THE FUTURE OF ELECTRONIC WASTE RECYCLING IN THE UNITED STATES:
Obstacles and Domestic Solutions

By

Jennifer Namias

Advisor: Dr. Nickolas J. Themelis, Columbia University
Co-advisor: Dr. Phillip J. Mackey, P.J. Mackey Technology Inc.

Submitted in partial fulfillment of the requirements for

M.S. degree in Earth Resources Engineering

Department of Earth and Environmental Engineering

Columbia University

July 2013

Research sponsored by the

Earth Engineering Center

Columbia University

EXECUTIVE SUMMARY

Consumer electronics have become an integral part of daily life and revolutionized the way we communicate, retrieve information, and entertain ourselves. Between cell phones, computers, televisions, iPads, and e-Readers, it is estimated that the average person in the United States (U.S.) uses 24 electronic products (CEA, 2008). Rapid technological advancements and growth in the electronics industry have led to a constant stream of new products and a resulting decrease in the life span of electronics. Globally, more than 50 million tons of e-waste were discarded in 2009 and 72 million tons are expected to be disposed in 2014 (Ping Jiang et al.). Europeans produce approximately 20 kilograms of e-waste/person/year[1], while U.S. residents produce about 7 kilograms of e-waste/person/year[2]. This discrepancy may be attributed to the varying definitions of e-waste; in the U.S. electronic waste generally consists of information technology (IT) and telecommunications equipment, monitors and televisions, whereas in Europe it also includes large household appliances, cooling and freezing appliances, and medical devices.

E-waste contains precious and special metals, including gold, silver, palladium and platinum, as well as potentially toxic substances such as lead, mercury, cadmium and beryllium. Therefore, responsible end-of-life management of e-waste is imperative in order to recover valuable components and properly manage hazardous and toxic components. End-of-life management of e-waste includes reuse of functional electronics, refurbishment and repair of electronics, recovery of electronic components, recycling e-waste, and disposal. Reuse, refurbishment or repair of electronic products is most desirable since this option increases the life span of the electronic product and higher resource efficiency. Recycling of electronics allows for precious and special metals to be recovered, reduces the environmental impact associated with electronic manufacturing from raw materials, and ensures that hazardous and toxic substances are handled

[1] Huisman, J. UNU – ISP SCYCLE, STEP ADDRESS Worldwide EEE and WEEE estimates, update 31–01–2011, Bonn Germany.
[2] According to the U.S. Environmental Protection Agency (EPA), 2.44 million short tons of e-waste was generated in 2010 (source: http://www.epa.gov/wastes/conserve/materials/ecycling/docs/fullbaselinereport2011.pdf). By dividing the total e-waste generated by the 2010 U.S. population (308,745,538), the total amount of e-waste generated per person per year can be calculated. It should be noted that there are significant shortcomings in data collection and methodology surrounding e-waste, and e-waste generation and recycling statistics vary significantly between sources.

properly. Although there are clear benefits to recycling e-waste, the recycling rate of e-waste is relatively low, due to lack of recycling and regulatory infrastructure. The global rate of e-waste recycling has been estimated at about 13% in 2009 (Jiang et al.), while the estimates of recycling in the U.S. range from 13.6%[3] to 26.6%[4]. Based on the estimated U.S. generation of e-waste in 2010 of 2.44 million short tons (EPA; 1 ton=1.1 short ton) and the above range of recycling rates, 332,000 to 649,000 short tons of e-waste were recycled in the U.S. in 2010.

Currently, the main driver for the recycling of e-waste is the pressure of regulatory factors. Lack of national regulation has been shown to significantly hinder recycling rates in other nations (Solving the E-waste Problem (StEP), 2009). Currently, there is no U.S. federal mandate to recycle electronic waste but twenty five states have enacted legislation requiring statewide e-waste recycling. States with the highest per capital collection volumes of e-waste are Minnesota, Oregon, and Washington, at 6.37, 6.31, and 5.92 pounds (1 lb=0.45 kg) per person, respectively (Electronics TakeBack Coalition). Key lessons learned from the e-waste collection and recycling programs within these States include: (a) high collection volumes are seen when laws make the collection convenient, or when they establish collection goals; (b) states with high collection volumes have laws covering collection costs, encouraging a variety of collector types, including government, private and non-profit; and (c) landfill bans boost recycling levels.

Generally, the e-waste generated in the U.S. is pre-processed domestically and then sent overseas for end-processing, including the recovery of precious and special metals. It is estimated that 50 to 80 percent of the e-waste collected in the U.S. is exported to developing countries such as China, India and Pakistan, due to low-cost labor and less stringent environmental regulations (StEP), 2009). The remaining e-waste collected in the U.S. is processed via pyrometallurgical processing methods at copper smelters in Western Europe and Canada. The U.S. does not have integrated smelting capacity, and therefore does not process any of the e-waste it generates. These integrated smelters are used to process e-waste due to the advancement of pyrometallurgical processes and their capacity for relatively low cost metal recovery from e-waste. However, there is not enough capacity at these smelters to process global e-waste

---

[3] Advanced Technology Materials Incorporated (ATMI)
[4] United States Environmental Protection Agency (U.S. EPA)

volumes, and it is not financially feasible or suitable to build capital-intensive smelters in every region. The U.S. does have small scale recycling plants for the recovery of precious metals from spent automotive and industrial catalysts, and while the technology may be different, these small-scale pyrometallurgical processing plants could be an option for recycling e-waste in the U.S. E-waste is also recycled on a much smaller scale using hydrometallurgical processes, which utilize acidic leaching agents to recover metals. However, traditional leaching agents, such as cyanide and aqua regia, result in hazardous effluents that must be handled and disposed of properly.

Currently the smelting and refining industry dominates e-waste recycling; hydrometallurgical processing is just emerging as a potential domestic solution for treating e-waste. Advanced Technology Materials Inc. (ATMI) has developed a selective chemical process that recovers valuable materials from obsolete wiring boards (PWB) using a "green chemistry" technology. The ATMI eVolv© process is cost-effective, environmentally safe, and does not require shredding or grinding, thus reducing the loss of precious metals. Non-toxic hydrometallurgical processing is a promising recycling method for e-waste, and a potential domestic solution for the U.S.

Despite the benefits of metal recovery from e-waste, its recycling in the U.S. is limited due to: (1) insufficient collection (2) no federal legislation or policy mandating e-waste recycling (3) lack of recycling and recovery technologies and (4) illegal export of hazardous e-waste to developing countries where recycling processes pose serious risks to human health and the environment. In order to increase the e-waste recycling rate in the U.S., Federal regulation is needed in order to develop the necessary infrastructure, by setting mandatory recycling targets and establishing financing and enforcement mechanisms for e-waste collection and recycling. Also, regional and local authorities need to increase public awareness and provide the means for consumers to bring electronics to collection points. Promising end-processing methods, such as non-toxic hydrometallurgical processing methods, should be implemented as a domestic solution to e-waste recycling in the U.S. Also, global efforts should be geared toward increasing the e-waste recycling capacity of existing and additional smelters, and streamlining the process for e-waste recyclers.

Acknowledgements

First and foremost, I would like to thank my advisor Dr. Nickolas Themelis for his support and guidance throughout my research process. This project would not have been possible without his expertise and insight into the waste management field.

I would also like to thank Dr. Phillip Mackey from P.J. Mackey Technology Incorporated, John Walsh from Greene Lyon, and Michael Korzenski from Advanced Technology Materials Incorporated (ATMI) for the wealth of information and direction they have provided me.

Lastly, I would like to thank my family and friends for their support and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Consumer electronics have become an integral part of daily life and revolutionized the way we communicate, retrieve information, and view entertainment. Between computers, televisions, mobile devices, electronic games, and even devices which measure metabolic rate, it is estimated that the average person owns 24 electronic products (Consumer Electronics Association (CEA), 2008). We live in a society where newer is better, and for each new electronic gadget that reaches the market, one or more becomes outdated or reaches end-of-life. As a result, electronic waste (e-waste), which is defined as any piece of electronic equipment which has reached the end of its useful life, has become the fastest growing component of the municipal solid waste (MSW) stream worldwide. Globally, more than 50 million tons of e-waste were disposed in 2009 and tis number is projected to increase to 72 by 2014 (Ping Jiang et al.). Europeans produce approximately 20 kilograms of e-waste/person/year[5], while the United States (U.S.) produces approximately 7.2 kilograms of e-waste/person/year[6]. This discrepancy may be attributed to the varying definitions of e-waste; in the U.S. electronic waste generally consists of information technology (IT) and telecommunications equipment, monitors and televisions, whereas in Europe it also includes large household appliances, cooling and freezing appliances, and medical devices.

However, the significant increase in electronic devices has not corresponded to growth in collection, reuse and recycling (Kahhat et al). As technology rapidly advances and electronics reach the end of their useful life at a faster rate, there is a growing need for end-of-life management options. Electronic devices contain up to 60 different elements, many of which are valuable, such as precious and special metals, and some of which are hazardous. Landfilling electronics is undesirable for many reasons, including the fact that trace amounts of precious metals including gold, silver and palladium, and larger quantities of metals and alloys including

---

[5] Huisman, J. UNU – ISP SCYCLE, STEP ADDRESS Worldwide EEE and WEEE estimates, update 31–01–2011, Bonn Germany.

[6] According to the U.S. Environmental Protection Agency (EPA), 2.44 million short tons of e-waste was generated in 2010 (source: http://www.epa.gov/wastes/conserve/materials/ecycling/docs/fullbaselinereport2011.pdf). By dividing the total e-waste generated by the 2010 U.S. population (308,745,538), the total amount of e-waste generated per person per year can be calculated. It should be noted that there are significant shortcomings in data collection and methodology surrounding e-waste, and e-waste generation and recycling statistics vary significantly between sources.

copper, aluminum, and steel used in electronics are not recovered. Recycling electronics reduces the environmental impact of manufacturing products from raw materials, reduces cost and waste, and also lessens the United States (U.S.) dependence on foreign supplies or minerals and other valuable materials found in electronic devices. However, there are many obstacles to recycling electronic waste, including uncertainty surrounding the end-of-life management of electronic devices, lack of recycling infrastructure, lack of regulatory infrastructure, etc.

Discarded consumer electronics (otherwise known as e-waste) comprise the fastest growing waste stream in the United States, and the fastest growing component of the municipal solid waste (MSW) stream worldwide. Currently there is no U.S. Federal mandate to recycle electronic waste; however twenty five states have enacted legislation requiring statewide e-waste recycling. Despite state-wide recycling efforts, some authors have estimated that approximately 13.6%[7] to 26.6%[8] of e-waste is recycled in the U.S.

In June 2011, two pieces of federal e-waste regulation were introduced in Congress; "The Responsible Electronics Recycling Act of 2011" (H.R. 2284) which proposed to prohibit the export of certain electronics to developing nations, and "Electronic Device Recycling Research and Development Act" (S.1397) which proposed to authorize the U.S. Environmental Protection Agency to issue grants for research and development projects aimed at increasing e-waste recycling, in addition to funding a study on the obstacles to e-waste recycling. Neither H.R. 2284 nor S. 1397 was enacted.

1.1 Reasons for Recycling E-waste

The driving forces behind recycling e-waste are economic, environmental, public health and data security. A description of these factors can be found below:

---

[7] Source: ATMI
[8] Source: U.S. EPA

Economic Factors

Electronic devices contain up to 60 different elements, many of which are valuable, such as precious and special metals, and some of which are hazardous. Precious metals are rare, naturally occurring metallic elements which traditionally have a higher melting point, and are more ductile than other metals. They have a high economic value, as demonstrated by the two most well-known precious metals; gold and silver. Special metals include nickel, nickel base alloys, cobalt base alloys, titanium and titanium base alloys. Electronic equipment is a primary consumer of precious and special metals and therefore it is imperative that a circular flow is established in order to recover these metals and valuable elements. Investments are being made to treat e-scrap and reclaim the valuable metals, especially as raw materials become more scarce and expensive. Table 1 below displays the concentration of metals in common electronic products.

Table 1. Concentration of Metals in Electronics (2007)

Electronic	Copper (% by weight)	Silver (ppm)	Gold (ppm)	Palladium (ppm)
Television (TV) Board[(1)]	10%	280	20	10
Personal Computer (PC) Board[(1)]	20%	1000	250	110
Mobile Phone[(1)]	13%	3500	340	130
Portable Audio Scrap[(2)]	21%	150	10	4
DVD Player Scrap[(2)]	5%	115	15	4

(1) Source: Umicore Precious Metals Refining. Metals Recovery from e-scrap in a global environment. Geneva, September 7 2007. http://archive.basel.int/industry/sideevent030907/umicore.pdf
(2) Source: Jirang Cui and Lifeng Zhang. Metallurgical Recovery of Metals from Electronic Waste: A Review. Journal of Hazardous Materials 158 (2008) 228 – 256.

Circuit boards contain the highest value of precious metals in a computer, as well as most of the heavy metals (United States Geological Survey (USGS), 2001). The components of a personal computer have the highest economic value, due to gold plated connectors, components, pins and transistors:

- Motherboard (main circuit board)
- Peripheral Component Interconnect (PCI) boards (connects to motherboard)
- Random Access Memory (RAM) (long, rectangular small circuit boards)
- Processor (large chip that plugs directly into the motherboard)

Environmental/Resource Factors

In addition to recovering precious metals, recycling electronics also reduces the environmental impact associated with primary production of electronic products. The primary production of precious and special metals, including energy intensive stages such as mining and smelting, has a significant impact on carbon dioxide emissions. Reuse and recovery of electronics reduces the environmental impact of these products, as well as the impact from primary production of metals and fractions found in electronics.

Public Health Factors

Discarded electronics contain a variety of toxic metals, including lead, cadmium, mercury, chromium, and polyvinyl chlorides, and thus the disposal of electronics poses a significant environmental and health risk when not properly handled. Although e-waste represents less than 2% of landfill mass, it contains 70% of the hazardous waste in heavy metals (Jiang et al). The following hazardous components can be found in e-waste (see Table 2).

Table 2. Potentially Hazardous Materials in E-waste

Hazardous Component	Electronic Components and Devices
Lead	Cathode ray tubes and solder
Mercury	Switches and housing
Antimony trioxide	Flame retardant
Polybrominated flame retardants	Circuit boards, plastic casings, and cables
Selenium	Circuit boards
Cadmium	Circuit boards and semiconductors
Chromium	Corrosion protection for steel
Cobalt	Structural strength and magnetivity in steel

Source: http://electronicrecyclers.com/ewaste-defined.aspx

It is estimated that 50 to 80 percent of e-waste collected in developed nations is exported to developing countries such as China, India and Pakistan due to cheap labor and lenient environmental regulations (StEP, 2009). These developing nations lack the health and safety infrastructure to process and dispose of materials safely, and consequently workers handle toxic metals without proper equipment. While there are operators in China who are licensed to process e-waste, the market is dominated by small-scale entities that are not authorized, nor properly equipped to treat e-scrap. Common techniques for processing e-waste in developing nations include manual dismantling of hazardous materials and open-air burning, which generates significant accounts of dioxins and furans if performed without proper emission control systems. Cyanide leaching is also a prevalent technique for processing e-waste in developing countries, posing a significant concern to worker well-being if the spent leaching solution is not properly disposed.

Data Security Factors

Privacy protection concerns have also fueled the processing of electronic waste. Confidential and personal data must be destroyed properly in order to ensure the safety of organizations and individuals information.

1.2 End-of-Life Options for E-waste

End-of life management options for electronic waste include:

(1) Reuse of functional electronics

(2) Refurbishment and repair of electronics

(3) Reuse and recovery of electronic components

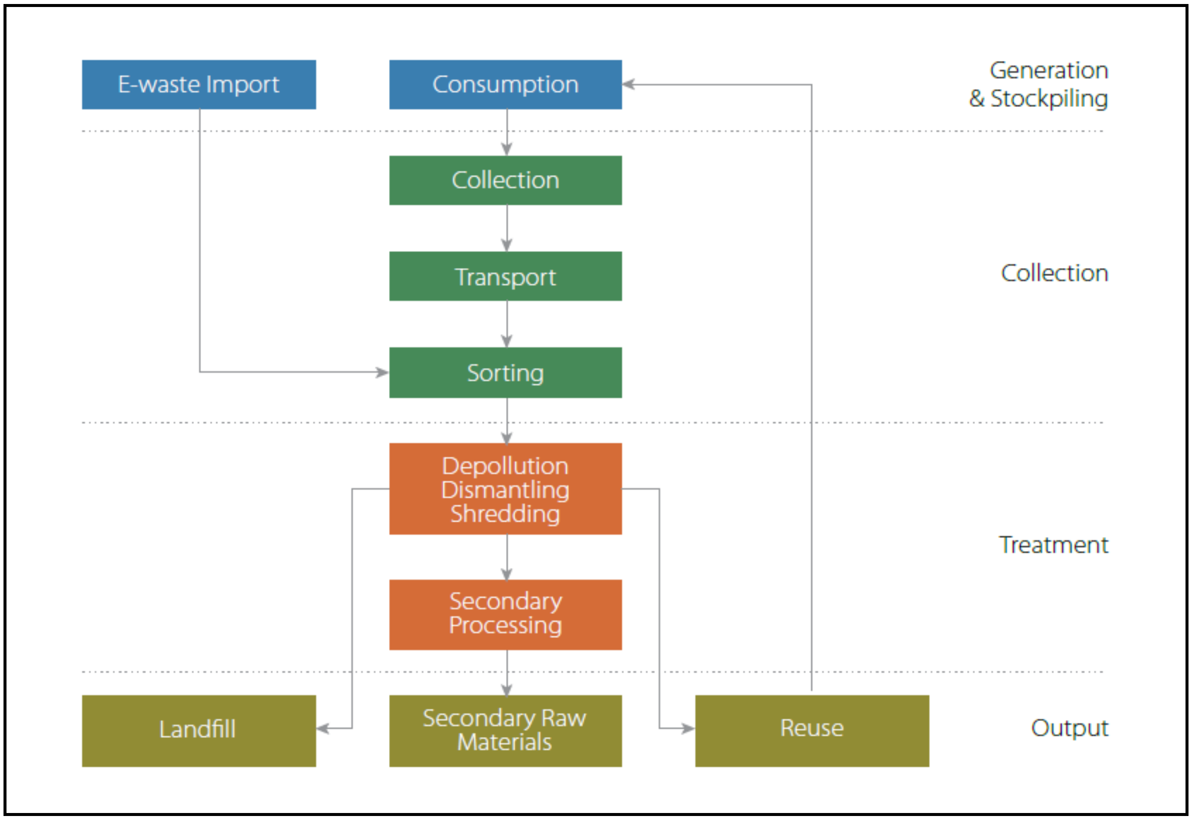
(4) End-processing for recovering metals

(5) Disposal

Reuse, refurbishment or repair of electronic products is most desirable since this option increases the lifespan of the electronic product in order to achieve greater resource efficiency. However, in order to reuse electronics, the equipment must be functional and working. The minimum requirements for donation vary depending on the organization receiving the electronics. Recycling of electronics allows for precious and special metals to be recovered, reduces the environmental impact associated with electronic manufacturing from raw materials, and ensures that hazardous substances in electronics are handled correctly. It should be noted that reuse and recycling are not alternative options; reused products need to be recycled properly and efficiently at the end of their useful life.

E-waste processing can be broken into three major steps; (1) collection, (2) sorting/dismantling/mechanical processing (including shredding, magnetic separation, etc.), and (3) end-processing. See Figure 1 below.

Figure 1. E-waste Processing Steps

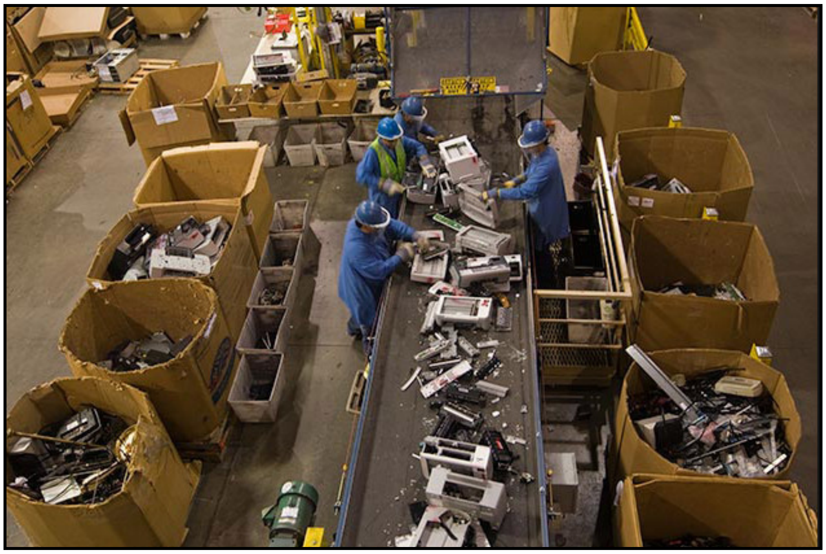


Source: *info*Dev (The World Bank Group). *Wasting No Opportunity: The case for managing Brazil's electronic waste.* April 2012. Web. 22 January 2013.

Collection: Collection generally takes place at a regional or national level and is achieved through take-back programs sponsored by retails and manufacturers of electronics, municipal drop-off collection centers, and non-profit and for-profit collection programs. There are many different entities which collect e-scrap for recycling, ranging from local municipal governments, to large waste management companies.

Sorting/Dismantling and Mechanical Processing: Sorting, dismantling and pre-processing generally takes place at a regional level or national level, and has the end goal of separating device streams into material streams, primarily metals, glass and plastics, for end-processing. The goal of this stage is to upgrade the valuable material content, and remove and safely dispose of hazardous. It should be noted that the optimal level of pre-processing is dictated by the quality of feed requirements for end-processing. Excessive pre-processing not only adds cost, but also may lead to significant losses of precious metals. Therefore there is an optimal level of pre-processing that needs to be achieved.

Figure 2. Sorting and Dismantling E-waste



Source: Sims Recycling Facility in Roseville, California
http://www.wired.com/gadgets/miscellaneous/news/2009/03/gallery_ewaste_recycling?currentPage=all

Once components are separated, ferrous fractions are sent to steel plants for recovery of iron, aluminum fractions are sent to aluminum smelters and copper alloys are sent to an integrated smelter to recover precious metals, copper and other non-ferrous metals.

End-Processing: End-processing takes place at a global level and is dictated by the material stream. The goal of this step is to recover valuable components (i.e. precious metals) and remove impurities. Sampling and assaying is necessary in order to determine the composition and content of precious metals in the e-waste stream, and to ensure that the optimum process is used to recover precious metals.

Pyrometallurgical is the primary method used to recover precious metals, however hydrometallurgical and biometallurgical methods have been gaining in popularity over the last two decades. This will be further discussed in Section 5.0.

Collection, dismantling, pre-processing and recovery from the less complex parts of e-waste (e.g. ferrous, copper and aluminum) generally takes place at local or regional facilities (StEP, 2009). End processing of the more complex components of e-wastes (e.g. circuit boards, batteries, cell phones) commonly occurs in integrated copper smelters and takes place in a global context. These smelters use non-ferrous extractive metallurgy to separate complex fractions into their constituent metals. These plants are very costly to build and therefore it is not feasible or practical to build them in every country.

It is important to note that Steps (1) and (2) have been developed with a focus on the electronic device stream (i.e. ICT equipment, C&F appliances, and monitors and TV), whereas end-processing technologies have been developed with a focus on the material stream. Sorting/dismantling/mechanical processing generally uses mechanical processes, whereas chemical processes are used in end-processing.

Table 3. Methods for E-waste Processing

Recycling Stage	Stream	Process	Level
(1) Collection	Device	Manual	Regional or National
(2) Sorting/dismantling and mechanical processing	Device	Manual and Mechanical	Regional or National
(3) End-processing	Material	Chemical	Global

The processing sequence is dictated by the geographic location, type of device, grade of components, and toxicity. For example, devices such as mobile phones and MP3 players do not always require shredding or dismantling processes, and can be sent directly to an end-processor to recover the metals; whereas computers require manual dismantling and mechanical pre-processing in order to separate and sort the various fractions. It is very important to optimize all steps of the recycling stage. Generally speaking, the greater the number of steps in a recycling process, the greater the risk of losing precious metals. The processes employed during sorting/dismantling influence how e-waste is treated in end-processing steps. Attention needs to be paid to the interfaces between the many steps in the e-waste recycling change in order to ensure that the highest quality metals are recovered.

1.3 Financing the Recycling of E-waste

Approaches to financing e-waste recycling depend on many factors including state legislation and policies, social preferences, commodity prices, and available recycling facilities. Although many programs offer "free" recycling to the consumer, recycling is never truly free because of costs associated with collecting, transporting, processing, refurbishing, and disposing electronic waste. Before discussing the current state of e-waste disposal in a global and national context, it is important to understand the two main financing models for e-waste collecting and recycling efforts; Extended Producer Responsibility (otherwise known as Manufacturers Responsibility), and Advance Recycling Fee.

1.3.1 Extended Producer Responsibility

Extended Producer Responsibility (EPR) assigns collection and recycling responsibility to the manufacturer. 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" (Lindhqvist). The purpose of EPR is to promote social responsibility by encouraging manufacturers to take into account end-of-life management during the product design phase.

In addition to recycling e-waste, electronic manufactures can take the following actions to achieve a level of EPR:

- Use recycled and environmentally friendly materials
- Design products that minimize resource use
- Re-use byproducts and waste of manufacturing process
- Minimize packaging or use recyclable packaging

- Reduce toxic and hazardous substances used in the manufacturing process and product itself
- Recycle e-waste through certified electronic recyclers to ensure that e-waste is properly managed

Currently the EPR approach is used in all European Union countries, and twenty-three of the twenty-five States in the U.S. that have enacted e-waste legislation. In the U.S., the lack of federal legislation is one of the largest obstacles to widespread adoption of this concept.

1.3.2 Advance Recycling Fee

The Advance Recycling Fee (ARF) is a fee paid by the customer at the point of purchase, depending on the size and type of the electronic. In California, the fee is then deposited into a state recycling fund, which is used to pay qualified e-waste collector and recyclers to cover the cost of managing e-waste. In South Korea, consumers are not required to pay a collection fee if they buy a replacement product; and the retailer collects the e-waste. ARF models are also in place in Switzerland, Belgium and select provinces in Canada.

Regardless of whether the producer or consumer is assigned direct financial responsibility, end-of-life management costs are incorporated into the market price. This can either result in a reduction in sales, whereby the financial impact is borne by the producer, or an increase in sales price, causing the consumer to be financially impacted.

2.0 GLOBAL E-WASTE MANAGEMENT

Globally, more than 50 million tons of e-waste was disposed of in 2009 and 72 million tons are expected to be disposed of in 2014, while the global e-waste recycling rate is projected to increase from 13% to 18.4% between 2009 and 2014 (Jiang et al.). It is estimated that 50% to 80% of e-waste from developed countries is exported to developing countries (Wang et al.). While some governments are forbidding the export of e-waste to developing nations, exportation is on the rise due to economic incentives of informal recycling. Developed nations benefit from cheap labor costs in developing nations, while the imported e-waste creates jobs for developing nations and provides second hand products for reuse. Because the majority of e-waste is processed through informal recycling systems, there is limited data on the volumes of e-waste collected and treated through the formal sector.

The following section describes e-waste recycling policies in Europe and Japan, nations which take different approaches but both boast high recycling rates. Using the EPR concept, the European Union (EU) is reported to have achieved a recycling rate of about 35% (CRU). Japan uses a combination of EPR and ARF to achieve an estimated recycling rate of 75% (CRU).

2.1 European Union E-Waste Recycling Policies

The e-waste recycling rate for the European Union is significantly higher than the e-waste recycling rate of the U.S., at approximately 35% (CRU). The United Nations University estimates that e-waste generation in EU countries is rising by 8.3 to 9.1 million tons per year, while global e-waste generation is increasing about 40 million tons per year (StEP, 2009). The EU's approach to e-waste recycling and management is guided by two directives; the Waste Electrical and Electronic Equipment (WEEE) Directive (Directive 2002/96/EC; amended 2010) and RoHS Restriction of Hazardous Substances (RoHS) Directive (Directive 2002/95/EC).

The goal of the WEEE directive is to increase the collection rate for discarded electronic and electrical products from 65% by 2012 and to 85% by 2016. The WEEE directive adopted regulations in five major categories: (1) electrical and electronic equipment (EEE) product design, (2) e-waste collection, (3) e-waste recovery, (4) e-waste treatment and treatment financing and (5) EEE user awareness. Producers of these goods are responsible for collection and recycling once the products reach the end of their useful life. Producers include primary manufacturers as well as companies that import and rebrand products. In many cases, distributors offer take-back schemes and producers come together to invest in central schemes, such as take-back facilities.

Under the WEEE directive, processors of e-scrap must comply with the following regulations:

- Be an authorized treatment facility
- Have an environmental permit, a pollution prevention control permit or a waste management license
- Treat WEEE according to the guidance on best available treatment, recovery and recycling techniques

RoHS (Restriction of Hazardous Substances) Directive (Directive 2002/95/EC) controls the use of hazardous materials in electronics, and requires safer materials be substituted for heavy metals typically found in electronics such as lead, mercury, cadmium, and polybrominated biphenyls (PBB).

2.2 E-waste Recycling Policy in Japan

In Japan, e-waste policies require manufacturers and importers to take-back electronics for end-of-life management. Japan's "Home Appliance Recycling Law" (1998) mandates that four types of household e-wastes be collected: televisions, refrigerators, washing machines and air conditioners. Consumers are required to pay an end-of-life fee that covers a portion of the recycling and transportation costs. The total fees vary between US$27 and US$65 depending on the type of appliance (Kahhat et al.). Consumers are required to bring e-waste to the establishment they purchased the product. Retailers then ship the products to designated collection sites, and manufacturers are responsible for ensuring the e-scrap is recycled. Manufactures can also sell the e-scrap for reuse or pay to have another company recycle the waste. Japan's e-waste recycling rate is approximately 75% for products covered under the

Home Appliances Recycling law, due to the fact that greater financial responsibility is placed on the consumer (CRU).

3.0 E-WASTE MANAGEMENT IN THE U.S.

3.1 E-waste Policy in the U.S.

Currently there is no U.S. Federal mandate to recycle electronic waste; however twenty five states have enacted legislation requiring statewide e-waste recycling. Despite state-wide recycling efforts, it is estimated that 13.6%[9] to 26.6%[10] to e-waste is recycled in the U.S. According to the U.S. Environmental Protection Agency (EPA) Office of Resource Conservation and Recovery report "Electronics Waste Management in the United States through 2009," 2.44 million short tons were ready for end-of-life management in 2010 (Table 4 below). Based on this estimated generation and the aforementioned U.S. e-waste recycling rates, approximately 332,000 to 649,000 short tons of e-waste was recycled in the U.S. in 2010.

[9] ATMI
[10] U.S. EPA

Table 4. E-waste End-of-life Management in the U.S. (2010)[11]

Device	Total units ready for end-of-life management	Units Disposed	Percentage Disposed	Units Recycled	Percentage Recycled
Computers	51.9 million	31.3 million	60%	20.6 million	40%
Computer displays	35.8 million	24.1 million	67%	11.7 million	33%
Hard-copy devices	33.6 million	22.4 million	67%	11.2 million	33%
Keyboards and mice	82.2 million	74.4 million	91%	7.83 million	10%
Televisions	28.5 million	23.6 million	83%	4.94 million	17%
Mobile Phones	152.0 million	135.0 million	89%	17.4 million	11%
Total Units	**384 million**	**310 million**	**--**	**73.7 million**	**--**
Total Short Tons	**2.44 million**	**1.79 million**	**73.4%**	**649,000**	**27%**

Source: United States Environmental Protection Agency Office of Resource Conservation and Recovery. *Electronic Waste Management in the U.S. through 2009.* EPA 530-R-11-002. May 2011. Estimates are projected to 2010 based on estimates from previous years.

Because there are no federal regulations mandating recycling, states have taken widely different approaches to recycling. It is now illegal for most American businesses to place electronics in the trash, and some states prohibit electronics from being disposed of in the municipal solid waste stream. Many states are also requiring that local governments offer e-waste recycling for residents through curbside collection, collection events, or take-back programs. Twenty-five states have enacted legislation requiring statewide e-waste recycling, nineteen of which have

[11] It should be noted that e-waste generation was based on the following methodology, and was not directly measured. EPA calculated the tonnage of e-waste generated by using sales data to determine the number of electronic products use for a given year and weight data to estimate the weight of these products. Data was then applied on the lifespan of electronic products to the sales data to estimate the number and weight of products in use, storage, or end-of-life management for each year. Finally, data was used on the share of electronic products that are collected for recycling or disposed of to estimate how products are managed at their end-of-life.

bans on disposing e-waste in landfills (Electronic Recyclers International (ERI)). The statewide recycling laws cover 65% of the United States population (Electronics Takeback Coalition). States which have enacted e-waste recycling legislation include California (2003); Maine (2004); Maryland (2005); Washington (2006); Connecticut, Minnesota, Oregon, Texas and North Carolina (2007); New Jersey, New York City, Oklahoma, Virginia, West Virginia, Missouri, Hawaii, Rhode Island, Illinois and Michigan (2008); Indiana, Wisconsin (2009); Arizona, Utah, Colorado, Iowa, Kentucky, Georgia, Pennsylvania, New Hampshire, and Massachusetts have proposed legislation that is pending approval in 2013. All of these states, except for California and Utah, use some variation of the Extended Producer Responsibility approach, which gives manufactures financial responsibility for recycling their electronic products. E-waste recycling policies in California, New York, and Maine are highlighted in the following sections.

3.1.1 California Policies

California spearheaded the State legislative movements on e-waste recycling through the 2003 Electronics Waste Recycling Act (SB 20). The 2003 Electronics Waste Recycling Act aims to reduce the use of hazardous substances, specifically cadmium, hexavalent chromium, lead and mercury, in certain electronics sold in California. In addition, SB20 requires retailers to collect an Electronic Waste Recycling Fee ranging from $6 to $10 from consumers who purchase certain electronics with cathode ray tubes (CRT), liquid crystal display (LCD) and plasma display devices. Retailers are able to retain 3% of the collected fees in order to cover the costs of collection. Retailers then submit the rest of this fee to the Board of Equalization, who reimburses recycling centers and organizations, such as GreenCitizen, which provide free recycling of e-waste to consumers and businesses.

3.1.2 New York Policies

The New York State Electronic Equipment Recycling and Reuse Act (NYS-EERRA) requires manufacturers of certain electronic equipment to collect and recycle or reuse their brands of products, for free for residents and small businesses. Under NYS-EERRA, it is legal for residents to discard electronics in the trash until 2015, with the exception of rechargeable batteries. By

2015, certain electronics, including computers, tablets, e-readers, televisions, small scale servers, computer and TV peripherals, and portable devices will be banned from disposal in the MSW stream and will be eligible for free collection through a manufacturer take-back program. The law phased in a disposal ban for discarded electronics, starting with manufacturers, retailers, owners or operators of an electronic waste collection site/consolidation facility or recycling facility by April 1, 2011, and extended to any entity or organization other than an individual or household by January 1, 2012.

The NYS-EERRA establishes annual statewide reuse and recycling goals for all electronic waste and requires manufacturers of certain electronic equipment to establish a convenient system for the collection, handling, and recycling or reuse of discarded electronic waste, starting in 2011. The law imposes a recycling surcharge if the goals are not met, and a credit system it the goals are exceeded. The law also describes proper forms of collection, facilities and reporting requirements for manufacturers.

The NYC Department of Sanitation is currently working with manufacturers to accept electronics at SAFE (Solvents, Automotive, Flammable, Electronics) disposal events, which are held every Spring in each NYC borough. Highlighted take-back programs include Electronic Manufacturers Recycling Management Company, Goodwill Industries, Dell Reconnect, We Recycle!, Lower East Side Ecology Center, Office Depot, Sims Recycling Solutions, Staples, etc. Sims Recycling Solution offers New York residents a free, postage-paid mail-back program for any brand of electronic equipment, as well as local collection events.

Cell phones are regulated under the New York State Wireless Recycling Act. The law requires all wireless telephone service providers that sell cell phones in New York State to accept up to 10 cell phones from any person for reuse or recycling, or provide a method for shipping the phones for recycling at no cost, effective January 1, 2007.

3.1.3 Maine Policies

In 2006, Maine enacted legislation (Title 38, Section 1609) based on the Manufacturers Responsibility model, covering household monitors, televisions and laptops. Maine's e-waste system mandates that the responsibility is shared by municipalities and manufacturers. Municipalities cover collection and process costs, while manufacturers cover consolidations, transportation from consolidators to processors, and processing costs (Kahhat et al.).

3.2 E-waste Collection in the U.S.

Collection of e-waste is the first step in the recycling chain, and is critical to ensuring that e-waste is recycled or reused. Without a successful collection system, e-waste will continue to be stockpiled in homes, offices and warehouses. Because the resource impact of electronic waste is still not widely understood, collection rates of e-waste are relatively low.

3.2.1 **E-waste Collector Types in the U.S.**

Current e-waste collection programs in the U.S. include curbside collection, short-term drop-off events, permanent drop-off, and take-back programs (Kahhat et al.). Drop-off centers generally include retail stores that recycle electronics, municipal government sites, and charitable drop-off centers. Collection efforts in the U.S. have historically been insufficient due to the lack of Federal legislation mandating the recycling of e-waste, and also due to consumer's lack of awareness about methods of handling obsolete electronics. However, collection efforts are steadily on the rise. The number of recycling drop-off centers in the U.S. increased from 5,000 in 2011 to close to 7,500 in 2012 (eCycling Leadership Initiative (ELI)). The following section discusses the different types of collection programs across the U.S.

For-Profit Organizations

For-profit organizations, such as Electronic Recyclers International (ERI) and WeRecycle! process e-waste for a fee. ERI is North America's largest recycler of electronic goods, collecting e-waste from retailers, non-profits, recycling corporations, governments, liquidators, etc. All material that is sent to ERI is recycled into metals, plastics and glass, and nothing is placed in landfills or exported illegally to other nations. ERI uses a bar code tracking system which allows customers to track e-waste at all stages of the end-processing. This allows for a transparent and traceable process and assures customers that their e-waste is being processed responsibly, and is not ending up in landfills, or being sent to ill-equipped developing nations for disposal. In addition, Certificates of Destruction are issued to all customers of ERI, which transfers all liability to ERI. Video verification is another service that ERI offers in order to provide assurance that confidential information is destroyed.

WeRecycle! is an e-Stewards certified company offering public collection programs as well as mail-back programs. WeRecycle! works with towns and cities, local organizations, and electronic manufacturers to provide convenient recycling and waste management solutions via both permanent collection programs and one-day sponsored events.

Non-Profit Organizations

The GreenCitizen organization (http://www.greencitizen.com) provides free electronic recycling services, with the exception of media disks ($5 per cubic foot), hard disk destruction ($20.00) and cell phone erasure ($10.00). GreenCitizen reuses approximately 5% of all electronic equipment received and sells reused electronics to schools, non-profits and individuals.

Non-profits such as, The Salvation Army and Goodwill, accept electronic waste for free and make a profit when the electronic is refurbished and resold.

Take-Back Programs (Best Buy)

Best Buy has one of the most comprehensive electronic recycling programs of any major corporation. Consumers are allowed to drop off three items per household per day, regardless of the manufacturer and the location where the item was originally purchased. Customers can trade in old electronics for a Best Buy gift card, purchase a new electronic from Best Buy and have its Geek Squad or Best Buy Home Delivery come remove the old electronic for free, or drop off electronics at a designated kiosk.

When the program was originally launched in 2009, it required customers dropping off e-waste to buy a $10 gift card, but this fee was dropped in November 2011 (Aston, 2012). Best Buy has two main streams of revenue: (1) Best Buy is entitled to a percentage of money from its recycling partners for the sale of metals and alloys after processing, and (2) electronic manufacturers, who are required by many states to recycle a portion of what they sell each year, buy access to Best Buys recycling capabilities. Best Buys biggest costs are labor and storage space, as well as running its audit program in order to enforce a corporate recycling policy and ensure that electronic processing meets or exceeds state and federal guidelines. In 2010 Best Buy joined the U.S. EPA Responsible Alliance Disposal (RAD) Program.

Best Buy sends collected e-waste to recyclers in three different regions: materials collected at Best Buy locations in the western U.S. are sent to ERI in Fresno, California; Midwestern U.S. materials are sent to Regency Technologies in Cleveland, Ohio; and eastern U.S. materials are sent to E-Structors in Baltimore, Maryland (Aston). As of September 2012, Best Buy required that its electronic recyclers be certified by both the e-Stewards Standard and R2 Standards. Refer to Section 4.0 below for a description of these Standards.

In Best Buy's 2010 Sustainability report, the company laid out a plan to collect approximately 1 billion pounds of e-waste over the next five years. In Best Buys 2011 Fiscal year, customers brought in 85.7 million pounds of electronics for recycling (Best Buy).

3.3 Successful State E-waste Recycling Programs

Factors affecting State recycling rates include collection programs, recycling materials targeted, recycling goals, and regulatory approaches. States with the highest per capita collection volumes are Minnesota, Oregon and Washington at 6.37, 6.31, and 5.92 pounds per person, respectively (Electronics TakeBack Coalition). The Electronics TakeBack Coalition published a report titled "Ten Lessons Learned from State E-Waste Laws", which analyzes state programs and their successes and failures. The following key lessons were learned from States with high collection volumes per capita.

1. High collection volumes are attained when laws make the collection convenient, or when they establish collection goals.

Washington and Oregon State laws require that there be a collection site in every county and in every city over 10,000 people. In Washington, 92% of residents have a collection site located within 10 miles of their home.

In Minnesota, manufacturers have specific collection goals based on how much they sold in the previous year. If the manufacturer collects less than their goal, they must pay a price for each pound they fall short.

2. States with high collection volumes have laws covering collection costs, encouraging a variety of collector types, including government, private, and non-profit.

Both Washington and Oregon require manufactures to cover the costs of collecting and recycling e-waste.

3. Landfill bans boost recycling levels.

The collection of e-waste in Maine doubled following the implementation of the landfill ban, from approximately 1.29 million pounds in the six months prior to the landfill ban to 2.87 million pounds in the six months after the landfill ban took effect.

E-waste recycling stakeholders at national, regional, and local levels can learn from these lessons and use them to enhance the effectiveness of their recycling programs.

4.0 ELECTRONIC WASTE CERTIFICATION STANDARDS AND E-WASTE RECYCLING INITIATIVES IN THE U.S.

With a growing number of options for recycling e-waste, it is important to have a rating system established to ensure the proper disposal of e-waste. Currently there are two voluntary electronic waste certification standards that are accredited by the American National Standards Institute (ANSI) American Society for Quality (ASQ) National Accreditation Board (ANAB); Responsible Recycling (R2) Practices Standard, and e-Stewards Standards.

4.1 E-Stewards Certification

The e-Stewards Initiative is a project of the Basel Action Network (BAN), a 501(c)3 charitable organization which focuses on "confronting the global environmental injustice and economic inefficiency of toxic trade (toxic wastes, products and technologies) and its devastating impacts" (Basel Action Network). The e-Stewards Initiative, works to ensure that exports of hazardous electronic waste to developing countries are eliminated, and supports greener legislation and producer responsibility. The e-Stewards Initiative has not only exposed the electronic waste toxic trade issue to the world, but it has also developed market-based solutions for responsibly recycling electronics.

The e-Stewards Pledge program was launched in 2003, which certified 40 e-recyclers with 100 locations across the U.S. who pledge to only use globally responsible means and best practices to process e-waste. These certified e-recyclers are not allowed to dispose of electronics in landfills or incinerators, export e-waste, or use cheap labor to process waste. In 2006 this program was transitioned into an independently audited certification program in order to participate in the U.S. EPA-funded R2 multi-stakeholder process to create a voluntary U.S. e-recycling standard. However, many stakeholders did not agree with aspects of the R2 standard and in 2008 the e-Stewards Certification for electronics recyclers was initiated in order to provide a rigorous, internationally compliant certification program. Today, several Fortune 500 companies commit to using e-Stewards Recyclers including Bank of America, Samsung, Wells Fargo and LG.

4.2 Responsible Recycling (R2) Practices Standards

The R2 Standard is a voluntary electronic waste certification standard that aims to create a market-based mechanism for ensuring responsible recycling of electronics. One of the major differences between e-Stewards and R2, is with respect to import laws in developing countries. R2 allows for the export of toxic e-waste to developing countries, among other allowances. R2 also supports the use of municipal landfills and incinerators for e-waste, and the use of prison labor for processing e-waste.

4.3 StEP Initiative

The Solving the E-waste Problem (StEP) Initiative, was launched by the United Nations University (UNU) in 2007 and today has more than 60 members consisting of companies, academia, and governmental and non-governmental organizations. There are five Task Forces of StEP; Policy, ReDesign, ReUse, ReCycle and Capacity Building. All of these Task Forces focus on globally accepted practices, principles and standards.

4.4 EPA's Plug-In to eCycling

The EPA is currently supporting a number of initiatives in order to increase the national recycling rate by 35%, one of its goals for encouraging the reuse, recycling and purchasing of greener electronics. These initiatives, including the Plug-In to eCycling Campaign and the Federal Electronics Challenge, aim to spread the word about opportunities to reuse and recycle old electronics, as well as work with stakeholders such as electronics manufacturers, retailers and agencies to reduce the environmental footprint of electronics during all life cycle stages.

4.5 Consumer Electronic Association's eCycling Leadership Initiative

The Consumer Electronic Association's eCycling Leadership Initiative, which was announced in April of 2011, is a national initiative which aims to recycle one billion pounds of electronics annually by 2016, up from the approximately 300 million pounds of electronics recycled by consumer electronics manufacturers and retailers in 2010. ELI seeks to increase awareness of industry sponsored collection sites, increase the amount of electronics recycled responsibly, and provide transparent metrics on eCycling's efforts. Customers participating in ELI recycled 460 million pounds of electronics in 2011, an increase of 53% over 2010 volumes.

5.0 RECOVERING METALS FROM E-WASTE

As noted earlier, electronics contain up to 60 different elements, many of which are valuable, such as precious and special metals, and some of which are hazardous. Electronics consist of the following elements:

- Precious Metals: Gold (Au), Silver (Ag), Palladium (Pd)
- Base and Special Metals: Copper (Cu), Aluminum (Al), Nickel (Ni), Zinc (Zn), Iron (Fe), etc.
- Toxic/Hazardous Metals: Mercury (Hg), Beryllium (Be), Cadmium (Cd), etc.
- Halogens: Bromine (Br), Chlorine (Cl), etc.
- Organics, including plastics
- Glass and ceramic

The major economic driver for recycling e-waste is from the recovery of precious metals due to the value of precious metals in electronics; precious metals make up more than 70% of the value of cell phones, calculators, and printed circuit board scraps, and 40% of TV boards and DVD players (J. Cui and L. Zhang). Precious metals are widely used in electronics due to their high chemical stability and conducting properties, making them a valuable contact material. Platinum group members are used in relays and switches or as sensors (J. Cui and L. Zhang). Other metals which drive recycling include copper and zinc.

The following materials can be ranked based on their relative value:

- High Value: circuit boards from mainframes, mobile phones, capacitors
- Medium Value: PC-boards, laptop-and handheld-computer circuit boards
- Low Value: TV-boards, monitor boards, printer boards, cordless phones, calculators, shredded bulk material after aluminum/iron separation

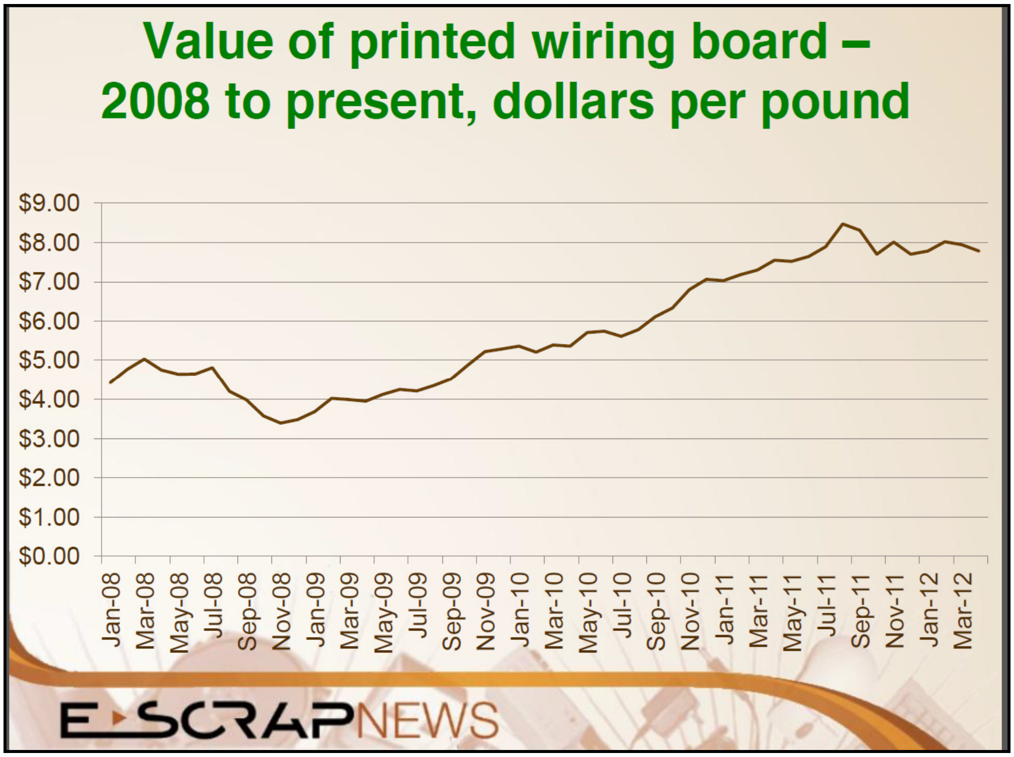
Table 5. Value of Metals in Electronics

Electronic	Copper	Silver	Gold	Palladium
TV Board	50%	7%	22%	7%
PC Board	18%	5%	61%	15%
Mobile Phone	9%	13%	64%	14%
DVD-player	42%	5%	32%	5%

Source: Umicore Precious Metals Refining. Metals Recovery from e-scrap in a global environment. Geneva, September 7 2007. http://archive.basel.int/industry/sideevent030907/umicore.pdf

The volume of precious metals in printed wiring boards (PWBs) varies from televisions, computers, DVD players, calculators, etc., but it has been found that PWBs from personal computers and mobile phones contain the highest volume of valuable metals. It should be noted that PWBs may contain hazardous components such as relays, switches, and batteries which must be manually removed prior to any processing. As can be seen in Figure 3 below, the value of PWBs has almost doubled between 2008 and 2012.

Figure 3. Value of Printed Wiring Boards



Source: www.resource-recycling.com

5.1 Urban Mining

Urban mining describes the process of reclaiming valuable components from existing products, buildings and waste. Urban mining is a growing trend that has resulted in new job opportunities and environmental and economic benefits from the reclamation of components through recycling as opposed to primary non-renewable resources. Primary production of metals (e.g. mining, concentration, smelting, refining) has a significant environmental impact, especially for precious and special metals, because of the low concentration of these metals in the ores.

Reclaiming materials from e-scrap is more profitable than processing concentrates largely due to the savings in energy associated with e-scrap recycling. According to Boliden, extracting metals from e-scrap requires only 10-15% of the energy required in smelting and refining concentrates (CRU).

Table 6. Urban Mining Potential

Metal	Primary Mining	Urban Mining
Gold[(1)]	5 grams/ton in ore	200-250 grams/ton in PC PWBs 300-350 grams/ton in cell phones
Copper	4,500 – 9,100 grams/ton in ore[(2)]	112,500 – 131,250 grams/ton in cell phones[(3)]

Notes:
(1) Umicore. *"Technology" metals scarcity and Umicore's offering*. Second Quarter 2011. Presentation.
(2) Copper concentration in ore range from 0.5 to 1.0%. Source: http://www.epa.gov/rpdweb00/tenorm/copper.html.
(3) Based on the fact that one million cell phones can recover 9,000 kg of copper.

According to the EPA, one metric ton of circuit boards can contain 40 to 800 times the amount of gold, and 30 to 40 times the amount of copper mined from one metric ton of ore in the U.S. While the amount of precious and special metals used in a cell phone is very small, the total amount of metals contained in the nearly one billion cell phones sold globally is significant. The combined 2007 unit sales of mobile phone and personal computers added up to 3% of the world mine supply of gold and silver, 13% of palladium and 15% of cobalt (StEP, 2009)

Investments are being made to treat e-scrap and reclaim the valuable metals, especially as raw materials are becoming more scarce and expensive. Copper produced from primary production methods involves many processes including crushing, grinding, roasting, smelting and refining, in order to produce one ton of copper from over 200 tons of copper ore. It is estimated that approximately 80% of the energy required to produce copper from mined sources is related to the mining and milling processes, due to the need for energy intensive steps like ore hauling, crushing and grinding (Harper et al.). Since recycled copper avoids the energy-intensive stages of the copper production process and has a much higher copper content than copper ore, it is advantageous to recycle copper. Recycled copper constitutes 13-19% of the annual global copper consumption; therefore, it is imperative that copper be recycled as much as possible (Harper et al.). One of the biggest advantages to recycling metals is that they can be recycled an infinite number of times without any loss in quality.

5.2 Pre-Processing

As discussed in Section 1.2, the level of mechanical pre-processing directly affects how e-waste is treated in end-processing, as well as the concentration of metals that can be recovered. It is often beneficial to remove components with high precious metal value prior to pre-processing. Highly complex devices and components, such as circuit boards, cell phones and other small high grade devices, should be removed from the e-waste stream prior to mechanical processing. When circuit boards are not manually dismantled and are shredded, precious metals mix with other fractions, such as glass or aluminum. Shredding or grinding of high-grade e-waste can result in the loss of up to 40% of precious metals, as well as the formation of dangerous dusts and dioxins (Jiang et al.).

As can be seen in Table 7 below, the metal composition of recycled cell phone components depending on the pre-treatment process employed.

Table 7. Metal Composition of Recycled Cell Phone Components

Electronic	Copper (%)	Silver (grams/metric ton)	Gold (grams/metric ton)	Palladium (grams/metric ton)
Cell Phone Handset	12.8%	3630	347	151
Shredded Mobile Phones	13.4%	2273	354	113
Cell Phone Circuit Boards	25.1%	5541	982	287

Source: Umicore Precious Metals Refining. Metals Recovery from e-scrap in a global environment. Geneva, September 7, 2007. http://archive.basel.int/industry/sideevent030907/umicore.pdf

5.3 Extractive Metallurgy

Copper is the most widely used metal in electronics due to its high electrical conductivity. Metals are often added to copper in order to change the strength, hardness, and/or resistance to corrosion. Copper alloys are metals that have copper as their main component (Copper Development Association (CDA)). The following is a list of the primary types of copper alloys:

(1) Bronzes: Copper alloyed with tin, aluminum or silicon
(2) Brass: Copper alloyed with zinc
(3) Precious Metal Alloys: Copper alloyed with silver, gold, palladium, etc.

Many metals dissolve in copper, including gold, silver, platinum, palladium, selenium and tellurium; therefore recovering metals from electronic waste focuses on smelting them to recover impure copper and then electrorefining the copper into pure copper and all other metals. There are two main processes to recycle e-waste, pyrometallurgy and hydrometallurgy, with pyrometallurgy serving as the primary method. Pyrometallurgy uses high temperatures for melting e-waste into impure copper that contains all other metals. Hydrometallurgy is a low temperature method that uses aqueous chemistry for the recovery of metals. In the past decade, attention has turned from traditional pyrometallurgical processing to hydrometallugical processing (J. Cui and L. Zhang).

5.3.1 Pyrometallurgical Processing

Pyrometallurgical processing consists of melting electronic waste in a high temperature furnace, and is the most common process used for metal recovery from WEEE. This process is called "smelting" and is used to recover the copper content of electronic scrap plus any other "noble" metals that on melting dissolve in copper, such as silver, gold, platinum, and palladium. Iron and aluminum are not recovered in the copper smelting process, and instead are oxidized to slag.

Electronic waste can be processed in small furnaces. However, the most common industrial process is to co-process them with copper sulphide concentrates in large copper smelting furnaces, such as copper converters, anode copper furnaces, and copper smelting and converting furnaces such as the Noranda Process.

There are four global leaders in recovering metal values from e-waste by means of smelting and refining: Boliden, Xstrata Copper (formerly Noranda), Aurubis and Umicore. Global e-waste is primarily sent to four integrated smelters/refineries worldwide that process e-waste and recover precious metals (*info*Dev). Three of these are located in Europe – Belgium, Germany and Sweden – and one in Quebec in Canada. Moderately sized e-scrap smelters are also located in Japan and South Korea. The U.S does not have any treatment capacity despite being the largest producer of e-waste in the world.

The need for e-waste recycling and processing capacity is widely recognized by the global leaders in smelting. In January 2008, Xstrata Copper announced plans to double electronic scrap recycling capacity at its Horne smelter, providing the smelter with the capacity to receive and process 100,000 metric per year. In April of 2010, Boliden announced that it would be investing SEK 1.3 billion ($202 million U.S. dollars) in order to triple its electronic scrap recycling capacity its Ronnskar smelter from 45,000 to 120,000 metric tons per year. This expansion will allow for 2.7 million metric tons of e-waste to be recycled, and increase e-scrap's share of Ronnskar's raw material feeds from 6% to 14% (Boliden, 2010). The capacity of the major global smelters can be seen in Table 8 below.

Table 8. Capacity of Major Global Smelters

Company/Smelter	2008 Electronic Scrap Recycling Capacity (metric tons)	2012 Electronic Scrap Recycling Capacity (metric tons)	2012 Original Volume of Electronics to be recycled based on capacity of smelter (metric tons)[5]
Boliden's Ronnskar Smelter *(Skelleftehamn, Sweden)*[1]	45,000	120,000	2,700,000
Xstrata Copper's Horne Smelter *(Quebec, Canada)* [2]	50,000	100,000	2,250,000
Aurubis's Elektro-Recycling NORD GmbH Smelter *(Hamburg, Germany)*[3]	N/A	60,000	1,350,000
Umicore *(Hoboken, Belgium)*[4]	27,000	40,000	900,000
Total	**142,000**	**290,000**	**6,525,000**

Notes:
(1) Source: http://www.boliden.com/Documents/Press/Publications/Broschures/Atervinning_Ronnskar_eng.pdf
(2) Source: www.xstrata.com
(3) Source: http://online.wsj.com/article/SB10001424052970204301404577172803991997364.html
(4) Source: Umicore. *"Technology" metals scarcity and Umicore's offering.* Second Quarter 2011. Presentation
(5) A conversion factor was calculated based on 120,000 metric tons of electronic scrap will have initially comprised 2.7 million metric tons of electrical and electronic waste (source: http://partner.boliden.com/www/en/bolidenen.nsf/40a8f8235c678d63c1256f5d003b5671/5b8e7ef2866a27c3c1257711002b7043?OpenDocument). Using this conversation factor, the 2012 volume of original electronics to be recycled was computed for the major worldwide smelters.

5.3.1.1 General Process

The general process followed at the global smelters is as follows[12]:

Sorting/Dismantling:

1. *Removal of Hazardous Components.* Hazardous components, such as batteries, cathode ray tubes and mercury bulbs, are removed at designated sorting stations. At Xstrata's Horne smelter, cathode ray tubes are completely recycled; the plastic tube is sent to a smelter, the glass is re-used at the facility as a fluxing agent, and the lead is recovered.
2. *Particle Size Reduction.* Once the electronics have been removed of their hazardous components, they are shredded into scrap metals and fines. The shredded material is then further separated using vibratory conveyors, shaker tables, cross-belt magnets, eddy current and sand flow units, among other density and/or magnetic separation methods.

   Dusts are generated during pre-treatment processes and are collected in filter and bag-house systems. These dusts can have high precious metals content but also contain significant amounts of pollutants and high burn-loss components like plastics, paper and wood. The dusts can be sent to the smelting process for recovery of precious metals.

   It is common for high-grade e-waste not to go through mechanical shredding processes. At Umicore, shredding of mobile phones and computer circuit boards is not performed and devices are instead sent directly to integrated smelters. Shredding of high grade e-waste is not performed due to:

   - The creation of precious metal containing dust.
   - Significant losses of metals and components in side steams that cannot be recovered (such as plastic, aluminum, and iron).
   - The economic value of precious metals far exceeds the value of base metals, such as iron and aluminum. It is not worth losing precious metals to recover base metals.
   - Savings in time and money spent on pre-treatment.
3. *Sample Assay.* E-scrap is sampled in order to assess copper and precious metals content.

Separated materials are then sent to the smelter.

[12] This general process was devised by comparing processing methods at Xstrata Copper, Boliden, and Umicore Precious Metals Refining. Please refer to Appendix A for a detailed explanation of processes at Xstrata Copper's Horne Smelter, Boliden's Ronnskar Smelter, and Umicore's Hoboken Smelter.

End-Processing:

1. *Smelting Stage.* Shredded e-scrap is sent to an integrated smelter. A solution of copper and iron sulfide is produced ("matte") while iron and other oxides form a silicate solution called "slag". The precious metals are contained within the matte, which goes to the converting stage. The slag is treated separately through the use of a lead blast furnace, lead refinery and special metals plant.

   It is important to note that high grade e-waste can be sent directly to the convertor and does not need to go through the smelting process.
2. *Converting Stage.* The smelting stage is followed by a "converting" stage where matte is converted to impure copper, called "blister" copper.
3. *Anode Furnace.* Liquid blister copper is then refined in the anode furnaces. The blister copper is cast into anodes that are then electrorefined to pure copper.
4. *Electrorefining.* During this process, copper anodes are refined to produce pure copper cathodes and precious metals such as silver, gold, selenium and tellurium settle as precipitates at the bottom of the electrorefining cell.
5. *Precious Metals Refinery.* The precious metal residue is then melted, casted and refined to produce precious metal bullion.

Plastic components of e-waste cannot easily be recycled due to the mix of flame retardants, pigments and mixed types of plastics. However, smelting processes are able to use the energy content of the plastics. Energy usage is reduced due to the combustion of plastics and other flammable materials in the e-waste feed, which partially substitute the coke needed as a reducing agent and energy source.

Although pyrometallurgical treatment is the most common method for recovering valuable metals from e-waste, there are some disadvantages:

- Smelting cannot recover certain product components, such as chips or bare fiberglass boards.
- Smelting cannot recover aluminum and iron since they are oxidized and transferred in the slag.

- Smelting flame retardants and polyvinyl chloride (PVC) present in e-waste leads to the formation of dioxins, requiring special emission controls.
- Pyrometallurgical processing cannot fully separate all metals, and therefore hydrometallurgical processing methods must be used subsequently.

5.3.2 Hydrometallurgical Processing

Hydrometallurgy processing of e-waste has become more popular in the last two decades, due to the fact that hydrometallurgical methods are more exact, predictable and more easily controlled than pyrometallurgical methods (J. Cui and L. Zhang). Hydrometallurgy can be broken down into three general areas; leaching, solution concentration and purification, and metal recovery. The general process is as follows:

1. *Mechanical Treatment.* Prior to chemical treatment, mechanical processing is often necessary in order to convert waste material into a granular form.
2. *Leaching*. E-waste goes through a series of acid or caustic leaches, which is a process whereby a soluble component is extracted from a solid by means of a solvent. The most efficient leaching agents are acids, due to their ability to leach both base and precious metals (Kamberovic et al., 2009). Cyanide, halide, thiourea and thiosulfate are the most popular leaching agents (J. Cui and L. Zhang). The following agents are used to leach specific metals:

Table 9. Leaching Agents used in Hydrometallurgical Processing

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

3. *Separation and Purification*. The leachate solutions then go through separation and purification processes in order to concentrate the valuable metals and separate impurities.
4. *Precious Metals Recovery*. Recovering precious metals from leachate can be done via electrorefining processes, chemical reduction or crystallization.

Cyanide, aqua regia, thiourea and thiosulfate leaching solutions are corrosive and/or toxic solutions and therefore require that special equipment be used to resist the highly caustic conditions. While cyanide is the most economically feasible of common leaching methods, it is also the highest in terms of toxicity. Once the leaching process is completed, the toxic by-products, including the spent leaching solution, must be properly treated and disposed of. Spent aqua regia cannot be recycled; while cyanide can be recycled but it is extremely costly to do so.

Previous studies focused on the optimal leaching parameters for recovering precious metals have found that the effectiveness of hydrometallurgical processing is dependent on a number of factors including pouring density, percentage of magnetic fraction, particle size distribution, leachability rate, temperature, time, solid:liquid ratio, and mixing velocity. This paper will not address the results of these studies, however the reader should acknowledge that changes in these factors can dramatically increase the percentage of metals recovered.

One study that will be mentioned was performed by Kamberovic et al. (2011) and supported by the European project "Innovative Hydrometallurgical Processes to recover Metals from WEEE including lamp and batteries – HydroWEEE", looked at the economic feasibility of investing in a small, mobile hydrometallurgical processing pilot plant. The study found the following sulfuric acid and thiourea leaching process to be economically beneficial for an amount of gold exceeding 500 ppm:

(1) Copper is extracted from the granulated waste material using a leaching agent (sulfuric acid).
(2) Copper is treated via electrowinning in order to extract copper from the leaching solution.

(3) The solid residue from copper leaching is treated by thoireau in the presence of a ferric ion as an oxidant in sulfuric acid solution, in order to extract gold.

Results of the study also show that the payback time is approximately seven years, depending on two different amounts of input waste material. A notable finding of the study was that the most important factor in determining economic feasibility was the quantity of gold present in the waste material.

Studies have also focused on other leaching agents besides cyanide and aqua regia, which are the two most popular. A critical comparison of the economic feasibility and environmental impact of various leaching methods found that leaching of gold by thiourea may be the most realistic substitute for cyanide, and could achieve gold recovery of up to 99% (J. Cui and L. Zhang).

New developments in this field have focused on the use of leaching solutions which do not contain acids or cyanide in order to recover precious metals. This will be further described in the following section.

5.3.2.1 Advanced Technology Materials Incorporated, Inc.

Currently the smelting and refining industry dominates e-waste recycling and hydrometallurgical processing of e-waste is just emerging as a potential domestic solution for treating e-waste. Advanced Technology Materials Incorporated (ATMI) has developed a selective chemical process which recovers valuable materials from obsolete populated circuit boards/printed wiring boards (PWBs) using green chemistry and green engineering. ATMI's mission is *"to provide an economically feasible, environmentally responsible and safe process for recovering the highest value from printed wire boards and integrated circuits."* ATMI first presented the chemical-based system, known as eVOLV^{TM}, to the public as a revolutionary solution for recycling e-waste at the e-waste Management Summit in November 2012. The closed-loop was developed as a domestic solution for the recovery of precious metals and components from PWBs, which is environmentally safe, cost-effective, fully automated and scalable. According to ATMI, the process results in a 99% metals recovery and 99% purity.

As is described in Section 5.2, when circuit boards are not manually dismantled and are shredded, precious metals mix with other fractions, such as glass or aluminum. Shredding and grinding can result in the loss of up to 40% of precious metals. ATMI's process does not include shredding of PWBs thereby reducing the loss of precious metals from shredding, and no smelting is involved.

The following table displays the components of PWBs as a percentage of PWBs by weight.

Table 10. Component Percentages of Printed Wiring Boards by Weight

Component	**Percentage of PWB by weight (%)**
Fiberglass	45% - 50%
Copper	15% - 20%
Components/Integrated Circuits	10% - 25%
Precious Metals	0.4%
Lead, tin & other base metals	Remainder

ATMI's technology recovers all valuable components from PWBs using the following process methods:

Table 11. Processing Methods for Reclamation of Valuable Components

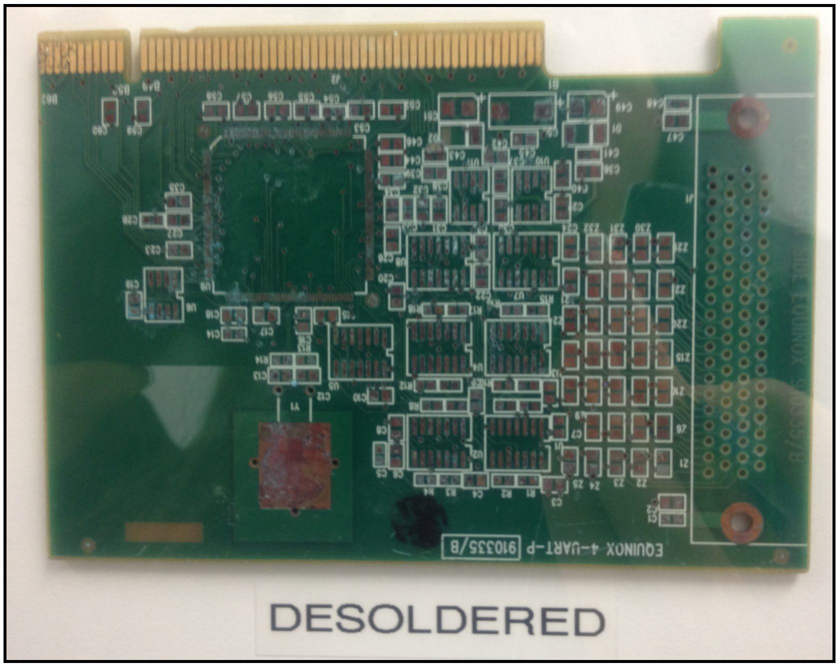
Component	**Processing Method**
Chips	Reclaimed during desoldering process. Operational chips can be sold for re-use; or precious metals, including gold, silver and palladium, can be extracted from the chips.
Solder	Reclaimed during desoldering process.
Gold	Reclaimed during gold leaching process and melted into gold bars.
Bare Fiberglass Boards	Remain at the end of the process. Can either be sold and smelted to reclaim copper; or chopped and used as filler in various applications.

Below is a brief overview of the process steps:

(1) **Pre-sorting**. Intact PWBs are sent to ATMI's pilot plant. There is no shredding, grinding or burning of PWBs.

(2) **Desolder**. PWBs cycle through the desoldering process, which takes anywhere from 5 to 20 minutes at 35 to 40 degrees Celsius. The selectivity of the desoldering chemistry allows copper, gold, and base metals to be left on the board, while the desoldered chips disengage from the PWB and are collected in a bin.

Figure 4. Desoldered Printed Wiring Board



Source: Photo taken by Jennifer Namias on January 29, 2013 during a visit to ATMI's eVolv Pilot Plant in Danbury, Connecticut.

(3) **Gold Leaching**. Desoldered PWBs then go through the gold leaching process, which takes 5 to 10 minutes at less than 30 degrees Celsius. Once the chemistry is saturated with gold, it is pumped to an electroplating tool which extracts the gold from the chemistry. Gold is plated onto a carbon cathode, and then removed from the carbon cathode and melted down into bars. The outputs of this process are bare fiberglass boards, and gold bars.

Figure 5. Desoldered and Gold Leached Printed Wiring Board

Source: Photo taken by Jennifer Namias on January 29, 2013 during a visit to ATMI's eVolv Pilot Plant in Danbury, Connecticut.

ATMI is currently using the eVOLV™ system to process PWBs at a pilot plant in its Danbury, Connecticut headquarters. The pilot plant processes approximately 200 pounds of PWBs per hour, with a capacity of 400 pounds per hour. The process is fully automated and includes a conveyor system to move boards through its chemical process. The only waste generated during the process is approximately 200 gallons of treated wastewater on a weekly basis. No solid waste is generated as a result of the eVOLV process. The gold leaching process is performed for approximately five hours per day, three days per week. Approximately 40 ounces of gold can be leached in two weeks, valued at approximately $79,000[13].

ATMI's license model is structured such that the specifics of the chemistry are never disclosed. ATMI supplies the licensees with the chemistries, as well as ATMI personnel to run the processes. By supplying ATMI personnel, ATMI is able to guarantee system efficiencies and ensure that technology remains undisclosed. ATMI received a royalty based on the percentage of components recovered.

[13] Based on gold price of $1572.33 /troy ounce. One troy ounce is approximately 1.09714 avoirdupois ounces.

The first two commercial plants utilizing eVOLV technology are scheduled to open in the Summer of 2013. ATMI is also launching 2 eVOLV pilot programs in the Summer of 2013; recovering valuable metals from chips, and recovering valuable components from cell phone PWBs. There are approximately 30 to 50 pounds of chips in 100 pounds of RAMs and therefore the recovery of chips is an important component of the e-waste recycling process. Cell phone PWBs are different than all other PWBs because they are enclosed in a steel casing for Wi-Fi connectivity purposes. Therefore, the eVOLV process must be refined to recover valuable components from cell phone PWBs.

5.3.3 Biometallurgical Processing

Biometallurgy for the recovery of valuable components from e-waste has been gaining popularity over the years. Biometallurgy is built on the concept that microbes interact and depend on metals to carry out their cellular functions. Interactions between bacteria and metals include sorption, reduction, oxidation, and sulfide precipitation. There are two main methods of biometallurgy to remove metals: bioleaching and biosorption. Bioleaching has traditionally been used in industrial applications in order to leach metal concentrate from ores, most notably gold and copper. Currently, research and development are in progress for bioleaching of copper, nickel, cobalt, zinc, gold and silver. However, the complete recovery of gold and silver has not yet been achieved.

Biosorption uses algae, bacteria, yeasts and fungi to accumulate heavy and precious metals. These microbes are used as adsorbents for precious metal biosorption, through a complex process involving a physical or chemical adsorption of metals onto the cell walls or cell associated materials. Suitable bacteria for biosorption have the following properties: high specific surface area (100 m^2/g), high affinity for metals, and metal speciation. Adsorption capacities vary depending on the types of biomass, ranging from 0.003 to 40 mmol/gram (J. Cui and L. Zhang). Biosorption can be made further effective by the addition of metal-sorbing agents such as chitosan. Current studies are focused on finding the most effective organisms for the bioleaching process.

Biometallurgical processing of e-waste has a number of benefits over traditional methods, including low operating costs, minimization of the volume of chemical and/or biological sludge to be handled and high efficiency in detoxifying effluents (Kamberovic et al., 2011).

6.0 RECOMMENDATIONS

The following section discusses the major obstacles to e-waste recycling in the U.S., as well as recommendations for implementing effective recycling programs.

Obstacle #1: Inadequate Regulatory Environment.

One of the main drivers for the creation of recycling technology and markets are regulatory factors. Currently, the U.S. does not have in place a Federal directive for e-waste recycling, largely because there is no national consensus on recycling[14]. Lack of national regulation has been shown to significantly affect e-waste recycling efforts in other nations. For example, an e-waste pilot project in China showed that the lack of a formal collection system and national regulation of WEEE, can cause a technology transfer project with significant subsidies to fail (StEP, 2009).

Recommendation #1: The U.S. must devise a national approach to e-waste recycling.

A national approach is necessary in order to manage e-waste efficiently, economically and safely. Federal regulation will provide the necessary structure and framework by setting mandatory recycling targets and establishing the implementation of financing and enforcement mechanisms for e-waste collection and recycling. Federal regulation will act as a primary driver of improved recycling/recovery rates in the U.S., and incentivize capacity building in the recycling sector.

Policy and legal framework define roles and responsibilities among e-waste stakeholders, establish enforcement mechanisms and procedures, and increase public awareness. Once regulations are implemented, recycling methods and procedures can be established, and financial incentives will be developed to assist with implementation of recycling policies.

---

[14] Note: there are Federal Regulatory Requirements for the disposal of CRTs and other electronics that contain hazardous or toxic components.

Obstacle #2: Low collection rates.

Consumer's lack of awareness or willingness about how to handle obsolete electronics, combined with the lack of collection facilities, have resulted in a low domestic e-waste recycling rate.

Recommendation #2: Increase collection efforts.

(a) Increase ease of collection and public awareness of the need to recycle e-waste.
Increasing the ease for consumers to bring their electronics to collection points, through paid-postage mail in services and retail collection points, will contribute to collection growth rates.

A notable new model for e-waste collection convenience is ecoATM, the first and only company to create an automated self-serve kiosk that uses patented, advanced machine vision, electronic diagnostics and artificial intelligence to evaluate and buy back used cell phones and MP3 players directly from consumers for cash or store credit. By visiting ecoATM's website (www.ecoATM.com), it is possible to find the ecoATM closest to your location. ecoATM has 300 machines in 20 states which buy back used, new or broken electronics and pay customers on the spot. Through ecoATM's services, approximately 25% of the phones are smelted down for gold, platinum and palladium, and 75% are refurbished.

The concept behind ecoATM has proven to be very successful. In February 2013, ecoATM announced plans to install an additional 600 to 700 kiosks by the end of the year. Providing consumer's access to convenient recycling solutions, such as ecoATM, will significantly increase e-waste collection rates.

(b) Increase public awareness.
As consumers, we must learn to balance technological innovation with responsible end-of-life management. In order to increase participation in e-waste collection and recycling programs, the public must be aware of the options for recycling e-waste. Given the varying degree of State regulations, number of collector types, and types of collection systems, it is important that the

public is informed about the correct process to be followed when recycling e-waste. Educational tools should be developed to increase public awareness about e-waste recycling. Consumers will be more inclined to participate in e-waste recycling if they are knowledgeable about the health and environmental risks of sending e-waste to developing nations for end-processing, and the environmental and financial benefits of processing options.

Obstacle #3: Lack of Processing Infrastructure and High Capital Costs.

Responsible recycling of e-waste is costly due to the number of steps involved, many of which must be done manually. The United States does not have any integrated smelters, nor does it have any large-scale systems for recovering precious metals for e-waste. All of the e-waste generated in the U.S. is sent to smelters in Europe for metal recovery. Traditional automated recycling processes are capital intensive systems which require significant financial incentives, regulatory support, formal recycling infrastructure and a skilled workforce (Reinhard and Fisher, 2009). Therefore, it is not financially feasible or practical to build these types of systems in every country.

Recommendation #3: Research, develop and build domestic end-processing capacity for e-waste.

A domestic solution will minimize costs and environmental impacts associated with manufacturing primary products, eliminate the need to ship e-waste overseas, and will contribute to job growth in the U.S. As is aptly pointed out in many research reports, just because a system appears to be successful in one country, does not necessarily mean it will be successful in another country. The U.S. must find an effective solution given the cultural, social, and political context through which the processing system will exist.

(a) Further explore non-toxic hydrometallurgical processing methods.

Given that the U.S. is the largest producer of electronic waste and does not have any refining capacity, could hydrometallurgical processing be the answer for the U.S.? There are many advantages of treating e-waste domestically via hydrometallurgical methods, such as the green technology used by ATMI, over pyrometallurgical treatment of electronic waste overseas. Advantages include:

(1) Cost-effectiveness: Smelters require high capital investments. Non-toxic hydrometallurgical processes can be established in small plants.
(2) Domestic solution: Non-toxic hydrometallurgical treatment methods can be used in the U.S., which eliminates the need to ship waste overseas.
(3) Value of e-waste: Shredding and grinding techniques do not need to be used which reduces the loss of precious metals. In addition, recyclers can be paid based on the actual content of the e-waste, rather than a sample assay. This is possible because the e-waste is not mixed with other scrap metals and components to be refined, and therefore the exact value of the e-waste can be determined after recovery.
(4) Non-toxic hydrometallurgical treatment does not require burning, or generate toxic fumes or toxic fluid discharge associated with pyrometallurgical treatment.

Biometallurgical methods for the recovery of metals from e-waste should also continue to be researched and developed. However, currently hydrometallurgical processing is further developed and better suited for immediate implementation.

(b) Foster a competitive market.

Given the free market culture in the U.S., in order for an end-of-life management system to be successful, it must be a market-driven solution that enables competition (Kahhat et al.). Kahhat et al. have proposed a deposit-refund system as a domestic solution for e-waste recycling in the U.S., and lists the following three characteristics of the system:

(1) collects revenue to ensure proper recycling;
(2) provides a financial incentive for consumers to turn in their equipment; and
(3) creates a competitive market in which firms compete to offer more efficient reuse and waste management services.

Currently, e-waste is processed primarily by major global players due to the huge infrastructure framework that is needed to guarantee a steady supply of e-waste. In order to incentivize investment in e-waste recycling infrastructure and technology in the United States, investors must be assured that there will be long-term access to sufficient volumes of quality material feed. Federal regulation will enable a competitive market by promoting collection, reuse and recycling of e-waste. This is turn will spur investment in e-waste recycling infrastructure and technology in the United States.

Currently we are exporting recycling and repair jobs that could be held by workers in the U.S. Developing a domestic solution to e-waste recycling will eliminate the need to ship waste overseas, and create U.S. jobs. It is estimated that for every job exporting waste products, seven jobs can be created in the U.S. recycling industry (E-cycle Environmental).

(c) Design recycling systems to be flexible and resilient in order to handle the increasing complexity and range of feed materials.

Over the years there has been a linear trend for PC's, TV's and refrigerators, while mobile phones have shown exponential growth, and there is a trend towards new, small, inexpensive IT items such as iPad and tablets (StEP, 2009). Successful recycling systems must be able to adapt to the evolving electronic types and material compositions. As electronics become more complex, it often becomes more difficult to separate materials from one another. New polymers used in electronics, such as graphane, will pose new issues moving forward.

7.0 CONCLUSION

Despite the many reasons to recycle e-waste, U.S. recycling and recovery of e-waste is limited due to: (1) insufficient collection (2) no Federal legislation or policy mandating e-waste recycling (3) lack of recycling and recovery technologies and (4) illegal exports of hazardous e-waste to developing countries where recycling processes pose serious risks to human and environmental health.

In order to increase the e-waste recycling rate in the U.S., Federal regulation is needed in order to provide a cohesive approach to e-waste recycling. Federal regulation will provide the necessary structure and framework by setting mandatory recycling targets and establishing the implementation of financing and enforcement mechanisms for e-waste collection and recycling. However, EPA is generally reluctant to tell State authorities how to manage their solid wastes. Local and regional authorities should focus on the increased collection of e-waste through efforts geared towards convenience of collection and increased public awareness. Increasing the ease with which consumers can bring electronics to collection points through paid-postage mail in service and retail collection points, will contribute to collection growth rates.

National agendas should be geared towards capacity building in the e-waste recycling sector. Promising end-processing methods, such as non-toxic hydrometallurgical processing methods, should be implemented as a domestic solution to e-waste recycling in the U.S. In addition, global efforts should be geared towards increasing the e-waste recycling capacity of existing and additional smelters, and streamlining the process for e-waste recyclers.

REFERENCES

Aston, Adam. "How Best Buy makes money recycling America's electronics." *Greenbiz.* 24 April 2012. Web. 23 September 2012.

Best Buy Co., Inc. 2010 Sustainability Report. *Best Buy.* Web. 17 February 2013.

Boliden. Press Release. Boliden expands electronic scrap recycling. Stockholm. April 27, 2010.

Boliden. Interim Report January – June 2011. July 19, 2011.

Chehade, Youssef, A. Siddique, H. Alayan, N. Sadasivam, S. Nusri, and T. Ibrahim. "Recovery of Gold, Silver, Palladium, and Copper from Waste Printed Circuit Boards." *International Conference on Chemical, Civil and Environmental Engineering (ICCEE'2012)* March 24-25, 2012. Dubai. Planetary Scientific Research Center. Web. 2 January 2013.

Copper Development Association (CDA). "Equilibrium Diagrams: Selected Copper Alloy Diagrams Illustrating the Major Types of Phase Transformation." CDA Publication No 94. 1994.Web. 2 April 2012.

Consumer Electronics Association (CEA). "eCycling Leadership Initiative." Web. 10 December 2012.

Consumer Electronics Association (CEA). Market Research Report: Trends in CE Reuse, Recycle and Removal. April 2008. Web. 10 December 2012.

Copper Studies. E-scrap – Urban Riches? *CRU*. January 2011 Vol 38 No 7. Print.

Dorin, R. and R. Woods. "Determination of leaching rates of precious metals by electrochemical techniques." *J Appl. Electrochem.* 21 (5) (1991) 419. Web. 15 May 2012.

E-Cycle Environmental. “Domestic E-waste Recycling: Reduce, Reuse, Create Job Opportunities.” Web. 2 February 2013.

Electronics TakeBack Coaliation. “State Legislation”. Web. 10 December 2012.

Electronics TakeBack Coalition. “Ten Lessons Learned from State E-waste Laws.” Web. 2 February 2013.

Harper, Helen, P. Healey and D. Picard. “50 Years of Recycling Copper and Precious Metals in Canadian Copper Smelters”. Conference of Metallurgists 2011. Print.

Huisman, J. UNU – ISP SCYCLE, STEP ADDRESS Worldwide EEE and WEEE estimates, update 31–01–2011,Bonn Germany.

*info*Dev (The World Bank Group). *Wasting No Opportunity: The case for managing Brazil’s electronic waste.* April 2012. Web. 22 January 2013.

Jiang, Ping, M. Harney, B.Chen, Y. Song, Q. Chen, T. Chen, G. Lazarus, L. Dubois, M. Korzenski (Jiang et al). *Improving the End-of-Life for Electronic Materials via Sustainable Recycling Methods.* Advanced Technology Materials Incorporated, Inc. Print.

Jirang Cui and Lifeng Zhang. Metallurgical Recovery of Metals from Electronic Waste: A Review. *Journal of Hazardous Materials* 158 (2008) 228 – 256. Elsevier. Web. 26 September 2012.

Kahhat, Ramzy, J. Kim, M. Xu, B. Allenby, E. Williams, and P. Zhang (Kahhat et al.). “Exploring e-waste management systems in the United States.” *Resources, Conservation and Recycling* 52 (2008) 955-964. Elsevier. Web. 5 January 2013.

Kamberovic, Zeljko, M. Korac, D. Ivsic, V. Nikolic, and M. Ranitovic (Kamberovic et al., 2009). “Hydrometallurgical Processing for Extraction of Metals from Electronic Waste- Part I:

Material Characterization and Process Option Selection." *Association of Metallurgical Engineers of Serbia.* UDC: 661.061.34:4.043. Accepted December 28, 2009.

Kamberovic, Zeljko, M. Korac, and M. Ranitovic (Kamberovic et al., 2011). "Hydrometallurgical Process for Extraction of Metals from Electronic Waste – Part II: Development of the Processes for the Recovery of Copper from Printed Circuit Boards (PWB)." *Association of Metallurgical Engineers of Serbia.* UDC: 628.477.6. Accepted August 15, 2011.

Noranda Recycling. Fact Sheet Noranda Recycling. June 2005. Print.

Northeast Recycling Council (NERC). "Recycling Economic Information Study Update: Delaware, Maine, Massachusetts, New York, and Pennsylvania." February 2009. Web. 6 June 2012.

Reinhard, Keith and L. Fisher. "E-Waste Recovery and Recycling." *ABI Research*. 2009. Print.

Robinson, Brett. "E-waste: An assessment of global production and environmental impacts." *Science of the Total Environment* 408 (2009) 183-191. Elsevier. Web. 15 May 2012.

Roubein, Rachel and Mike Snider. "As e-waste piles up, disposal issues grow." *USA Today*. 23 June 2011. Web. 02 February 2013.

Shuey, S.A., F.F. Vidal and P.R. Taylor. "Pyrometallurgical Processing of Electronic Waste." *SME Annual Meeting*. March 27-29, 2006. Print.

Shuey, S.A. and P. Taylor. "A Review of Pyrometallurgical Treatment of Electronic Scrap." *SME Annual Meeting*, February 23-25, 2004. Print.

Solving the E-waste Problem (StEP). "Annual Report 2011." *United Nations University/StEP Initiative 2012.* Web. 2 January 2013.

Solving the E-waste Problem (StEP). “Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling From E-Waste To Resources.” *United Nations Environment Programme.* July 2009. Web. 28 December 2011.

Thomas Lindhqvist, "Towards an [EPR]- analysis of experiences and proposals," April 1992. Web. 4 February 2013.

Umicore. “Technology metals scarcity and Umicore’s offering.” *Umicore: Investor Relations*. Presentation. 2011. Web. 4 April 2012.

United States Environmental Protection Agency (USEPA) Office of Resource Conservation and Recovery. “Electronic Waste Management in the United States Through 2009.” EPA 530-R-11-002. May 2011. Web. 28 December 2011.

Unites State Geological Survey (USGS). “Obsolete Computers, “Gold Mine,” or High-Tech Trash? Resource Recovery from Recycling. Web. 4 February 2013.

Wang, Feng, J. Huisman, C. Meskers, M. Schluep, A. Stevels, C. Hageluken (Wang et al). “The Best-of-2 Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies.” *Waste Management* 32 (2012) 2134-2146. Elsevier. Web. 4 February 2013.

APPENDIX A:
PYROMETALLURGICAL PROCESSING AT MAJOR GLOBAL SMELTERS

The Horne Smelter of Xstrata Copper (Noranda, Quebec, Canada)

Xstrata Copper’s Horne Smelter has a capacity of approximately 714,000 metric tons of copper concentrates amd other copper bearing materials per year. The facility accepts the following electronics: computers, peripherals, network hardware, tape drives, disk drives, modems, compact disks (CD), digital video disks (DVD), CD writers, circuit boards, copiers, cellular phones, telephones, typewriters, fax machines, printers, plotters, calculators, etc.

Electronics to be sent to the Horne smelter from the U.S. are sampled at U.S. locations prior to being sent, in order to assess copper and precious metal content. Electronics are brought to the plant from across Canada and the U.S., where they are weighed and a bar code is assigned.

Hazardous electronic components, such as batteries, cathode ray tubes and mercury bulbs, are removed at designated sorting stations. Cathode ray tubes are separated into the plastic tube, the glass component, and lead. The plastic tube is sent to a smelter, the glass is re-used at the facility as a fluxing agent, and the lead is recovered. Batteries and ink cartridges are recycled, and plastics from these hazardous components are used as fuel for the facility.

Once the electronics have been removed of their hazardous components, they are shredded into scrap metals and fines. The shredded material is then further separated using a vibrator conveyor and shaker table. Cross-belt magnets are used to separate fines and steel, and then an eddy current and sand flow unit is employed to separate aluminum from copper and plastics based on density differences. Materials such as scrap and residues are sampled based on the characteristics of each stream.

Separated material is then sent to Xstrata's Horne smelter in Quebec for further processing and metal recovery. The Horne smelter is a continuous primary smelting operation with a daily capacity of approximately 700 short tons of scrap per day. There are three major stages of smelting which occur in the Noranda Process reactor, converters and the anode furnaces. The smelting process oxidizes iron, lead and zinc into a silica-based slag, which is cooled and milled to recover precious metals. The precious metals, which are contained in the copper matte, are transferred from the furnace to the converters. Liquid blister copper is then refined in the anode furnaces, producing A-grade copper anodes of 99.1% copper. The remaining 0.9% contains precious metals such as gold, silver and palladium, along with selenium, tellurium and nickel. These metals are recovered in the subsequent electro-refining process where the impure anode copper is dissolved and deposited on cathode sheets while the impurities contained in the anode are recovered as "copper slimes". The electrolytic refining produces 99.99% pure copper cathodes. Precious metals are separated from the copper slimes collected in the bottom of the electrorefining tank. The residue is melted, casted and refined to produce silver and gold bullion on site. Additional byproducts recovered include platinum, palladium, tellurium, and selenium.

Energy usage in the Noranda reactor is reduced due to the combustion of plastics in the e-waste feedstock.

Boliden's Ronnskar Smelter (Skelleftehamn, Sweden)

Boliden's Ronnskar Smelter is Boliden's largest unit and the world's largest recycler of copper and precious metals from e-scrap. Boliden's expansion of Ronnskar's scrap handling capacity from 45,000 to 120,000 metric tons per year have increased the e-scrap share of Ronnskar's raw material feeds from 6% to 14%. Recycling of e-waste will produce approximately 22,000 metric tons of copper, 80,000 kilograms of silver and 7,500 kilograms of gold (Boliden, 2010). The majority of the e-scrap sent to Ronnskar comes from Europe and North America.

In addition to refining metals from e-waste, the Ronnskar Smelter refines metals from copper scrap, copper/zinc residues, electric arc furnace dust, and lead scrap. The total capacity of the Ronnskar smelter is approximately 857,000 metric tons per year, and Ronnskar has an annual production of more than 200,000 metric tons of copper, 13,000 kg of gold and 400,000 kg of silver.

Low grade e-waste is first fed into the Kaldo Furnace, which produces a mixed copper alloy and dusts. The mixed copper alloy is sent to the convertor for recovery of copper, gold, silver, palladium, nickel, selenium and zinc, while the dusts (Pb, Sb, In and Cd) are sent for further metals recovery. High grade e-waste is sent directly to the convertor and does not need to go through the Kaldo Furnace.

UMICORE (Hoboken, Belgium)

Umicore Precious Metals Refining is one of the world's largest recycler of precious metals from e-waste. Umicore treats approximately 250,000 metric tons annually, with approximately 10% of the feed constituting electronic waste (Umicore). Umicore has an integrated metals smelter and refinery where precious and other non-ferrous metals are recovered from e-waste. The major steps in Umicore's process are collection, dismantling, shredding/pre-processing, and end-processing.

Umicore ranks the following materials based on their relative value:

- High Value: circuit boards from mainframes, mobile phones, ICs, MLCCs
- Medium Value: PC-boards, laptop-and handheld-computer circuit boards, etc.
- Low Value: TV-boards, monitor boards, printer boards, cordless phones, calculators, shredded bulk material after Al-/Fe- separation, etc.

E-waste is first fed into the IsaSmelt furnace, which separates precious metals in a copper bullion from all other metals which are concentrated in a lead slag. The lead slag is treated at the Base Metals Operations (BMO), which involves lead blast furnace, lead refinery and special metals plant. The copper bullion goes through copper-leaching, electrowinning and a precious metals refinery in order to recover copper and precious metals.

Umicore requests that categories of production residues are kept separate in order to facilitate optimum sampling and treatment. In addition, customers are requested to provide information on the quantities and quality of their production scrap and end-of-life streams when requesting a recycling quote.

Printed Circuit Boards are categorized based on their quantity of gold:

- Very high grade: gold content of at least 400 ppm
- High grade: gold content of at least 200 ppm
- Medium grade: gold content of at least 100 ppm
- Low grade: gold content of at least 50 ppm
- Very low grade: gold content of lower than 50 ppm
- Components ranging from ICs to small entire devices (i.e. mobile phones):

Umicore's process is to remove batteries and then treat material directly in their integrated smelter/refinery without shredding or sorting into fractions before treatment. This direct form of treatment reduced the losses of valuable metals into side streams (Fe-, Al-, plastics, etc.), and saves money that would have been spent on pre-treatment costs.

In small devices such as mobile phones, the value of the precious metals generally far exceeds the value of the iron and aluminum they contain. In addition, their plastic components cannot be feasibly recycled due to the mix of flame retardants, pigments and mixed types of plastics. Umicore's integrated smelting/refining process recovers Sn, Pb, In, etc. from mobile phones and uses the energy content of the plastics.

Computers require manual dismantling and mechanical pre-processing in order to separate and sort the various fractions. During mechanical pre-processing stages, large volumes of mixed plastic fractions are generated. It is not economically feasible to separate and recover these types of plastics. However, Umicore can process mixed plastic fraction in order to recover copper, precious metals, etc. while at the same time using the organic content of the plastics to replace the fuel used in this process.

Dusts are generated during pre-treatment processes and are collected in filter and bag-house systems. These dusts can have high precious metals content but also contain significant amounts of pollutants and high burn-loss components like plastics, paper and wood. Umicore is able to process these dusts depending on the quality and quantity of precious metals.