	Al, Fe, Cu
Precious Metals	Au, Ag, Pd
Glass	-

Table 17 Raw materials content in e-waste[7,66,73,74]

E-waste Type	Glass (kg/unit)		Base Metals (kg/unit)			Precious Metals (mg/unit)		
	Leaded	Unleaded	Cu	Al	Fe	Au	Ag	Pd
Air conditioner	0.00	0.00	9.18	4.75	23.44	20.66	79.87	-
Refrigerator	0.00	0.00	1.57	0.59	21.42	9.90	9.45	-
Washing machine	0.00	0.00	2.58	1.60	41.49	23.12	69.36	-
PDP TV	0.00	5.92	0.45	2.46	5.40	374.40	499.20	-
LCD TV	0.00	1.13	0.36	0.57	5.45	290.46	871.39	-
CRT TV	8.43	4.75	1.67	0.24	4.78	16.01	384.19	64.03
LCD monitor	0.00	0.56	0.18	0.28	2.73	145.23	435.70	-
CRT monitor	4.21	2.37	0.83	0.12	2.39	8.00	192.10	32.02
Mobile phone	0.00	0.02	0.01	-	0.00	60.45	153.14	12.09
Laptop	0.00	0.83	0.13	0.09	0.71	306.40	534.99	97.27
Desktop	0.00	0.00	0.34	-	5.81	276.59	656.89	172.87

In 2015, the domestic e-waste generation and imported e-waste amount can be obtained from Table 10 and Table 15 respectively. Together with the information about e-waste flow in China in Figure 8, material recovery efficiency listed in Figure 24-26 as well as the raw materials amount that could be hopefully recovered in each unit listed in Table 17, the total amount of raw materials could be conserved through e-waste recycling in different scenarios can be calculated as shown in Table 18-20.

Table 18 Potential recoverable raw materials from e-waste by informal recyclers in China (2015)

E-waste Type	Domestic+Imported (million units)	Glass (million tons)	Base Metals (million tons)			Precious Metals (tons)		
			Cu	Al	Fe	Au	Ag	Pd
Air conditioner	11.48	0.00	0.09	0.05	0.26	0.16	0.63	-
Refrigerator	4.21	0.00	0.01	0.00	0.09	0.03	0.03	-
Washing machine	6.38	0.00	0.01	0.01	0.26	0.10	0.31	-
PDP TV	1.59	0.00	0.00	0.00	0.01	0.41	0.55	-
LCD TV	4.31	0.00	0.00	0.00	0.02	0.86	2.59	-
CRT TV	17.05	0.00	0.02	0.00	0.08	0.19	4.51	0.75
LCD monitor	38.12	0.00	0.00	0.01	0.10	3.81	11.44	-
CRT monitor	16.40	0.00	0.01	0.00	0.04	0.09	2.17	0.36
Mobile phone	524.91	0.00	0.00	-	0.00	21.86	55.38	4.37
Laptop	35.12	0.00	0.00	0.00	0.02	7.42	12.95	2.35
Desktop	18.65	0.00	0.00	-	0.11	3.55	8.44	2.22
Total	**678.23**	**0.00**	**0.16**	**0.08**	**0.99**	**38.49**	**99.00**	**10.06**

Table 19 Potential recoverable raw materials from e-waste by formal recyclers in China (2015)

E-waste Type	Domestic+Imported (million units)	Glass (million tons)	Base Metals (million tons)			Precious Metals (tons)		
			Cu	Al	Fe	Au	Ag	Pd
Air conditioner	9.00	0.00	0.07	0.04	0.21	0.07	0.29	-
Refrigerator	3.30	0.00	0.00	0.00	0.07	0.01	0.01	-
Washing machine	5.01	0.00	0.01	0.01	0.20	0.05	0.14	-
PDP TV	1.21	0.01	0.00	0.00	0.01	0.18	0.24	-
LCD TV	2.78	0.00	0.00	0.00	0.01	0.32	0.96	-
CRT TV	5.15	0.02	0.01	0.00	0.02	0.03	0.79	0.13
LCD monitor	4.10	0.00	0.00	0.00	0.01	0.24	0.71	-
CRT monitor	0.66	0.00	0.00	0.00	0.00	0.00	0.05	0.01
Mobile phone	57.87	0.00	0.00	-	0.00	1.39	3.52	0.28
Laptop	3.45	0.00	0.00	0.00	0.00	0.42	0.73	0.13
Desktop	5.49	0.00	0.00	-	0.03	0.60	1.43	0.38
Total	**98.03**	**0.04**	**0.09**	**0.05**	**0.57**	**3.32**	**8.87**	**0.93**

Table 20 Potential recoverable raw materials from e-waste through proposed recycling chain in China (2015)

E-waste Type	Domestic+Imported (million units)	Glass (million tons)	Base Metals (million tons)			Precious Metals (tons)		
			Cu	Al	Fe	Au	Ag	Pd
Air conditioner	20.49	0.00	0.15	0.09	0.47	0.40	1.56	-
Refrigerator	7.51	0.00	0.01	0.00	0.16	0.07	0.07	-
Washing machine	11.39	0.00	0.02	0.02	0.46	0.25	0.75	-
PDP TV	2.80	0.01	0.00	0.01	0.01	1.00	1.33	-
LCD TV	7.09	0.01	0.00	0.00	0.04	1.96	5.89	-
CRT TV	22.21	0.28	0.03	0.00	0.10	0.34	8.13	1.36
LCD monitor	42.23	0.02	0.01	0.01	0.11	5.84	17.53	-
CRT monitor	17.06	0.11	0.01	0.00	0.04	0.13	3.12	0.52
Mobile phone	582.78	0.01	0.01	-	0.00	33.57	85.05	6.71
Laptop	38.57	0.03	0.00	0.00	0.03	11.26	19.66	3.58
Desktop	24.14	0.00	0.01	-	0.14	6.36	15.11	3.98
Total	**776.26**	**0.47**	**0.25**	**0.13**	**1.56**	**61.20**	**158.22**	**16.14**

Tables above show that among all the e-waste types studied here, waste CRT TVs contribute most to recycled glass while air conditioners and mobile phones contribute most to recycled base metals and precious metals respectively. The amount of raw materials that could be hopefully saved by changing the current e-waste recycling chains into proposed recycling chain is listed in Table 21.

Table 21 Raw materials conservation further achieved if proposed recycling chain adopted

Material	Amount (million tons)
Cu	0.01
Al	0.00
Fe	0.00
Au	19.39
Ag	50.35
Pd	5.15
Glass	0.43

5.2.2 Hazardous materials reduction

In this paper we mainly talk about the hazardous materials reduction by proper treatment of leaded glass and heavy metals, i.e. mercury, lead and cadmium, which are the major heavy metals in e-waste. Table 22 lists the heavy metals content in each e-waste unit. Based on this, potential hazardous materials reduction by taking care of the heavy metals exposure in e-waste is further calculated in Table 23. Since current formal recyclers are already recycling in an environmentally friendly way, the hazardous materials reduction is equal to the exposure amount in informal recycling sector.

Table 22 Heavy metal content in e-waste (g/unit)

E-waste Type	Hg	Pb	Cd	Leaded Glass
Air conditioner	-	7.987	-	0.00
Refrigerator	-	4.725	-	0.00
Washing machine	-	2.992	-	0.00
PDP TV	0.000	8.861	-	0.00
LCD TV	0.028	24.689	0.057	0.00
CRT TV	0.000	44.822	0.118	8427.20
LCD monitor	0.014	12.345	0.029	0.00
CRT monitor	0.000	22.411	0.059	4213.60
Mobile phone	0.000	0.524	0.000	0.00
Laptop	0.006	4.766	0.001	0.00
Desktop	0.000	26.506	0.000	0.00

Note: The amount of lead here does not include the part in CRT glass.

Table 23 Extra Hazardous Materials Reduction Achieved by Adopting Proposed E-waste Recycling Chain (2015)

E-waste Type	Hg (tons)	Pb (tons)	Cd (tons)	Leaded Glass (tons)
Air conditioner	-	91.70	-	0.00
Refrigerator	-	19.88	-	0.00
Washing machine	-	19.10	-	0.00
PDP TV	0.00	14.09	-	0.00
LCD TV	0.12	106.31	0.25	0.00
CRT TV	0.00	764.38	2.00	143713.56
LCD monitor	0.53	470.64	1.09	0.00
CRT monitor	0.00	367.47	0.96	69088.59
Mobile phone	0.00	274.99	0.00	0.00
Laptop	0.21	167.41	0.04	0.00
Desktop	0.00	494.45	0.00	0.00
Total	0.87	2790.42	4.34	212802.15
	215597.78			

From Table 22, we are informed that lead is the most serious issue regarding heavy metals pollution while leaded glass is the main contributor to e-waste pollution. As discussed before, all the heavy metals content could be either recovered or properly disposed. And leaded glass can be transferred into unleaded glass while the lead will also be recovered or safely treated. In either case, it will not threat the environment and human health. The total amount of hazardous materials exposure, which can be further avoided by changing to the proposed e-waste recycling chain compared to current situation, is estimated to be 0.22 million tons.

5.2.3 Energy saving

During the manufacturing of electronic products, raw materials acquisition is one of the biggest energy-consuming sectors. By recycling waste electronic products, the energy used for raw materials production can be saved. However, the materials recycling process also takes energy, especially for electronic products, which are usually manufactured complicatedly. As illustrated in Figure 27, each kind of raw material should first be extracted from the ground and further purified. Then it will be alloyed to have its own shape. Next, it will be mixed with other components to form complete product. At the end of the product's life, it will go together with obsolete product and get mixed with other waste. To get recycled, it should be got out of the waste stream and back to purified state again.

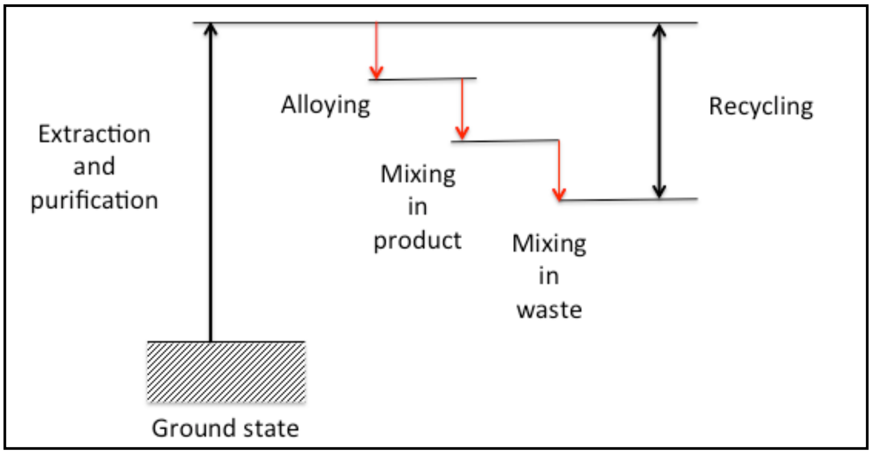

Figure 27 Life of raw material in electronic product

Therefore, the benefit here should be the energy consumption difference between raw material recycling and production. It could be either positive or negative, depending on the actual situation. Thermodynamics can be applied into calculating the minimum amount of work required to separate a mixed waste and to restore the original value of the materials. Actually, the minimum work of separation is negative the Gibbs Free Energy of mixing. In Figure 28, recycled material values ($\Sigma m_i k_i$) and material mixing entropy (H) are represented for 20 products in the U.S..

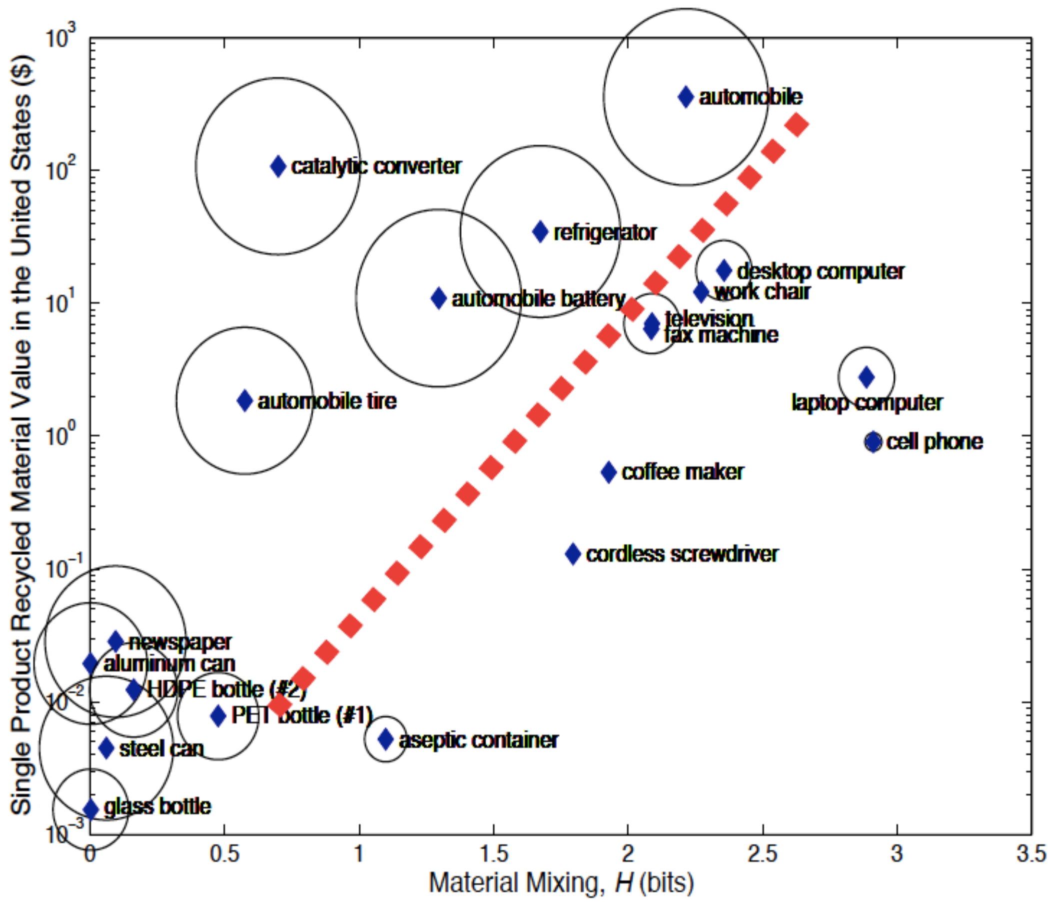

Figure 28 Single product recycled material values ($\Sigma m_i k_i$) and material mixing entropy (H) with recycling rates (indicated by the area of the circles) for 20 products in the U.S.[75]

We can see from the figure above, the recycling of computer, television and cell phone is relatively hard compared with other waste products. This makes sense since all these kinds of consumer electronics are usually compact and complicated, which makes them hard to be recycled. The red line is called "apparent recycling boundary". This line provides us with a general idea about whether a certain product is worth recycling or not. For example, the products above the line can usually be recycled in a profitable manner while those below the line require a recycling fee to be profitable or simply are not recycled. Even though in this many electronic products are still below the line, as we have scaled up the recycling process and improved the recycling technology, the recycling boundary can hopefully be shifted down and to the right.

According to the database provided by EPA[66] regarding electronics environmental benefits, the energy needed for primary materials production and materials recovery per kilogram materials are listed in the table below.

Table 24 Energy consumption intensity for materials' primary production and recovery[66]

Materials		Primary Production (MJ/kg)	Recovery (MJ/kg)
Base Metals	Cu	32.19	0.01[a]
	Al	139.58	6.13
	Fe	79.97	5.82
Precious Metals[b]	Au	214334	8509.03
	Ag	1459	145.78
	Pd	183737	4456.95
Glass	Unleaded	7.47[76]	4.92[76]
	Leaded		4.92/4.92+0.01[c]

Note:

a. The energy consumption used for copper recovery looks quite small compared to primary production. Since copper is always recycled together with other precious metals, this energy is used by per kilogram metal recovered (efficiency rate is included).

b. Precious metals should go through copper recovery stage first before getting recovered. Therefore, the recovery energy here is the sum of the energy consumption of copper recovery stage and downstream precious metals recovery stage.

This can be deemed as a pre-processing stage of precious metals recovery (efficiency rate is included).

c. Leaded glass can be reused to produce CRT or it can be smelted to get lead out to produce clean glass. The energy consumption in the cleaning stage is assumed to be the same as copper smelting. Also, efficiency rate has already been included.

Before recovering raw materials separately, there is a pre-processing line used for e-waste shredding and separating. If using mechanical pre-processing, according to EPA database, the energy consumption in this stage is about 0.9 MJ/kg e-waste[66]. However, in our proposed recycling chain, we are using manual dismantling and sorting to conduct pre-processing. Besides, because the market of CRT products is now shrinking, assume all the leaded glass will be cleaned instead of being recycled to make CRT. Figure 29 shows the typical glass manufacturing process. The virgin raw materials for glass production usually are limestone, soda ash and silica sand. Recycled glass (i.e. cullet) can partly replace mineral raw materials. Since the melting point of cullet is lower than those mineral raw materials, adding cullet can help reduce energy consumption and associated GHG emissions. The recovery energy listed in Table 24 for glass includes the process energy and transportation energy.

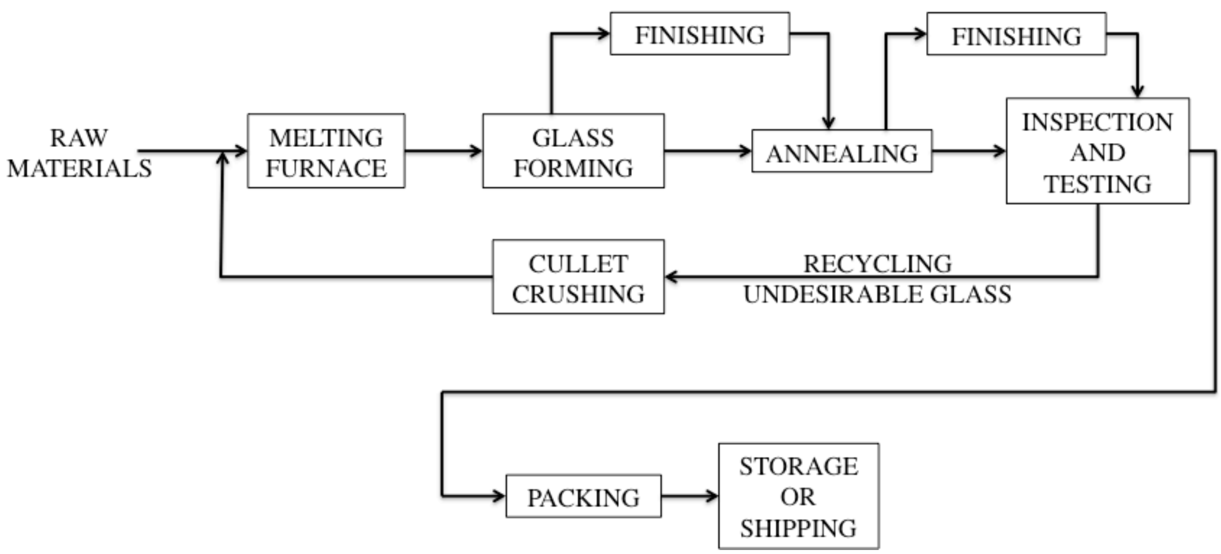

Figure 29 Typical glass manufacturing process[77]

The overall energy saving should be calculated using the formula below:

Energy Saving = E(primary materials production) - E(materials recovery)

E(primary materials production) and E(materials recovery) are estimated as shown in Table 25.

Table 25 Energy consumption for primary materials production and materials recovery

Materials		Recoverable amount		Primary Production (TJ)	Recovery (TJ)
Base Metals	Cu	0.25	million tons	8161	3
	Al	0.13	million tons	18742	823
	Fe	1.56	million tons	124532	9057
Precious Metals	Au	61.20	tons	13117	521
	Ag	158.22	tons	231	23
	Pd	16.14	tons	2966	72
Glass	Unleaded	0.21	million tons	1552	1022
	Leaded	0.26	million tons	1935	1276
Total				**171236**	**12797**

Table 26 shows the overall energy saving by recycling e-waste in 2015.

Table 26 Potential energy saving achieved by recycling e-waste (2015)

Energy Consumption Description	Amount (TJ)
E(primary materials production)	171236
E(materials recovery)	12797
Energy Saving	**158439**

Urban household electricity consumption in China is estimated to be 1800 kWh per year[78]. Therefore, the energy saved from recycling raw materials from both domestically generated and imported e-waste in 2015 can support about 24.5 million urban households' annual electricity consumption in China.

5.2.4 GHG reduction

Energy consumption is the biggest contributor to GHG emissions during the process of both primary materials production and materials recovery. Beside, there are also some GHG emissions unrelated to energy. Table 27 shows the GHG emissions associated with materials' primary production and recovery processes[66].

Table 27 GHG emissions intensity of materials' primary production and recovery[66]

Materials		Primary Production (kg CO_2-e/kg)	Recovery (kg CO_2-e/kg)
Base Metals	Cu	1.71	0.88
	Al	8.31	0.41
	Fe	4.33	0.38
Precious Metals	Au	12621	8109
	Ag	95	139
	Pd	9297	4248
Glass	Unleaded	0.66[76]	0.31[76]
	Leaded		1.12

Similar to energy saving analysis part, the leaded glass here is assumed to be cleaned at the end of its life and then put into glass smelter as cullet. The formula for GHG emission reduction can be expressed as follow.

GHG emission reduction = GHG(primary materials production) - GHG(materials recovery)

GHG(primary materials production) and GHG(materials recovery) are estimated in Table 28 and the overall emissions and ultimate reduction benefit are shown in Table 29.

Table 28 GHG Emissions from Primary Materials Production and Materials Recovery

Materials		Recoverable amount		Primary Production (million tons CO_2-e)	Recovery (million tons CO_2-e)
Base Metals	Cu	0.25	million tons	0.43	0.22
	Al	0.14	million tons	1.19	0.06
	Fe	1.57	million tons	6.78	0.60
Precious Metals	Au	61.20	tons	0.77	0.52
	Ag	158.22	tons	0.02	0.02
	Pd	16.14	tons	0.15	0.07
Glass	Unleaded	0.21	million tons	0.14	0.06
	Leaded	0.26	million tons	0.17	0.29
Total				**9.65**	**1.85**

Table 29 Potential GHG emissions reduction achieved by recycling e-waste (2015)

GHG Emissions	Amount (million tons CO_2-e)
GHG(primary materials production)	9.65
GHG(materials recovery)	1.85
GHG Emissions Reduction	**7.80**

Annual emissions on the road per passenger car are approximately 4.75 metric tons CO_2-e[79]. The overall GHG emission reduction achieved by recycling raw materials from both domestically generated and imported e-waste in 2015 equals to the emission caused by 1.64 million passenger cars on the road per year.

All the calculations in this part just focus on the recycling effect. Actually, refurbishing and remanufacturing can avoid more energy consumption and associated GHG emissions by reusing the components. So, the environmental benefit by establishing advanced e-waste management system in China could be very impressive.

5.3 Social analysis

The social benefits of a well-established e-waste recycling system mainly exist in health, employment and accessibility of EEE, which will be illustrated in detail in the following part.

- Health

In our proposed e-waste recycling system, all the hazardous issues are well controlled. The health of employees in recycling entities can be guaranteed as well as people living nearby. In return, this can help to win more employees willing to work for formal e-waste recycling industry.

- Employment

Even though the formalization of e-waste recycling industry could result in unemployment because informal entities can hardly survive under the new system, proposed formal entities still provide a lot of job opportunities to previous people working in informal chain especially in pre-processing part. Also, as the refurbishing and remanufacturing industry develop in China, they will provide even more openings for people all over the country.

- Accessibility of EEE

As discussed before, the energy consumption is much lower when using recycled materials compared to primary materials. This is especially true when the products are refurbished or remanufactured, which can save even more energy compared to recycling. Since energy consumption is closely related to the price of products, the lower the energy consumption the lower the price should be. The low price of those remanufactured products, whose quality could be even higher than new products, can even drive the prices of new products down. In this way, more people in less developed areas can afford to buy EEE.

6 Conclusions

In 2012, the amount of e-waste generated in the U.S. was about 9.4 million tons, while that of China 7.3 million tons, just next to the U.S.[6]. The global e-waste generation amount in the same year was estimated to be 49 million tons[6]. The e-waste recycling rate in the U.S. is usually higher than other countries. However, even in the U.S. the recycling rate is less than 30%[80].

In addition to huge domestic generation of e-waste (7.3 million tons), China also needs to take care of about 2.6 million tons of imported e-waste from developed countries[42]. In total, China is now taking care of about 20% of electronic waste generated globally. This is a difficult issue for a large and rapidly developing country technically, economically and socially. The crux of the problem is the existence of the informal recycling chain (treating 38% of e-waste stream in China), which has an effective collection system and also receives illegally imported e-waste but uses processing methods that cause significant pollution and affect both public heath and the environment. Instead of banning informal recycling entities, China should find a way to integrate informal recyclers into its formal recycling chain.

Developed countries, like the E.U. and the U.S. set good examples for China. In the U.S., even though there is a lack of recovery technologies, such as the integrated smelting technology existing in Canada and Sweden, the overall e-waste recycling system is relatively developed. There are various recycling programs operating within various states, which provide recycling facilities with a steady flow of e-waste. The technologies are advanced in recycling facilities and the treatment process is streamlined. Manufacturers, retailers or even consumers are regulated to be responsible for the e-waste recycling. Waste is changed to a valuable resource in such an environmentally friendly system.

The national condition in China is different from the U.S.. China should adapt the valuable experience from the U.S. but not just copy it. China should keep its effective and harmless informal collection and divert the collected e-waste to formal recycling entities. Formal entities could hire current informal recyclers to conduct manual dismantling instead of the inefficient mechanical processing used in developed countries, because as of now the labor cost in China is still very low. As to end-processing, China should upgrade their recycling facilities. Before solving the technology issue, China could build relationships with the countries that have state-of-the-art treatment facilities and send pre-processed e-waste scraps overseas to get materials recovered. Annually, about 75 million tons of raw materials could be conserved and 0.22 million tons of hazardous materials could be avoided by adopting the proposed recycling chain. Not just the recycling industry, but also refurbishing and remanufacturing industries should be developed to further maximize the benefits of e-waste recycling.

The development of all the industries related to e-waste recycling mainly relies on the investment and regulations from the Chinese government right now. Besides, Chinese government should improve existing regulations to avoid loopholes allowing e-waste import and at the same time strengthen the inspection to enforce the implementation. Therefore, Chinese government should be the biggest participant in this reform regarding e-waste recycling.

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APPENDIX A DEFINITION OF E-WASTE IN EUROPEAN UNION

1. LARGE HOUSEHOLD APPLIANCES

Large cooling appliances
Refrigerators
Freezers
Other large appliances used for refrigeration, conservation and storage of food
Washing machines
Clothes dryers
Dish washing machines
Cookers
Electric stoves
Electric hot plates
Microwaves
Other large appliances used for cooking and other processing of food
Electric heating appliances
Electric radiators
Other large appliances for heating rooms, beds, seating furniture
Electric fans
Air conditioner appliances
Other fanning, exhaust ventilation and conditioning equipment

2. SMALL HOUSEHOLD APPLIANCES

Vacuum cleaners
Carpet sweepers
Other appliances for cleaning
Appliances used for sewing, knitting, weaving and other processing for textiles
Irons and other appliances for ironing, mangling and other care of clothing
Toasters
Fryers
Grinders, coffee machines and equipment for opening or sealing containers or packages
Electric knives
Appliances for hair cutting, hair drying, tooth brushing, shaving, massage and other body care appliances
Clocks, watches and equipment for the purpose of measuring, indicating or registering time
Scales

3. IT AND TELECOMMUNICATIONS EQUIPMENT

Centralized data processing:
Mainframes
Minicomputers
Printer units
Personal computing:
Personal computers (CPU, mouse, screen and keyboard included)
Laptop computers (CPU, mouse, screen and keyboard included)
Notebook computers
Notepad computers
Printers
Copying equipment
Electrical and electronic typewriters
Pocket and desk calculators
and other products and equipment for the collection, storage, processing, presentation or communication of information by electronic means
User terminals and systems
Facsimile machine (fax)
Telex
Telephones
Pay telephones
Cordless telephones
Cellular telephones
Answering systems
and other products or equipment of transmitting sound, images or other information by telecommunications

4. CONSUMER EQUIPMENT AND PHOTOVOLTAIC PANELS
Radio sets
Television sets
Video cameras
Video recorders
Hi-fi recorders
Audio amplifiers
Musical instruments
and other products or equipment for the purpose of recording or reproducing sound or images, including signals or other technologies for the distribution of sound and image than by telecommunications
Photovoltaic panels

5. LIGHTING EQUIPMENT

Luminaires for fluorescent lamps with the exception of luminaires in households
Straight fluorescent lamps
Compact fluorescent lamps
High intensity discharge lamps, including pressure sodium lamps and metal halide lamps
Low pressure sodium lamps
Other lighting or equipment for the purpose of spreading or controlling light with the exception of filament bulbs

6. ELECTRICAL AND ELECTRONIC TOOLS (WITH THE EXCEPTION OF LARGE-SCALE STATIONARY INDUSTRIAL TOOLS)

Drills
Saws
Sewing machines
Equipment for turning, milling, sanding, grinding, sawing, cutting, shearing, drilling, making holes, punching, folding, bending or similar processing of wood, metal and other materials
Tools for riveting, nailing or screwing or removing rivets, nails, screws or similar uses
Tools for welding, soldering or similar use
Equipment for spraying, spreading, dispersing or other treatment of liquid or gaseous substances by other means
Tools for mowing or other gardening activities

7. TOYS, LEISURE AND SPORTS EQUIPMENT

Electric trains or car racing sets
Hand-held video game consoles
Video games
Computers for biking, diving, running, rowing, etc.
Sports equipment with electric or electronic components
Coin slot machines

8. MEDICAL DEVICES (WITH THE EXCEPTION OF ALL IMPLANTED AND INFECTED PRODUCTS)

Radiotherapy equipment
Cardiology equipment
Dialysis equipment
Pulmonary ventilators
Nuclear medicine equipment

Laboratory equipment for in vitro diagnosis
Analyzers
Freezers
Fertilization tests
Other appliances for detecting, preventing, monitoring, treating, alleviating illness, injury or disability

9. MONITORING AND CONTROL INSTRUMENTS

Smoke detector
Heating regulators
Thermostats
Measuring, weighing or adjusting appliances for household or as laboratory equipment
Other monitoring and control instruments used in industrial installations (e.g. in control panels)

10. AUTOMATIC DISPENSERS

Automatic dispensers for hot drinks
Automatic dispensers for hot or cold bottles or cans
Automatic dispensers for solid products
Automatic dispensers for money
All appliances which deliver automatically all kinds of products

APPENDIX B ENVIRONMENTAL AND OCCUPATIONAL IMPACT OF INFORMAL RECYCLING

Computer/E-waste components	**Processes used**	**Potential occupational hazard**	**Potential environmental hazard**
Cathode ray tubes (CRT)	Breaking, removal of copper yoke, and dumping	- Silicosis -Cuts from CRT glass in case of implosion - Inhalation or contact with phosphor containing cadmium or other metals	Lead, barium and other heavy metals leaching into groundwater, release of toxic phosphor
Printed circuit boards	De-soldering and removing computer chips	- Tin and lead inhalation - Possible brominated dioxin, beryllium, cadmium, mercury inhalation	Air emission of same substances
Dismantled printed circuit board processing	Open burning of waste boards that have had chips removed to remove final metals	- Toxicity to workers and nearby residents from tin, lead, brominated dioxin, beryllium, cadmium, and mercury inhalation - Respiratory irritation	- Tin and lead contamination of immediate environment including surface and ground waters. -Brominated dioxins, beryllium, cadmium, and mercury emissions
Chips and other gold plated components	Chemical stripping using nitric and hydrochloric acid along riverbanks	- Acid contact with eyes, skin may result in permanent injury - Inhalation of mists and fumes of acids, chlorine and sulphur dioxide gases can cause respiratory irritation to severe effects including pulmonary edema, circulatory failure, and death.	- Hydrocarbons, heavy metals, brominated substances, etc. discharged directly into river and banks. - Acidifies the river destroying fish and flora
Plastics from computer and peripherals, e.g. printers, keyboards, etc.	Shredding and low temperature melting to be reutilized in poor grade plastics	Probable hydrocarbon, brominated dioxin, and heavy metal exposures	Emissions of brominated dioxins and heavy metals and hydrocarbons

Computer wires	Open burning to recover copper	Brominated and chlorinated dioxin, polycyclic aromatic hydrocarbons (PAH) (carcinogenic) exposure to workers living in the burning works area.	Hydrocarbon ashes including PAH's discharged to air, water, and soil
Miscellaneous computer parts encased in rubber or plastic, e.g. steel rollers	Open burning to recover steel and other metals	Hydrocarbon including PAHs and potential dioxin exposure	Hydrocarbon ashes including PAH's discharged to air, water, and soil
Toner cartridges	Use of paintbrushes to recover toner without any protection	- Respiratory tract irritation - Carbon black possible human carcinogen - Cyan, yellow, and magenta toners unknown toxicity	Cyan, yellow, and magenta toners unknown toxicity
Secondary steel or copper and precious metal smelting	Furnace recovers steel or copper from waste including organics	Exposure to dioxins and heavy metals	Emissions of dioxins and heavy metals

Source: Wath, Sushant B., P. S. Dutt, and Tapan Chakrabarti. "E-waste scenario in India, its management and implications." *Environmental monitoring and assessment* 172.1-4 (2011): 249-262.