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Review

Exploring e-waste management systems in the United States

Ramzy Kahhat[a,*], Junbeum Kim[a], Ming Xu[a], Braden Allenby[a], Eric Williams[a,b], Peng Zhang[a]

[a] *Department of Civil and Environmental Engineering, Arizona State University, Tempe, AZ 85287, USA*
[b] *School of Sustainability, Arizona State University, Tempe, AZ 85287, USA*

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ABSTRACT

Quantities of end-of-life electronics (or e-waste) around the world keep growing. More than 1.36 million metric tons of e-waste were discarded, mainly in landfills, in the U.S. in 2005, and e-waste is projected to grow in the next few years. This paper explores issues relating to planning future e-waste regulation and management systems in the U.S. It begins by reviewing the existing U.S. recycling systems in the U.S. to establish the importance of developing public responses. Other countries and regions around the world have already legislated and implemented electronic takeback and recycling systems. To establish the context of existing experience, e-waste management systems in the European Union, Japan, South Korea and Taiwan are explored. The paper then discusses what specific conditions are expected to influence the acceptability and implementation in the U.S. A key consideration is the cultural imperative in the U.S. for market-driven solutions that enable competition. Given this context, a solution is proposed that is designed to ensure a proper end-of-life option while at the same time establishing a competitive market for reuse and recycling services. The solution, termed *e-Market for Returned Deposit*, begins with a deposit paid by consumers to sellers at the time of purchase, electronically registered and tracked via a radio-frequency identification device (RFID) placed on the product. At end-of-life, consumers consult an Internet-enabled market in which firms compete to receive the deposit by offering consumers variable degrees of return on the deposit. After collection of the computer by the selected firm, the cyberinfrastructure utilizes the RFID to transfer the deposit to the winning firm when recycled. If the firm chooses to refurbish or resell the computer in lieu of recycling, the transfer is deferred until true end-of-life processing. Finally the paper discusses the domestic and international consequences of the implementation of the proposed design.

Contents

* Corresponding author at: Department of Civil and Environmental Engineering, Arizona State University, P.O. Box 875306, Tempe, AZ 85287, USA. Tel.: +1 480 727 8249; fax: +1 480 965 0557.
E-mail address: Ramzy.kahhat@asu.edu (R. Kahhat).

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1. Introduction

Electronic waste, commonly known as e-waste, waste electrical and electronic equipment (WEEE), or end-of-life (EOL) electronics, denotes electronic and electrical equipment, including all components, sub-assemblies, and consumables, deemed obsolete or unwanted by a user (Bhuie et al., 2004; Cairns, 2005). However, the word can be misleading because it characterizes used electronics categorically as waste, although the flows include some equipment that will be reused via secondary markets.

Functionality of information and communication technology (ICT) is growing rapidly, and from a sustainability viewpoint, there are clearly social benefits to ICT's technological evolution that contribute to its continuity. As technology advances, people purchase increasingly more electronic devices (such as computers, entertainment electronics, mobile phones and others) even though they are not essential. Meanwhile, the significant increase in e-waste has not corresponded to growth in the processes related to collection, recycle and reuse of these electronic devices. For example, it is estimated that 9% of the electronics sold between 1980 and 2004 in the United States (U.S.), or 180 million units, are still in storage awaiting disposal; TVs and desktop PCs account for 34–52% and 24% (by weight), respectively (U.S. EPA, 2007a). Also, in 2005, the U.S. discarded 1.36–1.72 million metric tons of e-waste, mainly into landfills, and only 0.31–0.34 million metric tons were recycled (U.S. EPA, 2007a). Consequently, the typical life cycle of an electronic product is a linear progression between manufacturing, use, storage and waste disposal.

For these reasons, it is time to design new approaches and systems for e-waste collection, recycle and reuse in the U.S. Ideally, such approaches will reduce environmental impacts by increasing reuse of equipment and parts, increasing the recyclability of materials found in e-waste, and developing a society that learns to balance rapid technological evolution with responsible product/material management. Compared with the current system in which electronic products end up in storage or landfills after use, the framework proposed herein closes the material flow cycle for electronic products by introducing collectors, recyclers and reusers into the system. This modification allows e-waste to be collected and reused or recycled.

Consequently, this paper explores issues related to planning future e-waste regulations and management systems in the U.S. It first explores the U.S. recycling systems for different products, taking as an example the 'bottle bill' and the end-of-life vehicle system. It then reviews what is known about the e-waste situation in the U.S. to establish the importance of developing public response. Other countries and regions around the world (e.g., European Union, Japan, South Korea, Switzerland and Taiwan) have already legislated and implemented electronic recycling systems. To establish the context of existing experience, e-waste management systems in the European Union, Japan, South Korea and Taiwan are reviewed. Based on the above reviews, the paper then considers what specific conditions influence acceptability and implementation in the U.S. A key consideration is the cultural imperative in the U.S. for market-driven solutions that enable competition. Given this context, we propose a form of deposit-refund system designed to ensure proper end-of-life while at the same time establishing a competitive market for reuse and recycling services. The proposal is termed the *e-Market for Returned Deposit*. Finally, the paper discusses the domestic and international consequences of the implementation of the proposed design.

2. U.S. recycling systems

In 2006, the U.S. recycled 32.5% of its generated municipal solid waste (MSW) (U.S. EPA, 2006). However, recycling rates vary between communities depending on their waste collection options, recycling materials targeted, regulatory approaches and other factors. For example, 11 states (California, Connecticut, Delaware, Hawaii, Iowa, Maine, Massachusetts, Michigan, New York, Oregon and Vermont) employ a beverage container deposit-refund system. A beverage container recycling program, commonly referred to as a “bottle bill,” is one important example of a successful deposit-refund system. The “bottle bill” is a system that encourages consumers to return beverage containers by providing a refund on the deposit, and this system is considered by many stakeholders as a successful recycling program that should be expanded as a federal policy (U.S. GAO, 2006) The eleven states employing this system have achieved higher recycling rates and have recycled more beverage containers than the other 39 states combined (DOC, 2007). The refund value of the container (usually 5 or 10 cents) provides a monetary incentive to return the container for recycling. California, for example, reported a 60% recycling rate for its beverage containers between January and December 2006; during that year, over 13 billion containers were recycled, which was 814 million more than the year prior (DOC, 2007).

In addition, possibly the best example of a free market-driven end-of-life option is the automobile market, which is driven by no regulations, but only by the economics of material recovery from car bodies. There are about 15 million end-of-life vehicles (ELVs) generated in the U.S. every year. Currently, 95% of cars in the U.S. are sent to existing recycling facilities for dismantling and shredding at the end of their service lives (Daniels, 2003). The management of ELVs involves dismantling, shredding, and recycling of parts and materials. The parts that have reasonable value are removed by the dismantlers, and then reconditioned and reused. The shredders group the remaining materials into ferrous and non-ferrous metals, which are all sent to recyclers. In 2001, 6000–7000 dismantlers were estimated in the U.S. (Staudinger and Keoleian, 2001). In addition, in 2006, around 75% of the materials found in vehicles were profitably recycled by the reuse or shredding industry (Jody and Daniels, 2006).

3. Principal e-waste collection and recycling systems in the world

The European Union, Japan, South Korea, Taiwan and other regions are currently working with e-waste management systems to handle this type of waste stream. In this section, we discuss the current e-waste collection, recycle and reuse systems and related regulations in these regions with the purpose of understanding them and evaluating their feasibility in the U.S.

3.1. Europe

The 25 Member States of the European Union have been adopting a number of community level regulations related to e-waste, which are intended to “preserve, protect and improve the quality of the environment, protect human health and utilize natural resources prudently and rationally” (European Commission-WEEE Directive, 2003). For example, in January 2003, the European Commission-WEEE Directive (2003) adopted regulations related to five categories: (1) EEE product design, (2) e-waste collection, (3) e-waste recovery, (4) e-waste treatment and treatment financing and (5) EEE user awareness. The main considerations of the Directive included the recovery, recycle and reuse of e-waste. The regulation aims to raise awareness of end-of-life factors during product design. These factors include dismantling of parts and recyclability of materials, proper collection systems that support separate collection of e-waste to reduce disposal in common municipal waste streams, and best practices for treatment, recovery and recycling of e-waste. In addition, according to the type of e-waste, producers should comply with the minimum recovery rates (70–80% by weight) and “component, material and substances reuse and recycling” rates (50–80% by weight) (European Commission-WEEE Directive, 2003). Also, distinctions are made depending on the source of the e-waste: private household or non-private household, historical products or new products (European Commission-WEEE Directive, 2003). Implementation has not been an easy task. Although some European Union countries are already implementing the regulation (e.g., Netherlands and Greece), others, mainly countries with no previous e-waste management system, have asked for extensions or temporary derogations to comply with the regulations (Magalini and Huisman, 2007; Savage, 2006). Two main factors delaying the transposition of the directive include the following: (1) transfer of previous regulations (e.g., Austria, Belgium, Denmark, Sweden and Luxemburg) and (2) negotiations with stakeholders regarding responsibilities in the process (e.g., France) (Magalini and Huisman, 2007).

In addition, the European Union Restriction of Hazardous Substances (RoHS) Directive (2002/95/EC) restricts (beginning July 2006) the use of six hazardous compounds: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDE), commonly found in EEE (European Commission-RoHS Directive, 2003).

Moreover, other European countries not part of the European Union have also been successfully handling e-waste. Switzerland, for example, has two different e-waste systems: Swiss Association for Information, Communication and Organization Technology (SWICO) for office, dental, graphic and telecommunication equipment and Swiss Foundation for Waste Management (SENS) for household appliances (Hischier et al., 2005; Streicher-Porte, 2005). The recycling companies associated with both systems have recycled 11 kg of e-waste per habitant in 2004, which amounts to 75,000 metric tons of e-waste; SWICO accounts for 47% (Hischier et al., 2005; Streicher-Porte, 2005; SWICO, 2005). By comparison, the European Commission-WEEE Directive (2003) recommends 4 kg/hab-year.

3.2. Japan

Japan’s e-waste laws require manufacturers and importers to take back end-of-life electronics for recycling and waste management and are meant to ensure separation of e-waste from the MSW stream (Widmer et al., 2005). Specifically, the Japanese “Home Appliance Recycling Law”, enacted in 1998 and fully enforceable as of 2001, forces producers or importers to recycle four types of household e-waste: televisions, refrigerators, washing machines and air conditioners. In addition, consumers will have to pay an end-of-life fee that covers part of the recycling and transportation expenses. The fees paid by consumers are between US$ 23 and US$ 46 (US$ 1 = JPY 107) that covers the recycling fee and an additional US$ 4 to US$ 19 (US$ 1 = JPY 107) collection fee to cover the transportation of the product to designated collection sites. Also, the system obligates retailers to collect and transfer discarded products from consumers.

In addition, Japan began compulsory recycling of business personal computers (PCs) in April 2001, and expanded the requirement to residential PCs in the summer of 2003 with the “Law for Promotion of Effective Resource Utilization.” The system was initially managed by local authorities, but for PCs sold after October 2003, manufactures grouped in the PC3R Promotion Center are responsible for collection and recycling/reuse of computers. Computers under the PC recycling program have a “PC Recycling Mark” and include an invisible non-refundable recycling fee in the sale price, so no additional charges are required. However, for products purchased before October 2003 and with no mark, customers will need to pay a collection and recycling fee that ranges from US$ 29 to US$ 40 (PC3R, 2008; Terazono et al., 2006; Yoshida et al., 2007).

3.3. South Korea

In South Korea, under the Extended Producer Responsibility (EPR) Law (Yoon and Jang, 2006), which came into effect in 2003, local manufacturers, distributors and importers of consumer goods such as air conditioners, TVs and PCs are required to achieve official recycling targets or face financial consequences. They must set up an account with the government to deposit recycling funds, which are refundable in proportion to the actual volumes of waste recycled. Manufacturers and importers can either outsource their waste recycling activities to industry cooperatives and professional recycling companies or establish their own recycling facilities to meet the EPR requirements. Retailers and suppliers are also required to collect and transport used equipment for free if the customer purchases a similar product.

According to Yoon and Jang (2006), approximately 70% of e-waste was collected by producers in 2003, which is the year the EPR program was first introduced. Moreover, that same year, 12% of collected e-waste was reused, 69% of collected e-waste was recycled, and the remaining 19% went to landfills or incinerators in South Korea (Ministry of the Environment Republic of Korea, 2003).

In general, e-waste is collected by local governments, producers/retailers, and recyclers/reusers. In South Korea, local governments collect about 40% of the total collected e-waste and produces/retailers about 50% (Ministry of the Environment Republic of Korea, 2003).

The recycling fee paid by manufacturers ranges from US$ 4 to US$ 17 (US$ 1 = 1160 won). However, consumers are responsible for the collection fee and have two options: (1) paying no collection fee if the consumer decides to buy a new replacement product, in which case the retailers collect the e-waste, or (2) paying a collection fee to the local government collection system. It is important to note that in the case of computers, there are companies that offer free collection of the e-waste; the fee is around US$ 8 to US$ 10.

3.4. Taiwan

Taiwan began enforcing the Waste Disposal Act Amendments (AWDA) in 1998. The Amendments ensure manufacturers and importers a financial responsibility by enforcing the payment of a recycling fee, similar to the Korean system. Funds are collected by an organization known as the "Recycling Management Fund" and transferred to the recycling facilities. The e-waste includes TV sets, refrigerators, washing machines, air conditioners, PCs and others. Recycling fees are between US$ 8 and US$ 21 (US$ 1 = TWD 32) (Terazono et al., 2006).

3.5. Discussion of the international systems

The above examples of e-waste management systems inevitably raise a discussion regarding their probability of success in the U.S. Although the systems appear to be successful in the aforementioned countries, the success of one system does not necessarily portend success in another country. Moreover, these systems may not be the most sustainable approach for e-waste management. Developing a sustainable e-waste system begins with understanding the culture within which the material flows take place. In order to be responsive, a sustainable system must address the physical flows, the ICT infrastructure and the incentives. This approach will help differentiate the U.S. from other societies and determine which system is most suitable for the U.S.

Nevertheless, it is important to understand existing systems and learn from their experiences. For example, although the systems rely on an EPR principle that enforces a financial or physical responsibility to producers, the end-of-life management is not necessarily performed by producers, but by recycling companies. Moreover, if manufacturers take financial responsibility of the electronic product, the collection and recycling cost will still be assimilated by the consumer. For this reason, the important question is not who is paying but what other aspects and levels are desired in the end-of-life flow, such as developing social responsibility.

Also, it is important to note that in systems similar to that of South Korea, the high economic value of the e-waste may be sufficient to drive the recycling and reuse market. Consumers could sell unwanted electronic products to the recycling facilities to recover some of the initial costs, consumers would no longer be required to pay a collection fee, and recycling facilities could profit from the recovered components. This scenario demonstrates an e-waste market driven by economic benefits rather than legislation.

4. E-waste situation in the U.S.

In the U.S., e-waste could be the fastest growing component of the MSW stream mainly because people are purchasing, upgrading and discarding electronic products more frequently than ever before. This trend is likely to continue given the existing vigorous rate of technological progress and subsequent decreasing life spans of electronic products.

Currently, the U.S. e-waste debate focuses on two main points: (1) U.S. e-waste disposal in U.S. landfills and (2) U.S. e-waste exportation. The following paragraphs will discuss each of these in detail.

4.1. Landfill disposal of e-waste

According to the U.S. Environmental Protection Agency (EPA), between 2003 and 2005, about 80–85% of the e-waste ready for end-of-life management ended up in U.S. landfills (U.S. EPA, 2007a). This statistic raises the following question: Are landfills an environmentally secure place for e-waste disposal? It is true that e-waste contains hazardous elements such as lead, chromium, cadmium and mercury. However, a better understanding of the fate and transport of these hazardous elements in landfills is needed to predict the threat of e-waste. In the last years, some research groups have used the U.S. EPA's Toxicity Characteristics Leaching Procedure (TCLP) test to simulate the lead leachability of e-waste in landfills. Lead is commonly found in solders for circuit boards and in cathode ray tube (CRT) glass. Results showed that for the different electronic equipment tested (e.g., circuit boards, CRTs, mobile phones, computers, etc.) lead exceeded the TCLP federal limits (Jang and Townsend, 2003; Lincoln et al., 2007; Musson et al., 2006; Townsend et al., 2002; Yang, 1993).

Table 1
E-waste retirement estimates by management method (thousands of metric tons) (source: U.S. EPA, 2007b)

	Recycled		Landfilled		Incinerated		Total	
2003	315.5	20%	1234.9	78%	35.1	2%	1585.5	100%
2004	326.5	20%	1281.9	78%	36.5	2%	1644.8	100%
2005	343.8	20%	1353.7	78%	38.5	2%	1736.0	100%

However, Jang and Townsend (2003) compared the TCLP results with results obtained from 11 Florida landfill leachates, both for circuit boards and CRTs. The results showed a significant difference in lead concentrations, concluding that TCLP can be overestimating lead leachability in real landfill conditions. Moreover, it is important to note that landfill conditions and composition play an important roll in the fate and transport of contaminants. For example, Vann and colleagues (2006) studied the influence of iron and zinc in lead leachability when running the TCLP test for computer CPUs. The study found that iron and zinc leachates contributed to suppress lead leachability and that larger ferrous metal amounts in the device will obtain lower values (Vann et al., 2006).

Whether or not e-waste landfill disposal is a threat to the environment and human health, major benefits can be realized from reuse and recycling that will discourage the disposal of e-waste via landfills. Further discussion of such benefits appears in the next section. Table 1 shows the e-waste retirement estimates by management method in the U.S. for the years 2003, 2004 and 2005. The results show that 80% of all e-waste ends in landfill disposal or incineration and only 20% is recycled (U.S. EPA, 2007b).

4.2. Exportation of e-waste

U.S. e-waste exportation is currently receiving a great deal of attention. E-waste is routinely exported by developed nations, including the U.S., to developing countries, which is in contravention of the Basel Convention Agreement in some cases. Although the U.S. does not violate any national law when exporting e-waste, a prior notification between the U.S. and the importing country is needed to comply with the Basel Convection Agreement. However, the U.S. has signed bilateral agreements that in some cases allow exportation and importation of hazardous materials (Secretariat of the Basel Convention-United Nations Environment Program, 1992; U.S. EPA, 2008).

The basel action network (BAN) and the silicon valley toxics coalition (SVTC), two non-governmental organizations (NGOs) in opposition to the export of e-waste to developing countries, estimated that up to 80% of the U.S. e-waste initially collected for recycling purposes is being exported to developing countries for informal recycling procedures (BAN and SVTC, 2002). BAN and SVTC have pointed fingers at the U.S. for "not facing the e-waste problem squarely" and making use of "hidden escape valves to export the crisis to developing countries of Asia" (China Environmental Regulation Net, 2004).

China currently receives the largest share of e-waste from around the world and is tapping into the huge market for used electronic products behind the phenomenon of backyard or informal recycling (Sina News, 2006). In informal recycling, e-waste is disassembled manually and recycled using archaic methods to obtain valuable materials. The recycling process itself, due to chemicals and wastes, puts the health and safety of the workers at risk, jeopardizes health in local and surrounding communities, and is potentially damaging to environmental systems (Greenpeace, 2005; Liu et al., 2006). To confirm this, recent studies have been performed in Guiyu, Guangdong Province, the most well-known center of e-waste scrapping in China. The studies show an important connection between informal recycling activities and several other parameters: (1) contamination of freshwater sources and sediments with heavy metals mainly due to acid leaching processes (Wong et al., 2007a,b); (2) contamination of air and soils with polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), polybrominated dibenzo-*p*-dioxins and dibenzofurans (PBDD/Fs), polychlorinated dibenzo-*p*-dioxins (PCDD) and polycyclic aromatic hydrocarbons (PAHs) mainly caused by open burning sites (Deng et al., 2006; Leung et al., 2007; Li et al., 2007; Yu et al., 2006); and (3) human health impacts, such as high lead blood levels found in Guiyu's children (Huo et al., 2007).

Although China is trying to prevent this trade by banning the import of e-waste, the laws are not working; e-waste is still arriving in China (Liu et al., 2006; Tong, 2004). Furthermore, India also has a growing e-waste trade with documented e-waste recycling yards in Bangalore, Chennai, Delhi and Mumbai (BAN and SVTC, 2002; Keller, 2006; Streicher-Porte et al., 2005).

While NGOs and some developing countries' governments are trying to forbid this trade, the e-waste exporting trend by developed countries to developing countries is increasing annually. One of the main reasons is that both sides (developed and developing countries alike) receive economic advantages from informal recycling. Specifically, developed nations benefit from relatively low labor costs in China, and the material flows from e-waste imports can offer business opportunities and satisfy the demand for cheap second-hand products in developing countries (Widmer et al., 2005). In addition, another economic factor that incentivizes e-waste exportations is the trade imbalance between the U.S. and other countries (for example China).

4.3. E-waste action in the U.S.

In the face of the U.S. e-waste situation, many states in the U.S. have begun efforts to collect (e.g., free e-waste collection events) and recycle the e-waste from residential and business sectors. For example, the State of California has passed a law charging consumer fees, called advanced recycling fees (ARFs), at the time products are purchased. The system covers monitors, TVs and laptops, and the ARF is between US$ 6 and US$ 10 (Gregory and Kirchain, 2007). Moreover, in 2006, the Washington State Legislature created the Electronic Product Recycling Law Chapter 70.95N RCW. This law requires manufacturers of computers, computer monitors, laptop and portable computers, and televisions to provide recycling services throughout the state at no cost to households, small businesses, small local governments, charities and school districts. Moreover, in January 2006, Maine started its e-waste program covering monitors, TVs and laptops discarded by households. In this system the responsibility is shared by municipalities (collection process and cost) and manufacturers (consolidation, transportation from consolidators to processors and processing cost) (Gregory and Kirchain, 2007; Natural Resource Council of Maine, 2007).

Of the 21 states/cities with bills pending, 15 of them have introduced producer responsibility bills: Connecticut, Hawaii, Illinois, Massachusetts, Maryland (where the bill would expand an existing program), Minnesota, Nebraska, New Jersey, New York, Oregon, Rhode Island, South Carolina, Tennessee, Vermont and New York City. Four of these states have also introduced ARF bills: Hawaii, Massachusetts, South Carolina and New Jersey (EIATRACK, 2007). However, it is important to note that the status of the bills is constantly changing.

In addition, more than 800 local communities with the creation of e-waste collection events are playing an important role in household e-waste management (U.S. EPA, 2007a). The various e-waste collection options currently used in the U.S. include curbside, special drop-off event, permanent drop-off, takeback and point-of-purchase (Kang and Schoenung, 2005). Furthermore, some organizations such as the Northeast Recycling Council, Northeast Waste Management Officials' Association and the Northwest Product Stewardship Council have been working on developing regulations at a regional, state and local community level (U.S. GAO, 2005). In addition, some manufacturers and companies have stepped up their efforts, among them AT&T, Dell, Hewlett Packard, Motorola, Sony and others.

The activities of all states and major companies are very important for a sustainable approach, but they are not sufficient for the U.S. The federal government will have to create a regulatory framework that, when combined with industry approaches, achieve a whole-system solution that addresses collection challenges, creates sufficient recycling facilities in each state, etc.

5. Proposal for e-waste collection, recycling and reuse in the U.S.: *e-Market for Returned Deposit*

5.1. U.S. context

End-of-life electronic product management, including reverse logistics systems and takeback regulation, needs to reflect not just technical requirements and efficiencies. It must also reflect the political structure and underlying cultural models of the society within which the system is to operate. In this instance, that means that any end-of-life management system in the U.S. must reflect the strong preference for economic incentives over regulatory incentives and the underlying free market philosophy that characterizes the culture. Thus, while we intend to learn as much as possible from experience gained from other countries and their e-waste policy initiatives, we will also be sensitive to the different cultural dynamics, and thus policy preferences, of the U.S.

There are a number of companies working on e-waste collection, recycle and reuse in the U.S., especially in the states with e-waste regulations, such as California. However, the lack of federal regulations that promote collection, recycle and reuse of e-waste is a barrier for further development across the country. Therefore, standardized and suitable policies and regulations are required to create a sustainable end-of-life management option and a recycling/waste processing system that facilitates increased e-waste recycling and reuse.

Whatever system is put in place, it is clear that financial responsibility will be needed to ensure proper management. One issue is the management of the new financial flows. One option – in a strict interpretation of the idea of EPR – is to make manufacturers entirely responsible for collection and disposal. However, other participants in the chain of electronic products, such as consumers and government, could also take partial responsibility for e-waste management.

5.2. E-waste definition for the system

Currently, there is no standard definition for e-waste in the world and the U.S. Depending on the organization or regulation, e-waste can include different types of equipment from different sectors. Because the e-market system is initially oriented to residential e-waste, the system will initially focus on some of the consumer electronic products under the International Association of Electronics Recyclers classification (IAER, 2006). The equipment includes TVs (CRT, Plasma and LCDs), DVD players, monitors (CRT and LCDs), computers (desktop and laptops) and cell phones.

5.3. Deposit-refund system

The lack of an efficient collection, recycle and reuse system is one of the problems for e-waste management in the U.S. Hence, some suggestions to improve the efficiency of e-waste collection, recycle, and reuse systems are provided. As stated before, a key consideration is the cultural imperative in the U.S. for market-driven solutions that enable competition. Given this context, we propose a form of deposit-refund system designed to incentivize collection while at the same time establishing a competitive market for reuse and recycling services

Following are three characteristics that a deposit-refund system in the U.S. should satisfy:

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

The *e-Market for Returned Deposit* proposed in this paper is an option that satisfies these conditions. As illustrated in Fig. 1, the system manages e-waste disposal via an electronic market enabled by cyberinfrastructure. The core concept of the system is that consumers pay a deposit at time of purchase, a variable portion of which is returned when turned in at the end-of-life. This deposit should be sufficient enough to cover transportation and recycling cost of the product. Reuse and recycling firms compete on an electronic market to receive the deposit by bidding different values of rebates to consumers. The possibility of reuse is also included in this process, in which case consumers may even receive more return than the deposit paid, for example, a functional computer still attractive for the reuse market. If the firm chooses to refurbish or resell the computer in lieu of recycling, the transfer of deposit is deferred until true end-of-life processing. This system is enabled by a cyberinfrastructure which includes a radio-frequency identification device (RFID) placed on the product to track economic and material flows. Fig. 1 shows the main information, monetary and product flows, to be further explained below. Further discussion will be needed to decide the location of the RFID in the product or the use of multiple RFID for a single product. This aspect will be important for the end-of-life management of the equipment and parts.

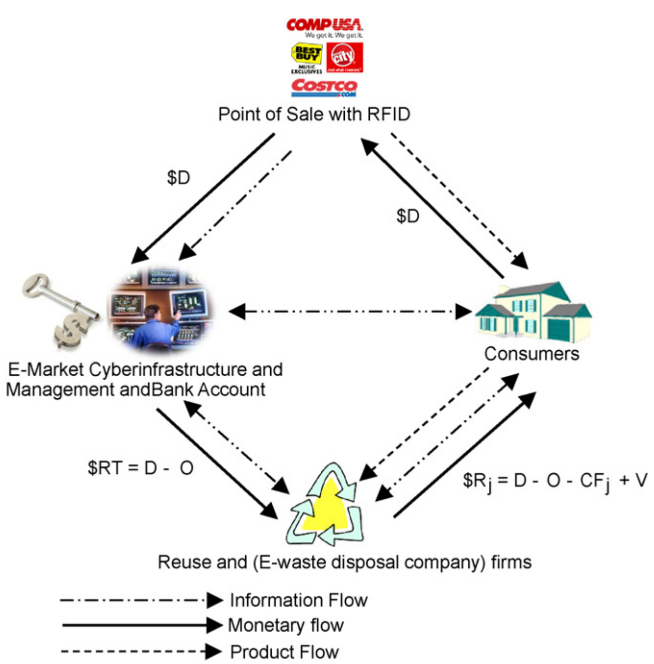

Fig. 1. *e-Market for Returned Deposit* System for given product (D = deposit, O = per product overhead for e-market management, R_j = rebate offered by firm j, CF_j = cost to firm j to recycle, RT = return made by the e-market management, V = e-waste additional value offered to the consumer).

5.4. Information flow

The information flow starts when the consumer purchases the product at the point of sale. After payment (product price and disposal fee or deposit), the retailer will encode the product's RFID with characteristics of the product (size, system characteristics, etc.) and link the stored information with the transaction details (e.g., date, point of sale, deposit paid by the consumer). Next, the retailer will be responsible for sending the information to the cyberinfrastructure, which will collect and keep the information until requested by the e-waste disposal company (collection, recycle or reuse companies). When the consumer decides to dispose of the product, he or she will consult an Internet-enabled market in which firms compete to receive the deposit by offering consumers variable degrees of return. The consumer will need to enter the product identification number and the current location of the product to receive the best available offers in the area. Disposal options and offers will vary from company to company, based on their competitiveness. E-waste disposal companies will constantly send their options and offers to the cyberinfrastructure, which will sort these options according to the consumer preferences: percentage of deposit returned, delivery options (customer delivery or company pick up), location of company, and so on. Based on this information, the consumer will select an e-waste disposal company. Finally, when the transaction between consumer and e-waste disposal companies is concluded, the e-waste disposal company will start a communication with the product's RFID. This communication will link the selected disposal option and the return fee agreed upon by the consumer with the RFID. For example, if the company decides to refurbish or reuse the equipment, the RFID tag will continue operating until the real end-of-life option, but if the company decides to recycle the equipment and/or reuse the parts, the RFID will be cancelled. The e-waste disposal company will then be responsible of sending this information to the cyberinfrastructure.

5.5. Monetary flow

Similarly, the monetary flow will start at the point of sale with payment of the deposit. The amount of the deposit fee will be decided by the entity in charge of the system in conjunction with a stakeholder advisory board. This process will ensure that the system incorporates the main characteristics described previously, allows for proper recycling, and creates sufficient financial incentives for consumers and for the e-market. Future deposit fees will follow the same sequence but should consider the economic evolution of the system. The amount of this deposit will vary by product type. In this proposal we do not suggest specific levels of deposit but note that the fee needs to be high enough to cover a worst-case scenario. The fee must be high enough to cover transportation and

Table 2
Hypothetical scenario for the interest generated by the deposit fee

Year	2,004
Flat screen sold units (residential)	21,194,475
Deposit to bank account (US$ 20 of deposit fee per unit)	423,889,498
Interest after 3 years (US$)	56,375,402

recycling costs and encourage consumers to engage in the process of utilizing the e-market. However, the deposit should not exceed a level which would affect the decision to purchase the product. This disposal fee will be kept in a bank account until the consumer agrees to transfer the e-waste to the preferred e-waste disposal company. The interest from this bank account will be used to pay for part of the cyberinfrastructure and administrative costs, and the other costs will be covered by the per product overhead for e-market management. Table 2 considers a hypothetical case scenario for the interest generated by the deposit fee when purchasing a flat screen computer monitor. The table uses an estimated residential share of sold units in 2004 (U.S. EPA, 2007c), an annual interest yield of 4.25% (assuming 01/18/08 U.S. Treasury Bond for 30 years), and a product life span of 3 years. Results show an approximate interest of US$ 56 million for the 3 years. It is important to note that the system will create a financial stock that will require financial management. In addition, like the “bottle bill” case, unclaimed deposits are expected and could also cover the management cost of the e-waste system.

Furthermore, based on information received from the e-waste disposal company, the cyberinfrastructure will transfer the deposit to the e-waste disposal company and the rebate offer to the consumer as follows:

$$\mathrm{RT} = D - O \ldots \quad (1)$$

$$R_{\mathbf{j}} = D - O - \mathrm{CF_j} + V = \mathrm{RT} - \mathrm{CF_j} + V \ldots \quad (2)$$

where D is the per product disposal fee paid in the point of sale by the consumer; $\mathrm{CF_j}$ the cost to firm (e-waste disposal company) j to recycle; O the per product overhead for e-market management; R_j the rebate offered by firm j; RT the return made by the e-market management to the e-waste disposal company; V the e-waste additional value offered to the consumer; j is the e-waste disposal company.

As stated before, $\$R_\mathrm{j}$ will depend on the e-waste disposal company offer and the amount $\$V$ can also be added by the e-waste disposal company based on the value of the product and efficiency of the recycling company. If the firm chooses to refurbish or resell the computer in lieu of recycling, the bank account transfer to the e-waste disposal company and secondary consumer will be deferred until true end-of-life processing. The original consumer will receive the rebate amount based on the agreement held with the e-waste disposal company.

5.6. Product flow

The product flow starts from the point of sale, which may be a physical or online location. In either case, the product will be transported to the desired consumer location. When the consumer decides to discard the equipment, the transportation will be based on the agreement between the consumer and e-waste disposal company. The agreement will include the transportation method and may require the consumer to deliver the e-waste to the e-waste disposal company or a collection point. Conversely, the e-waste disposal company could pick up the e-waste from a location specified by the consumer. In summary, the product flow will be an interaction between point of sale, consumer and e-waste disposal company and will be based on the previous agreements. E-waste disposal companies will be responsible for assuring environmentally sound recycling methods after use or reuse of the equipment. It is important to note that because of the characteristics of the systems (i.e., consumer pays the deposit fee), no additional action should be made for orphan products.

5.7. Development and management of the e-Market for Returned Deposit system

We propose that the *e-Market for Returned Deposit* system be initially developed and managed by the federal government. This federal entity will be in charge of the following system elements: cyberinfrastructure maintenance, data management, information flow, economic flow, system supervision, acceptance process of e-waste disposal companies, monitoring and inspection of e-waste disposal companies, creation and improvement of environmental and occupational health and safety standards related to recycling processes, and others. As stated previously, the administrative expenses will be covered by the per product overhead, interest gains, and unclaimed deposits. E-waste disposal companies will need to be licensed by the federal entity primarily based on the environmental and occupational health and safety criteria. Also, associations like the International Association of Electronics Recyclers (IAER) could play a major roll participating in certification programs for e-waste disposal companies.

5.8. Preliminary economic assessment

An in-depth economic assessment is not part of the scope of this paper. However, this section shows a preliminary economic assessment based on other studies and reports. This estimation takes

Table 3
Estimated budget of the e-market deposit-refund system in the U.S.

	California	Maine	Units	Source and notes
Units sold in 2004	44,155,156	44,155,156	Units	U.S. EPA (2007c)
Residential share	48%	48%	%	U.S. EPA (2007c)
Estimated weight	11.16	11.16	kg	U.S. EPA (2007c)
Collection and transportation cost	0.44	0.18	$/kg	Gregory and Kirchain (2007) and there in
Processing cost	0.62	0.37	$/kg	Gregory and Kirchain (2007) and there in
Total collection and transportation	104,059,921	42,569,968	US$/year	
Total processing	146,629,888	87,504,933	US$/year	
CF, cost to e-waste disposal company	250,689,809	130,074,901	US$/year	Collection, transportation and processing
Interest	18,791,801	18,791,801	US$/year	Table 2
Unredeemed deposits	0.00	0.00	US$/year	Consider 100% redemption
Administrative cost for U.S. e-market system	50,887,068	44,799,955	US$/year	NCER (2006) (FY 05-06) excludes ARF paid and Gregory and Kirchain (2007) and there in
O, overhead	32,095,267	26,008,154	US$/year	

Table 4
Estimation of the minimal rebate offered by the firm

	California	Maine	
D, deposit fee	20.00	20.00	US$/per product
CF, cost to firm	11.83	6.14	US$/per product
O, overhead per product	1.51	1.23	US$/per product
RT = return to e-waste disposal company	18.49	18.77	US$/per product
R, rebate offered by firm	6.66	12.64	US$/per product

into account data from two current e-waste systems in the U.S.: California and Maine. It is important to note that these systems use different operating models and that results do not necessarily represent the e-market system. For this reason, the purpose of this estimation is to have an idea of the possible rebate offered per product. The assumptions are as follows:

- *Product*: flat screen computer monitor.
- *End-of-life option*: recycling.
- *Product life span*: 3 years.
- *Deposit fee*: US$ 20.00.
- *Interest rate*: 4.25%.
- *U.S., California and Maine population for 2004*: 293,191,511; 35,721,991 and 1,308,892 habitants (U.S. Census, 2008).

From Tables 3 and 4 we can obtain that the minimal rebate offered for both systems, in the case of recycling, is between US$ 6 and US$ 13, or 33–63% of the deposit fee. Also, it is important to note that Table 3 considers no unclaimed equipment, which overestimates the overhead charged by the system to cover the administrative cost. The fact that we are only considering recycling as the end-of-life management and not reuse ensures a higher rebate offered to consumers. Moreover, although the system will provide an equivalent regulatory/operating baseline for all the U.S., e-waste flows between States will be likely to occur due to competitive advantages offered by some companies (e.g., recycling procedures, partnerships, geographic locations, etc.). This is entirely appropriate and will result in optimal financial efficiency in the e-waste management system.

5.9. Discussion on the consequences of the e-Market for Returned Deposit system

One important advantage of the proposed system stems from the fact that functional e-waste – before or after refurbishment – can be a potential product for secondary markets. Such reuse has both social and environmental benefits. This result in an decreasing digital divide which leads to lower future development gaps between communities (e.g., between developed and developing countries) (Baskaran and Muchie, 2006; Warschauer, 2004). In the case of PCs, the U.S. is said to need about 9 million PCs for its low-income schools (Lynch, 2004). However, technology in the U.S., with 544 PCs per 1000 people (U.S. AID, 2004), is abundant when compared with developing countries such as Bolivia and Honduras that have only 36 and 18 PCs per 1000 people, respectively. Fortunately, an increasing market for reused PCs in developing countries is allowing people to own PCs and access technology at more affordable prices. Moreover, charitable organizations, such as Computer Mentor, Computer Aid, World Computer Exchange, Computers for Schools and others are expanding their boundaries and providing used and refurbished computers to organizations (e.g., schools) around the world. Furthermore, reuse also reduces the environmental impacts of technological artifacts by increasing their life spans and thereby reducing the demand for new equipment. Again in the case of PCs, energy savings of 8.6% or 5.2% can be realized when reselling or upgrading 10% of the computers (Kuehr and Williams, 2003). Despite the value of e-waste in the reuse market, electronic products are currently unable to reach these markets due to many factors, including a lack of incentives, collection options and consumer awareness for recycle or reuse alternatives. Hence, electronic equipment often ends up in storage facilities after first use, thereby reducing their economic and useable value in the reuse market.

In addition to reuse, recycling is also important, both economically and environmentally. According to the IAER (2006), in 2006, the industry obtained approximately $1.5 billion annual revenue, giving work to 19,000 employers in 500 companies. However, the industry is not working at its full capacity (IAER, 2006). E-waste has important quantities of recyclable metals such as aluminum, steel, copper, lead, zinc, and precious metals such as gold, silver and palladium, making recycling economically favorable. For example, a desktop computer contains 0.36 g of gold and 1.4 g of silver (Kuehr and Williams, 2003). For 1 ton of electronic waste that contains 0.1% by weight of gold the revenue breakdown for gold can be as high as 86% (this percentage will vary depending on the current value of metals) (Sodhi and Reimer, 2001). However, there are some barriers for formal e-waste recycling such as difficulties in dismantling procedures and management of hazardous materials (Gibson and Tierney, 2006). Moreover, recycling also helps reduce negative environmental impacts. For example, the energy saving when recycling aluminum, copper, iron and steel, and lead over virgin materials are 95%, 85%, 74% and 65%, respectively (Cui and Forssberg, 2003).

In addition, the proposed e-waste management system will promote social awareness and responsibility towards product end-of-life management, especially important in the rapidly growing ICT sector promoting "operational and ethical responsibility for the system effects" which is impacting natural systems (Allenby, 2000).

One aspect that needs to be clarified in this model is how it treats exports of used electronics and e-waste. It could well be that a majority of e-waste collected in the U.S. ends up being exported for reuse and recycling in developing countries, such as China, India, etc. While economically favorable due to lower labor costs abroad (e.g., dismantling of devices) and higher demand for used goods (Williams, 2005), lack of regulation on end-of-life processing has

Table 5
Strengths, weaknesses, opportunities and threats of the *e-Market for Returned Deposit* system

Strengths	Weaknesses
Method is market-driven system	Exclusion of other electronic products
Uniform nation-wide e-waste system	Hassle process for consumer
Increment of residential e-waste collection, recycle and reuse	
Inclusion of orphan products	
Opportunities	**Threats**
Develop a society that learns to manage rapid technological evolution and responsible product/material management	Increment of e-waste exportation
Expansion of domestic recycling and reuse industry	Inadequate recycling in reuse markets
Develop of new and efficient technologies for recycling e-waste	

led to significant recycling impacts in informal recycling activities abroad. One option is that the recycling deposit can only be transferred in the case of domestically implemented recycling. The other option is to allow the deposit to transfer abroad to certified foreign firms participating in the network. This option supports the development of a recycling infrastructure outside of the U.S. In this case, an appropriate out-of-country infrastructure for e-waste treatment would be helpful. In this proposed system, the e-waste would first be collected in the U.S. using the *e-Market for Returned Deposit* system. Then the collected e-waste would be exported legally to other countries where they would be recycled in out-of-country infrastructure that meets U.S. occupational healthy and safety and environmental standards. Before exporting, the devices and parts would be designated for either reuse or recycling. The out-of-country infrastructure would be built in the target countries but with funds invested by exporting countries alone or all participating nations.

Moreover, the system is expected to promote competition and development in the recycling sector, which will lead to innovation in technology and efficiency and result in better end-of-life options for electrical and electronic equipment. For example, businesses using recycling technologies that depend on processes that are only capable of recovering seldom materials found in the electronics (such as gold for "agua regia" leaching processes or steel) could be beaten by businesses able to recycle more materials and hence obtain more revenue.

Table 5 summarizes the strengths, weaknesses, opportunities and threats of the *e-Market for Returned Deposit* system.

6. Conclusions

As stated in the article, some states are adopting e-waste regulations, but so far the U.S. does not have a federal regulation that addresses the complete e-waste situation, including residential and non-residential sectors. Federal level policies and regulations present the best way to address the e-waste situation (U.S. GAO, 2005) as they will overcome the lack of regulations in most states and will standardize regulations and policies in the country. This will create a more efficient national e-waste management system. In this scenario, the *e-Market for Returned Deposit* system will be the mechanism for residential customers to dispose of their devices in a way that motivates collection, recycle and reuse of e-waste.

The proposed system will intensify e-waste collection and lead to more appropriate use of resources by increasing material recovery for recycling and reducing the environmental impacts associated with extraction of natural resources or manufacturing of materials. The system will also promote reuse of equipment and parts, decrease the environmental burdens associated with the manufacture of new equipment, as well as increase the accessibility of technology to low-income communities.

Improving the domestic collection of e-waste by using the proposed system, *e-Market for Returned Deposit*, could also lead to resolution of other issues, such as exportation of e-waste to other countries. Hence, proper regulations that include clear responsibilities for e-waste disposal companies should be adopted, including total liability of the e-waste share they acquire. This liability will include transportation, treatment and disposal of recycling-reuse waste inside and outside the United States. Partnerships between qualified U.S. companies and formal foreign recycling companies should enforce these regulations to avoid improper and environmentally unfriendly procedures, such as China's informal recycle industry. Responsible domestic companies should assure proper environmental procedures from its international counterparts and report to the federal government. This trend is already being performed by associations like "World Reuse, Repair and Recycling Association" that are enforcing their members a trade that meets the association's environmental standard for foreign reuse, repair and recycling (W3RA, 2007).

Finally, it is clear that the U.S. needs to implement new collection, recycle and reuse systems for electronics e-waste management in the U.S. This will be an important issue for sustainability, both domestically and globally. Finding politically attractive solutions in the U.S. entails considering systems compatible with market principles, without ignoring the experience of other countries. This paper describes three different levels of operation for waste collection and recycling systems. In the first system, the market generates cyclical material flows, such as the ELVs system. In the second system, regulations establish incentives without requiring a specific behavior, such as in the beverage container system. In the third system, regulations mandate a specific behavior, such as in the European e-waste legislation. Based on this analysis, the proposed *e-Market for Returned Deposit* system combines the first two models by offering economic incentives established by law (deposit fee) without enforcing redemption. The proposed model also creates a market driven by economic incentives for product recycling or reuse. The *e-Market for Returned Deposit* system provides the most sustainable approach for e-waste management in the U.S.

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