Environ. Sci. Technol. **2008,** *42,* 6446–6454

Environmental, Social, and Economic Implications of Global Reuse and Recycling of Personal Computers

ERIC WILLIAMS,*,†,‡ RAMZY KAHHAT,†
BRADEN ALLENBY,† EDWARD KAVAZANJIAN,†
JUNBEUM KIM,† AND MING XU†

Department of Civil and Environmental Engineering and School of Sustainability, Arizona State University, Tempe, Arizona 85287

Received September 7, 2007. Revised manuscript received April 4, 2008. Accepted April 14, 2008.

Reverse supply chains for the reuse, recycling, and disposal of goods are globalizing. This article critically reviews the environmental, economic, and social issues associated with international reuse and recycling of personal computers. Computers and other e-waste are often exported for reuse and recycling abroad. On the environmental side, our analysis suggests that the risk of leaching of toxic materials in computers from well-managed sanitary landfills is very small. On the other hand, there is an increasing body of scientific evidence that the environmental impacts of informal recycling in developing countries are serious. On the basis of existing evidence informal recycling is the most pressing environmental issue associated with e-waste. Socially, used markets abroad improve access to information technology by making low-priced computers available. Economically, the reuse and recycling sector provides employment. Existing policies efforts to manage e-waste focus on mandating domestic recycling systems and reducing toxic content of processes. We argue that existing policy directions will mitigate but not solve the problem of the environmental impacts of informal recycling. There are many opportunities yet to be explored to develop policies and technologies for reuse/recycling systems which are environmentally safe, encourage reuse of computers, and provide jobs.

1. Introduction

The rapid pace of globalization continues. This is readily apparent from the diverse countries of origin of products on store shelves to the routing of a service request to a call center abroad. While we are accustomed to the idea of an international forward supply chain, reverse supply chains are globalizing as well with much less fanfare. A reverse supply chain is the network of activities involved in the reuse, recycling, and final disposal of products and their associated components and materials. The scale of internationalization of reverse supply chains is significant and increasing. For instance, export of waste and scrap and used goods from the United States was valued at $15 billion in 2005, 1.5% of total exports (*1*). Exports from Japan of recyclable materials such as scrap steel, paper, and plastic have shown dramatic growth in the past decade, on average 17%, 48%, and 25% per year, respectively, from 1993−2003, with exports of scrap steel reaching 5.7 million tons in 2003 (*2*).

At least as far as the public is concerned, the focus issue related to international reverse supply chains has been the environmental impacts of informal recycling activities. End-of-life electronics, for example, are often exported from developed to developing countries and then recycled via a "backyard industry" using primitive processes (*3*). Similar problems have been found for other products, such as informal dismantling of end-of-life ships (*4*). In response to this situation, U.S. nongovernmental organizations (NGOs) have called for bans on trade-in end-of-life goods deemed toxic (*3*).

Reverse supply chains also interface with economic and social issues. While reuse and recycling sectors are often neglected in economic analyses, they can be a significant source of employment and revenue (see section 4) (*5*). From a social perspective, markets for used goods play a role in developing countries in providing broader access to technologies important to both consumer and industrial sectors. A variety of products, including automobiles, computers, and cell phones, are too expensive for many in the developing world to purchase new. The significantly lower price of used goods can make the difference between access and unavailability.

In this article we explore the environmental, social, and economic aspects of a particular international reverse supply chain: reuse and recycling of computers. Computers are an important component of the growing volumes of end-of-life electronics, also known as e-waste. Disposal of used computers in the United States (*6*) and other developed countries is increasing. These computers are resold, sent to landfills, recycled domestically, or shipped abroad for reuse and recycling (*6*). While precise estimates remain elusive, a significant portion of end-of-life computers go abroad and are recycled by an informal or "backyard" industry (*3*). A primary reason that so little is known about the industry is that sales and trade-in used electronics is invisible to the statistics collection systems of most nations. Informal electronics recycling activities have been documented in many parts of the world, including Guiyu and Wenqiao in China (*3, 7–11*), Bangalore, Chennai, Dehli, and New Dehli in India (*3, 12–16*), Lagos in Nigeria (*3*), and Karachi in Pakistan (*3*). These reports indicate serious environmental implications of informal recycling. As seen in Table 1, part of the reason for this is that while computers have valuable recyclable materials they also contain toxic substances of concern. Backyard recycling processes both release these toxins as well as generate new ones. Growth of informal recycling informal reuse/recycling is economically driven

* Corresponding author fax:(480) 965-0557; e-mail: ericwilliams@asu.edu.
† Department of Civil and Environmental Engineering.
‡ School of Sustainability.

10.1021/es702255z CCC: $40.75

Published on Web 08/06/2008

TABLE 1. Content of Valuable and Toxic Metals in Desktop Tower/CRT Monitor

element	amount per unit: desktop and CRT monitor (g)	CERCLA priority ranking of hazardous substances (2007)[a] (*79*)	value (U.S. $)(*80*)
aluminum	680–960 (*17, 22*)	187	$2.0–2.80
antimony	2.4–17.5 (*18, 19*)	219	<$0.1
arsenic	0.06 (*19*)	1	
bismuth	0.23 (*19*)	not included	<$0.1
cadmium	3.28 (*18*)	7	<$0.1
chromium	0.05 (*19*)	77	<$0.1
copper	1370–2640 (*17, 22*)	128	$12–22
gold	0.39–0.67 (*17, 22*)	not included	$12–20
indium	0.04 (*17*)	not included	<$0.1
steel	7300–8880 (*17*)	not included	$6.40–7.70
lead	620–1373 (*17, 22*)	2	$1.70–3.80
nickel	4.5–30 (*17, 19*)	53	$0.10–0.90
platinum	0.066 (*60, 81*)	not included	$4.30
silver	0.86–2.64 (*17, 19, 22*)	214	$0.50–1.50
tin	67 (*22*)	not included	$1.40
zinc	21 (*17*)	74	<0.1

[a] The list has been developed by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). 275 Substances considered to pose the highest potential threat to human health, ranked using an algorithm that considers frequency of occurrence at Superfund sites, toxicity, and potential for human exposure.

because it runs a net profit as opposed to a net cost for recycling in the United States. The economic balance shifts because of higher revenues due to higher demand for used machines and parts, while costs are reduced by lower wages and environmental protection. Socially, computers are of particular importance vis a vis their enabling role in using information and communications technology (ICT). International used markets help to make inexpensive computers available to lower income people.

Our analysis has the following objectives. First, we aim to survey and characterize the environmental, social, and economic aspects of the international reverse supply chain for computers. On the environmental side we wish to examine closely if the risk of toxins leaching e-waste in landfills represents a significant risk and survey the state of knowledge of impacts of informal recycling in developing countries (section 2). We next bring in social and economic aspects, almost never considered in the context of environmental issues. On the social side our goal is to place the reuse of computers in the larger context of the adoption of information and communication technology (ICT) abroad (section 3). For economics, we explore the approximate economic scale of recycling and reuse activities in the United States and abroad (section 4). Current policy efforts to manage the end-of-life of electronics focus on mandating recycling systems, limiting toxic content of products, and trade bans. In section 5 we draw on the results of the review in sections 2, 3, and 4 to briefly discuss the effectiveness and tradeoffs of these policy options. Management of reverse supply chains is a new challenge and merits efforts to develop, evaluate, and realize new options. In section 6 we discuss possible new future policies and technologies aiming to meet multiple societal objectives. We hope that this synthesis of scientific and social perspectives will contribute to future efforts to understand and manage global reverse supply chains.

2. Global Environmental Implications of End-of-Life Computers

In this section we survey what is known about the environmental impacts of computers as pertains to their reverse supply chain. The primary potential impacts are generally conceived to be (1) potential emissions of toxins from disposal in landfills and (2) impacts on workers and communities involved in informal recycling operations in the developing world.

Before surveying these two areas we note that from a life cycle perspective computers are distinct from many other power consuming products in that the energy/resource used in manufacturing can well exceed that associated with operation. For example, the total energy used to manufacture a desktop computer could be as high as 4 times greater than the electricity consumed by the computer while in use (for a home user), and in total, the annual lifecycle energy for owning a computer exceeds that of a refrigerator (*20, 21*). This result can be attributed to the high energy intensity of electronics manufacturing and the rapid rate of obsolescence for personal computers. Thus, extension of lifespan through reuse is a strategy that can be particularly effective at mitigating life cycle impacts (*22*). Reuse of computers and components is a part of the reverse supply chain and thus connected to mitigating lifecycle impacts.

Emissions/Leakages of Toxic Materials from E-waste in Landfills. Computers contain toxic substances such as lead, mercury, and arsenic. Ranges for the typical content of potentially hazardous substances in desktop computers and CRTs are shown in Table 1. While these toxins are embedded inside the computer and separated from the user during operation, concerns have been raised regarding the environmental risk associated with the potential for toxic substances to leach or otherwise be emitted from personal computer equipment when disposed of in landfills. Current policies often target recycling as a preferable alternative to landfilling. The purpose of this section is to analyze the literature and characterize the risk of disposing personal computers to landfills. We note that there are also concerns regarding environmental risks of brominated flame retardants in circuit boards and casings, which may involve exposure associated with operation and/or end-of-life recycling or disposal. This issue is reviewed in the Supporting Information.

What is the degree of risk of emission of lead, mercury, and other heavy metals from electronics in sanitary landfills, and is this risk significant compared to other flows and exposures of these materials? Viewed through the lens of existing regulation, circuit boards and CRT glass in computers are classified as hazardous waste as defined by EPA standards, i.e., defined in terms of the Toxicity Characteristics Leaching Procedure (TCLP). This procedure involves grinding the test material, placing it in a buffered acidic solution (pH 4.93 ± 0.05), and then measuring the levels of lead, mercury, and other heavy metals which leach out after 18 ± 2 h. TCLP tests have shown that circuit boards and CRT glass exceed EPA limits for lead leachability (*23–25*). Furthermore, in standard and modified TCLP tests performed by Musson and colleagues on 13 different types of electronic devices, including

CPUs, CRTs, and laptops, lead concentrations also exceeded the Federal TCLP limits for classification as hazardous waste (*26*).

While the TCLP tests are the basis for current practice in the United States to classify waste materials as hazardous, they do not necessarily reflect the actual potential for leaching from the same waste material in a sanitary landfill. One reason for this is that the leaching liquids used in the TCLP test are considerably more aggressive, i.e., have a much lower pH, than typical municipal solid waste (MSW) leachate. A second reason is that there are a variety of attenuation mechanisms for heavy metals in sanitary landfill leachate, including formation of heavy metal precipitates due to the presence of sulfide, carbonate, and hydroxide ions and adsorption/absorption of heavy metals within the waste mass (*27*). Jang and Townsend compared leaching rates measured using the TCLP with leaching rates measured using leachate samples from 11 Florida landfills. A representative result was that crushed circuit boards and CRTs leached lead at average concentrations of 2.23 and 4.06 mg/L, respectively, using landfill leachate samples (well below the regulatory standard for classifying waste as hazardous in the TCLP), versus average concentrations of 162 and 413 mg/L using the TCLP solution, a difference of 2 orders of magnitude (*23*). Vann and colleagues studied how a CPU's heavy metal composition can affect lead leachability during the TCLP. Their study found that iron and zinc leached from the CPU contributed to suppression of lead leachability and that larger ferrous metal amounts in the electronic device led to lower lead concentrations in the TCLP (*28*).

Given the shortcomings in the TCLP test protocol discussed above, observations of heavy metal concentrations in leachate sampled from actual landfills, as opposed to laboratory leaching tests, are likely a better measure of the potential environmental threat due to e-waste in landfills. The mean concentration of lead in 2539 leachate samples from over 200 municipal solid waste landfills in a 2000 US EPA-funded study was 0.021 mg/L, the mean value was 0.133 mg/L, and the 90th percentile value was 0.250 mg/L (*29*) (1−2 orders of magnitude below levels of regulatory concern). Kjeldsen et al. (2002) summarize available data on lead concentrations in leachate for European landfills, including average lead concentrations from a 2001 study of 106 old Danish landfills, a 1999 study of 4 additional Danish landfills, a 1999 study of 20 German landfills, and a 1998 report on a full-scale leachate recirculation test cell and the range of lead concentration for 6 old landfills from the United Kingdom (*30*). The average lead concentration in leachate values varies from <0.005 to 0.188 mg/L, and the range for the United Kingdom landfills is from <0.04 to 0.13 mg/L, consistent with the values from the U.S. EPA study. Heavy metals, primarily mercury, may also be found in landfill gas. However, field data indicates that the quantities of heavy metals in landfill gas are also relatively low. Data from a Delaware Solid Waste Authority Sanitary landfill yielded mercury concentrations on the order of nanograms per cubic meter (*27*). In addition, we note that waste fluorescent lamps from buildings contribute about 1000 times more mercury to landfills than computers (*31*).

Concentrations of heavy metals in landfill leachate and landfill gas are only part of the overall question of how well sanitary landfills manage the toxic materials put into them. In addition, the containment, collection, and treatment of leachate and gas must also be considered. The primary pathways for the release of heavy metals from a landfill into the environment are by advective flow of landfill gas and leachate. Heavy metals may also be released from landfills by solid-state diffusion, but diffusive flux of heavy metals from landfills is generally too small to be considered of significance (*32*). Landfill gas collection efficiency in sanitary landfills has increased markedly since the 1993−1994 EPA study cited above due to the promulgation of the EPA's New Source Performance Standards for landfill gas control in 1996 and 1998 (40 CFR Parts 51, 52, and 60). This suggests that release of mercury from landfills is even lower than cited in the 1993−1994 study. Modern lined landfills collect over 99% of the leachate they generate (*33*); thus, heavy metal releases from modern lined facilities are very small.

We note that unlined landfills are still used in some parts of the United States under a "grandfather" clause in the federal regulations enacted in 1993 mandating modern engineered liner and leachate collection systems for MSW landfills. A study of leaching from 146 older, unlined U.S. landfill sites found only two cases of measurable leakage of lead into groundwater, attributed to large quantities of lead-containing industrial waste in the two landfills (*34*). Turbini and collaborators note that lead in circuit boards represents less than 4.4% of total lead found in landfills, and SWANA (2004) notes that despite the increase in the volume of e-waste in recent years, quantities of lead disposed of in MSW landfills have decreased over the past 15 years due primarily to the recycling of lead-acid batteries. Thus, even in older unlined landfills the risk of discharge of heavy metals leached from e-waste to the environment appears to be very small (*27*). This conclusion is consistent with the conclusion from SWANA (2004) that "MSW landfills can provide for the safe, efficient, and long-term management of disposed products containing RCRA heavy metals without exceeding limits that have been established to protect public health and the environment." (*27*) The combination of data on heavy metal concentrations in landfill leachate and mercury emissions in landfill gas along with evidence that modern landfill containment systems do an excellent job in preventing migration of these hazardous substances from the landfill (*35*) suggest that potential for discharge to the environment of hazardous substances from e-waste disposed of in a well-run modern landfill is negligible. Poorly designed, constructed, and operated landfills and older unlined landfills, on the other hand, may discharge some hazardous substances from e-waste to the environment (though the data suggests the actual level of emissions is still likely to be small).

Is recycling actually environmental preferable to putting e-waste in sanitary landfills? We argue that this is not known and that it is conceivable that recycling could emit more toxic heavy metals over the lifecycle. Recycling by definition mobilizes materials (e.g., via smelting) and depending on the level of process control can emit lead, mercury, and other hazardous substances. In contrast with landfills, however, recycling has the virtue of replacing production of virgin materials with recycled substitutes. If the avoided lead emissions associated with mining and milling are larger than for recycling, recycling would reduce total lead emissions. If not, recycling e-waste has the potential to release more lead to the environment than e-waste in landfills. At the time this review was undertaken, we identified no analyses addressing under what circumstances which option (recycle versus landfill) leads to lower lifecycle emissions of heavy metals. This question should be studied before public policy mandates recycling as the default environmentally preferable alternative.

Impact on Workers and Communities Involved in Informal Recycling in the Developing World. Informal recycling of e-waste in developing nations has come under increasing public scrutiny. Exposés by NGOs such as the Basel Action Network (BAN), the Silicon Valley Toxics Coalition, and Toxics Link argue that home-grown computer reuse/recycling systems in China, India, and Nigeria are causing serious environmental problems (*3, 16, 36*). For example, wires are pulled from computers, collected, and burned in open piles to remove casings and recover copper.

TABLE 2. Concentrations of Pollutants near Informal Recycling Sites in Guiyu, China (*9, 11, 40–45*)

contaminant	air (ng/m³)	sediments (mg/kg)	soil (mg/kg)	water (μg/L)
cadmium	7.3[a] (*42*) 7.3[b] (*42*)	n.d.−10.3 (*41*)	5.51−43[c] (*11*) n.d.[d] (*11*)	0.073−0.362 (*40*)
copper	483[a] (*42*) 126[b] (*42*)	17.0−4.5 (*41*)	1374−14 253[c] (*11*) 29.5−42.7[d] (*11*)	5.92−67.3 (*40*)
lead	444[a] (*42*) 392[b] (*42*)	28.6−590 (*41*)	856−7038[c] (*11*) 80−93[d] (*11*)	1.33−2.24 (*40*)
nickel	10[a] (*42*) 7.2[b] (*42*)	12.4−543 (*41*)	85−722[c] (*11*) 5.5−20[d] (*11*)	29.8−66.0 (*40*)
PAH	40.0−347[a] (*42*) 22.7−263[b] (*42*)	0.1−0.51 (*9*) 0.24[d] (*9*)	0.593[e] (*9*) 1.0−3.2[c] (*45*) 0.09[d] (*9*)	
PCDD/Fs	0.065−2.77 (*44*)		0.013−0.090[f] (*43*) 0.004−0.01[g] (*43*)	
PBDD/F	0.008−0.46 (*44*)			

[a] Associated with total suspended particles. [b] Associated with Particulate matter with diameter smaller than 2.5 μm. [c] At open burning site. [d] At reservoir. [e] At printer roller dump soils. [f] At acid leaching facilities. [g] At duck pond close to open burning site.

TABLE 3. Used PC and Monitor's Average Price in Developing Countries[a]

country	used tower/monitor	price
China	Pentium 4, 2.4−2.8 GHz/256 MB/40 GB	$170−200
	Pentium 4, 1.6−2.26 GHz/256 MB/40 GB	$140−150
	Pentium III, 600 MHz/128 MB/20 GB	$65−85
	Pentium II, 450 MHz/128 MB/4.7 GB	$20−30
	17″ CRT monitor	$20
	19″ CRT monitor	$70
	21″ CRT monitor	$80
	17″ LCD monitor	$130
India	Pentium 4, 1.6−2.4 GHz/256 MB/40 GB	$155−185
	Pentium III, 600 MHz/128 MB/20 GB	$50−70
	Pentium II, 450 MHz/128 MB/5 GB	$20−30
	17″ CRT monitor	$20
	19″ CRT monitor	$75
Peru	Pentium 4, 2.26−2.4 GHz/256 MB/40 GB	$200−240
	Pentium 4, 1.7 GHz/256 MB/40 GB	$140−160
	Pentium III, 1 GHz/256 MB/20 GB	$115−130
	Pentium III, 866 MHz/128 MB/20 GB	$80−90
	Pentium III, 733 MHz/128 MB/10 GB	$65−75
	15″ CRT monitor	$20−40
	17″ CRT monitor	$50−60

[a] Source: websites for used computer sales.

Circuit boards are treated to extract copper and precious metals using acid, cyanide, and/or and mercury, sometimes next to rivers.

There is an increasing body of scientific evidence confirming that the emissions and contamination associated with informal electronics recycling are indeed a serious concern. Researchers have undertaken field measurements of concentrations of metal and organics in ground, water, and air in Guiyu, China, the most well-known center of informal electronics recycling. Table 2 summarizes sample results from a number of studies of emissions of heavy metals, 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).

The release of heavy metals to water, for example, is thought to be mainly due to acid leaching of circuit boards next to the nearby Lianjiang and Nanyang rivers. Open combustion of equipment produces and emits dioxins, furans, and PAHs. In addition, the high degree of air emissions of PCDD/F and PBDD/F from open combustion of e-waste has been corroborated in laboratory simulations of the processes (*37*). To benchmark the emission figures in Table 2, note that measured Cd, Cu, and Ni levels in rivers exceed the EPA's criteria for freshwaters of 0.25, 9.0, and 52 μg/L, respectively, potentially risking aquatic communities in the river (*38*). Li and collaborators analyze dioxin and furan emissions and assert that total daily exposures to dioxins and furans in Guiyu are 15−56 times higher than the World Health Organization's recommended limits (*39, 44*).

Furthermore, studies have begun to explore human exposure to hazardous pollutants emerging from Guiyu's recycling activities. Measurements of blood lead levels were taken for children under 6 years old and compared to levels in Chedian, a textile industry town with no e-waste recycling industry, located to the southwest of Guiyu. Results were that children in Guiyu clearly had higher blood lead levels. A sample of 165 Guiyu children had lead levels from 4.4 to 33 μg/dL with 80% exceeding 10 μg/dL, while a sample of 61 Chedian children showed a range of 4.0−23 μg/dL with 38% exceeding 10 μg/dL (*8*). Note that blood lead levels exceeding 10 μg/dL are considered of concern by the U.S. Center for Disease Control and Prevention.

While further work is needed, these initial studies suggest that the environmental impact of informal recycling are the most significant of human health impacts associated with the lifecycle of ICT equipment.

3. Social Issues

The social and cultural implications of ICT are profound, little understood, and almost never addressed in environmental critiques of the sector; while this should not necessarily be allowed to delay implementation of environmental and e-waste initiatives, it is a glaring gap in any systemic effort to understand the sustainability implications of the sector (*46*). Personal computers in particular are important for social and economic development. They are key in running modern businesses and play an important role in education. The digital divide, which is the disparity between the adoption of ICT in the industrialized and industrializing world, continues to contribute to the gap in wealth. While there are many factors associated with the digital divide, the expense of ICT goods and infrastructure is one important obstacle (*47*). In addition, computers are a key tool for education and if used appropriately can bring important benefits for students, teachers, and their interaction. Computers are capable of incorporating an individualized interactive approach where the information is not only presented to the student but also received from the student (*48*). Lack of resources in developing countries and low-income communities in some developed countries create an educational disadvantage that not only affects the education per se but has an important impact on societies.

International trade-in quality used equipment represents an opportunity to bridge the digital divide by making computers more affordable. It is important to note that the price gap between used and new computers, expressed in terms of purchasing power, is far larger for those in developing countries than for those in rich nations. For example, for many U.S. consumers faced with the choice between a $700 new system or a $200 used one, the $500 difference does not pose an a particular burden. They generally choose the new system. For consumers in poorer countries, however, this difference can be decisive in enabling the purchase. Table 3 shows some used computers and monitor's average price in developing countries. A "starter" system, outdated compared to the state of the art but capable of handling office, education, and Internet applications, can be purchased for less than $100. Up-to-date, powerful systems can be purchased for around $300. In terms of software, while in principle open source options such as Linux are available, in practice the use of pirated operating systems and applications is common. The supply of used computers is and believed to be primarily, but not exclusively, from users in the developed world. It is important to note that the purchase of a new computer is normally driven by the desire to update software or other functionality, not due to breakage of the machine. In addition, computers are often stored unused in closets for years before being resold or otherwise disposed of (*49*). There are important questions to answer regarding how a timely flow of quality used equipment might better contribute to mitigating the digital divide.

Lastly, note that reuse and recycling of a computer is a source of employment in developing countries. Although the environmental and human negative impacts of informal recycling are clear and present, that the sector opens job opportunities also needs to be understood and addressed (*50*).

4. Economic Scale of the Reverse Supply Chain

Reuse and recycling activities are growing, especially in developing countries. Their economic scale and growth is difficult to gauge because current economics statistics and modeling systems generally ignore reuse, recycling, and waste management activities compared to traditional sectors such as agriculture, manufacturing, and services. In this section we combine alternate information sources to estimate the economic scale of computer reuse and recycling. To first review used computer markets, according to a study conducted by the International Data Corporation (*51*), the U.S. 1997 domestic used computer market was 5.5 million units with 14% annual growth. The study also predicted that the growth in the used market would decline to 10% growth per year due to competition from lower-priced new PCs. One estimate put the scale of domestic sales of PCs (including used) in the United States at 30.3 million machines in 1998 (*52*), suggesting that the used market has around an 18% market share in unit sales. While we found no publicly available follow-up analysis on U.S. reuse markets, our informal discussions with industry experts indicate that the domestic used computer market has suffered due to continuing price reductions of new PCs (*53, 54*). On the plus side, Internet auctions have proved to be a popular way to connect buyers and sellers of used equipment. E-Bay in particular facilitates a booming trade in ICT equipment, valued at about billion in 2001, of which 46% is used equipment, 14% refurbished, and 40% new (*55*). Looking abroad, consultants in Japan estimates the 2001 domestic market for used computers at 830 000 machines and on track for 18% annual growth in 2002 (*56*). By comparison, the Japanese market for new PCs in 2001 was 12 million units, down 11% relative to 2000 (*57*). More recently, consultants have analyzed the used computer market in the developing world and found it robust and growing, estimating 55 million machines being reused in 2004 with this figure doubling by 2009 (*58*). While 55 million used computers are certainly worth less the production of 240 million new ones (*60*), the secondary market is still of significant scale. The International Association of Electronics Recyclers reports annual revenues in 2006 of 1.5 billion of the combined U.S. reuse and recycling activities of member companies (*59*). To estimate the economic scale of recycling activities only, we assume that the recycling fee of a takeback system is analogous to price and multiply by the number of machines recycled. Note that the costs of recycling vary considerably from nation to nation. Japan has a relatively high recycling fee, with around $50 charged to recycle a desktop system with monitor. In Switzerland, the figure is around $50 per desktop system. The likely explanation for this large gap is that the Japanese system relies on manual separation while in Switzerland (and the U.S.), shredders are used to automate the process. Assuming a $10 per system fee in the U.S., the economic scale of 2005 computer recycling of 30 million machines is US$300 million. Revenues from U.S. sale of new machines are estimated at $90 billion (*60*), thus recycling is roughly 0.3% of market value.

Moreover, in the developing world recovering reusable machines, parts, and materials from obsolete equipment is a source of income for poor communities. Is the potential economic/employment contribution of a reuse/recycling sector significant? It is difficult to draw definitive conclusions given the current lack of information. Drawing on a case study of the informal CRT disassembly/regunning industry in Delhi, India (*61*), one can make a rough estimate of potential global scale. There are around 1 billion computers in use (*82*); we estimate that around 200 million become e-waste each year. This presumes a 5-year lifespan, a rough guess of the global average for the interval between purchases (it is 3 years in Japan (*62*)) and ignores the time spent in storage before eventual disposal (also about 3 years in Japan (*62*)). Amit Jain estimates that CRT reuse/recycling in Delhi uses 3000 total man hours at $2/h to process 350 CRTs, generating $50 revenue per unit (*61*). Scaling up these microresults suggests a global employment of 860 000 persons and $10 billion revenue if all computer reuse/recycling was implemented as in Delhi. The global industry producing new personal computers was worth $275 billion in 2003 (*60*); so, reuse/recycling is worth 3.6% of manufacturing. While we emphasize that this is a preliminary back-of-the-envelope estimate, it indicates that computer reuse/recycling can be viewed as an economic sector of reasonable scale in its own right.

5. Existing Strategies To Manage Reverse Supply Chains for Computers

E-waste has garnered public attention leading to policies and other efforts aimed to manage reverse supply chains for computers and other electronics. In this section we consider the three main policy approaches being applied in the electronics sector in light of the review of environmental, social, and economic issues in sections 2, 3, and 4. As quickly becomes clear, these policies have been adopted with different justifications and created unexpected consequences. Such difficulty is common in the policy arena, where competing interests support and oppose policies for a variety of different reasons and the link between knowledge and policy is not at all clear. By highlighting these issues, the challenges involved in connecting new knowledge about reverse supply chains to future policies becomes more tangible. Given this appreciation of the complexity of the policy process, the main purpose of this section is to contrast the different ways currently used to deal with the growing e-waste problem.

Legislating Takeback/Recycling Systems. The idea is to establish a system which ensures that waste computers and other electronics from households and businesses are collected and recycled, generally within legislative borders. The stated goals of this strategy are management of risks from toxic substances and improvement of recycling rates of materials such as steel, aluminum, plastics, and precious/rare metals. At the national level, Belgium, Denmark, Italy, Korea, Japan, The Netherlands, Norway, Portugal, Sweden, Switzerland, and Taiwan are countries that have already legislated takeback/recycling systems for different categories of electronics (including computers). The most well-known example has the broadest geographical scope: the Waste Electronic and Electronical Equipment (WEEE) Directive mandates electronics takeback/recycling systems for all 27 countries in the European Union (EC 2003) (*63*). This legislation along with RoHS (discussed below) are inducing major effects on the global electronics industry and indeed could be said to dominate the environmental activities of most manufacturers. In the United States a number of states have already or are moving to enact takeback systems (*64*). Briefly, the structure of the existing takeback/recycling system is that recycling fees are collected from either the consumer or the manufacturer and used to pay for logistics and recycling.

What are the environmental, social and economic benefits and costs of the takeback/recycling approach? While it is often taken for granted that recycling automatically entails net environmental benefits, we argue that that is not clear if computer takeback/recycling systems yield a net environmental benefit. Takeback and recycling affects flows of computers to landfills, reuse markets, and informal recyclers abroad. Diverting e-waste from landfills, as discussed in section 2, apparently does not directly lower risk of exposure to toxics. There are indirect benefits from recycling due to recycled materials substituting for mining and processing of virgin resources. Diverting computers away from informal recycling entails a significant environmental benefit. What particularly complicates the situation is that the environmental benefits of reusing computers far outweigh recycling (*22*). Depending on how it is implemented, a takeback/recycling system can either stimulate or inhibit reuse. We argue that increases or decreases in reuse significantly lower or increase net environmental impacts but are currently poorly understood. It is important to note that promoting and tracking reuse is not explicitly incorporated into most current takeback systems. Socially, takeback/recycling stimulates domestic logistics and recycling sectors, but reduces employment abroad if exports are diverted. Economically, domestic takeback systems normally represent a net cost because a domestic materials recycling-focused system is a net cost operation (thus the need for recycling fees).

Regulating Content of Toxics. The principle of this strategy is to find alternatives to replace materials of concern in electronics. By far the most important example of a policy enacting this approach is the Restriction on Hazardous Substances (RoHS) Directive, which bans or controls certain materials in electronics for all products sold in the European Community (*65*). RoHS restricts six hazardous elements in different applications: lead, mercury, cadmium, hexavalent chromium, and the polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) flame retardants in casings and circuit boards.

While the initiative shown in developing legislation such as RoHS is laudable, the domestic environmental benefits, at least with regard to heavy metals, are not clear. Heavy metals are embedded within components and do not pose an exposure risk during normal operation. The potential benefit of reduced content of heavy metals is lower leaching from landfills and emissions from recycling processes. The review in section 2 suggests the environmental risks of leaching are not significant. Exposure during recycling, at least in domestic facilities, has yet to be assessed. The case of brominated flame retardants is distinct from heavy metals in that the main exposure is presumably during use. Removing these from products has clear potential to reduce exposure.

Another key question is whether the alternatives to the banned toxins are indeed safe enough to be considered a solution. For example, there are a variety of alternatives to conventional lead−tin solder: tin−zinc, tin−bismuth−silver, tin−bismuth−silver−copper, tin−silver−copper, and tin−silver−copper−antimony. While one presumes that lead-based formulations will have the highest toxicity, the lifecycle of solder entails additional types of impacts such as climate change, ozone, particulate emissions, and eutrophication. Lifecycle impact assessment studies of solders suggest that nontoxicity risks of alternatives are often higher than lead-based versions, partly driven by the additional energy use associated with higher melting points (*66–68*).

Though apparently unforeseen when the legislation was developed, the main environmental benefit of RoHS could be in reducing exposure to workers and communities in developing countries involved in electronics recycling. Indeed, NGOs advocate removal of toxins as a key strategy to mitigate environmental impact in the informal recycling sector (*3*). While removing toxins from electronics will yield benefits, the crucial yet largely unrecognized point is this: it solves only part of the problem. There are significant emissions of toxins *generated* by informal recycling processes that were *not present* in the original computer. Even with a hypothetical computer containing no toxic substances, informal recycling would still generate significant harmful emissions such as dioxins, furans, acids, and cyanide. To fully mitigate environmental risk, a computer designed for informal recycling would need to be safe for open burning and also contain no precious metals which recyclers would recover using environmentally destructive processes. While the future may hold an entirely new design paradigm for ICT equipment, such a computer is not possible on the current technological horizon. Economically, at least in the short term while research, developing, and retooling is underway, materials restrictions increase the price of computers. The degree of short-and long-term price changes is not yet clear.

Trade Bans. The idea is to manage the environmental impacts associated with the informal recycling of waste electronics by cutting off the supply through import and export bans. This approach is particularly advocated by NGOs, who argue that the trade in waste electronics is unethical and in violation of international law (*3*). Trade bans could be implemented through a variety of mechanisms, ranging from multilateral environmental agreements, national level import/export law, to firm-level certification programs.

At the international level, the central framework for controlling international movements of hazardous substances is the Basel Convention (*69*). The Basel Convention requires prior notification between signatories when trading wastes classified as hazardous. Many categories of e-waste are classified as hazardous waste and thus are targeted for prior notification. Products intended for reuse, however, are exempt from control. The Convention does not however suggest how to establish the reusability of a given trade flow in practice, a nontrivial challenge. There is also a proposed amendment to the Convention, the so-called Basel Ban, which forbids international trade in all the materials categorized by the Convention as hazardous. This amendment has not been ratified and seems unlikely to be in the near future. The European Union, nonetheless, has stated its intention to voluntarily abide by the ban. Enforcing this ban in practice is complicated by the broadened membership in the EU (*70*).

At the national level, a number of countries have implemented bans or restrictions on imports of e-waste, which can include used computers. For example, China implemented a ban on imports of waste and used electronics in 2000 and further tightened it in 2002 (*71*). Due to lack of enforcement, however, imports continue, and the situation in Guiyu is much the same in 2007 as it was in 2002 (*72*). The major challenge is that e-waste processing is an income-generating industry in conditions with low labor costs. Thus, there is an economic incentive for the industry to develop wherever conditions are favorable. There is also the potential for displacement: successful enforcement of a ban in one area results in a shift to another with laxer regulation.

What are the environmental, social, and economic implications of a trade ban? Presuming successful enforcement, reduction of supply to informal recycling industries would mitigate environmental damage abroad. On the other hand, if the system inhibits reuse, additional manufacturing impacts associated with producing additional equipment are induced. Still, the serious problems with informal recycling reviewed in section 3 suggest that informal recycling impacts ought to take priority over manufacturing ones. Socially, reduction of trade in used equipment reduces availability to consumers in developing countries. Economically, a successful ban would eliminate jobs of those working in recycling and reuse. Compared to domestic reuse and recycling, a trade ban implies higher costs since it centers activities in areas with higher costs (labor) and lower revenues (less demand for parts and used equipment).

6. Directions for Future Management of International Reverse Supply Chains

We argue that none of the three policy types discussed in section 6, even if cumulatively and successfully applied, would solve the environmental problem associated with informal recycling in developing countries. The basic issue is increasing domestic generation of e-waste in the developing world. Consumption of computers and other electronics in many parts of the developing world is rising rapidly (*73*). Corresponding growth in the recycling infrastructure is not evident, and even if present, the same economics which drives exports from the United States abroad would likely stimulate trade between developing countries in e-waste. We thus argue that informal recycling is likely to increase even if the United States and other developed countries ban exports. Removing heavy metals and brominated flame retardants from computers would reduce impacts in informal recycling but not affect the considerable generation of toxins in the recycling processes. While emissions would be reduced and the consciences of developed world consumers assuaged, significant emissions due to informal recycling would continue.

If one includes social and economic considerations, the ethics of these policies become more complex. For example, is it ethical to ban a trade which enables employment for thousands of people in poverty without first making an attempt to address occupational risks in the industry? Is it ethical to undertake policies which will increase the price of computers for lower income consumers? We do not purport to have the answers but point out that policies imply tradeoffs between environmental, social, and economic issues.

The management of international reverse supply chains is a new challenge. We have shown that there are potent linkages between environmental, social, and economic issues. We thus argue that societies should explore policies and technology aiming to mitigate environmental impacts while improving social and economic benefits. It may turn out in the end that we are faced with the choice of choosing either environment or economy. Until society broadly considers its options however, possible paths and their multiple implications are not clear. In the remainder of this section we discuss issues we view as key to future work to develop, assess, and implement new systems for the sustainable management of the end-of-life electronics.

New Policies To Address Informal Recycling. Section 2 supports the case that environmental impacts of informal recycling are indeed severe. Given that these are likely the primary health impacts associated with the lifecycle of electronics, we argue that addressing informal recycling should be the main priority for environmental management efforts. Before exploring avenues to do so, we first discuss the question of responsibility. If informal recycling is driven by imports from the developed world, some argue that the developed world bears a degree of responsibility for resulting environmental impacts (*74, 75*). The situation is analogous with the case of “sweatshops” in the developing world. Increased concern over regional and global pollutants such as sulfur dioxide and carbon dioxide has stimulated awareness that purely domestic considerations can lead to leakage of emissions abroad (*76*). The question of responsibility for emissions with only local effects is an ethical one. We believe that enjoying the benefits of a product or service entails a measure of responsibility for what happens up and downstream. Does informal recycling only cause local environmental problems or regional ones as well? This needs to be explored further, but regardless of the answer we argue that actions should be taken to mitigate the local problems.

Having set this context, the next question is how occupational health and safety in the informal sector can be improved. There two basic approaches. The conventional approach is regulation: banning industry practice not meeting a certain standard. Presumably this would be done in conjunction with the establishment of a formal recycling infrastructure to handle displaced demand. The challenge is the economic stimulus driving the growth of the informal industry: enforcement is needed. In areas of the world with limited resources for governance, of which there are many, enforcement is a challenge. The continuation of informal recycling in Guiyu despite policies and the attention of the world is evidence of this (*71*).

The second approach is providing incentives for informal recyclers not to engage in destructive processes (*5*). A specific proposal is to fix market prices for select parts resulting from the disassembly process which result in environmental damage when recycled informally (such as circuit boards). The price is set to create a financial incentive for informal recyclers to deliver parts to central collection sites rather than process them on their own. This could be implemented as a government program which, in addition to mandating prices, would also ensure that these collected parts are processed in appropriate recycling facilities. The idea is to mitigate environmental impacts while maintaining reuse, profitability, and employment in the sector. Further work is needed, however, to determine the structure and flows of an environmentally and economically effective system (*5*).

Engineering/Policy Integration. Engineering has an important potential role to play in realizing policy systems and practice which achieve multicriteria objectives for international reuse/recycling systems. In the arena of Design for the Environment (DfE), physical design specifications such as material selection and assembly structures (i.e., screws versus snap fits) influence the performance of international reuse/recycling systems.

There is an additional design layer less often considered: using information technology to construct information systems to enhance the reusability and recyclability of products. For example, radiofrequency identification devices (RFIDs) could be placed in computers to provide information wirelessly to reuse/recycling systems (*77*). One concept is an RFID "blackbox" for each computer, which periodically records the functionality of different subsystems. At the end of life, a computer arriving at a processing center is wirelessly scanned for functionality and selected for reuse versus recycling. Tele-inverse manufacturing applied to disassembly and recycling is another application of informatics (*78*). The emphasis here is on remote observation and management of an international network of reuse and recycling facilities using advanced telecommunication systems. This concept could play a role in policy systems which rely on certification of appropriate treatment of internationally traded second-hand electronics/e-waste.

The above represents but a subset of the opportunity of new technologies and polices which could realize a reuse and recycling system that is environmentally safe and efficient, increases access to ICT equipment, and provides jobs. The challenge to explore, select, and make such systems a reality has arrived. We hope to see a broad and international group of activities develop to take on this challenge.

Acknowledgments

This work was supported in part by a U.S. National Science Foundation grant via Grant CBET-0731067 in the Environmental Sustainability program. The authors thank Zachary Pirtle and the manuscript reviewers for their valuable comments on this paper.

Supporting Information Available

Additional contextual information, review of environmental concerns associated with brominated flame retardants, information on computer recycling policies and donation/resell activities. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) U.S. International Trade Commission. USITC Interactive Tariff and Trade Data, Web Version 2.8.4, 2007; http://dataweb.usitc.gov/ (accessed Aug 23, 2007).

(2) Terazono, A.; Yoshida, A.; Yang, Y.; Moriguchi, Y.; Sakai, S. Material cycles in Asia: especially the recycling loop between Japan and China. *J. Mater. Cycles Waste Manag.* **2004**, *6*, 82–96; http://www.springerlink.com/content/98tf0eqmt5emvrdy/fulltext.pdf(accessed Aug 24, 2007).

(3) Basel Action Network (BAN) and Silicon Valley Toxics Coalition (SVTC). Exporting Harm: the High-tech Trashing of Asia, BAN, Seattle, WA and SVTC, San Jose, CA, 2002; http://www.ban.org/E-waste/technotrashfinalcomp.pdf (accessed Aug 23, 2007).

(4) Buerk, R. *Breaking Ships*; Chamberlain Brothers: New York, 2006.

(5) Williams, E. Mandated prices as an instrument to mitigate environmental impacts in informal reuse/recycling. *Proceedings of The Second National Institute for Environment Studies (NIES) Workshop on E-waste*, Nov 23, 2005, Tokyo, Japan; pp 43−56.

(6) United States Environmental Protection Agency (USEPA). Management of Electronic Waste in the United States, 2007; http://www.epa.gov/ecycling/manage.htm (accessed Aug 24, 2007).

(7) Qu, W.; Bi, X.; Sheng, G.; Lu, S.; Fu, J.; Yuan, J.; Li, L. Exposure to polybrominated diphenyl ethers among workers at an electronic waste dismantling region in Guangdong, China Environ. Int. 2007, *33*(8), 1029−1034.

(8) Huo, X.; Peng, L.; Xu, X.; Zheng, L.; Qiu, B.; Qi, Z.; Zhang, B.; Han, D.; Piao, Z. Elevated Blood Lead Levels of Children in Guiyu, an Electronic Waste Recycling Town in China. *Environ. Health Perspect.* **2007**, *115* (7), 1113-1117.

(9) Leung, A.; Cai, Z. W.; Wong, M. H. Environmental contamination from electronic-waste recycling at Guiyu, Southeast China. *J. Mater. Cycles Waste Manag.* **2006**, *8* (1)2133; http://www.springerlink.com/content/g8k452x2542hk200/(accessed Feb 2007).

(10) Tong, X.; Wang, J. Transnational Flows of E-Waste and Spatial Patterns of Recycling in China. *Eurasian Geogr. Econ.* **2004**, *45* (8), 608–621.

(11) Wong, M. H.; Wu, S. C.; Deng, W. J.; Yu, X. Z.; Luo, Q.; Leung, A. O. W.; Wong, C. S. C.; Luksemburg, W. J.; Wong, A. S. Export of toxic chemicals - A review of the case of uncontrolled electronic-waste recycling. *Environ. Pollut.* **2007**, *149* (2), 131–140.

(12) Jain, A.; Sareen, R. E-waste assessment methodology and validation in India. *J. Mater. Cycles Waste Manag.* **2006**, *8*, 40–45.

(13) Keller, M. Assessment of gold recovery processes in Bangalore, India and evaluation of an alternative recycling path for printed wiring boards, A Case Study. Diploma thesis at the Institute for Spatial and Landscape Planning, Regional Resource Management at the ETH Zurich, Oct 2006.

(14) Steiner S. Risk assessment of e-waste burning in Delhi, India. Diploma Thesis, Federal Institute of Technology ETH, Zurich, Oct 2004.

(15) Streicher-Porter, M.; Widmer, R.; Jain, A.; Baderd, H. P.; Scheideggere, R.; Kytzia, S. Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi. *Environ. Impact Assess. Rev.* **2005**, *25*, 472–491.

(16) *Toxics Link. Scrapping the High-tech Myth, Computer Waste in India*; Toxics Link: Delhi, 2003.

(17) Maeda, H.; Yamamoto, K. Evaluation of the environmental acceptability and efficiency of resource recovery from products container circuit board in personal computers. Master's thesis, Tokyo University, 2002.

(18) AEA Technology. WEEE & Hazardous Waste: A report produced for DEFRA, AEAT/ENV/R/1688, Mar 2004.

(19) Malhammar, G. Chemical Analysis of Printed Board Assemblies, High Density Packaging User Group (HDPUG) Report, Apr 2000.

(20) Williams, E. Energy intensity of computer manufacturing: hybrid analysis combining process and economic input-output methods. *Environ. Sci. Technol.* **2004**, *38* (22), 6166–6174.

(21) Williams, E.; Ayres, R.; Heller, M. The 1.7 kg microchip: Energy and chemical use in the production of semiconductors. *Environ. Sci. Technol.* **2002**, *36* (24), 5504–5510.

(22) Kuehr, R.; Williams, E., Eds.; *Computers and the Environment: Understanding and Managing their Impacts*; Kluwer Academic Publications: Dordrecht, 285 pages, 2003; 285 pages.

(23) Jang, Y. C.; Townsend, T. G. Leaching of Lead from Computer Printed Wire Boards and Cathode Ray Tubes by Municipal Solid Waste Landfill Leachates. *Environ. Sci. Technol.* **2003**, *37* (20), 4778–4784.

(24) Townsend, T.; Jang, Y.; Tolaymat, T.; Jambeck, J. Leaching tests for evaluating risk in solid waste management decision making. Draft report. Florida Center for Solid and Hazardous Waste Management: Gainesville, FL, 2001.

(25) Yang, G. Environmental threats of discarded picture tubes and printed circuit boards. *J. Hazard. Mater.* **1993**, *34* (2), 235–243.

(26) Musson, S. E.; Vann, K. N.; Jang, Y. C.; Mutha, S.; Jordan, A.; Pearson, B.; Townsend, T. G. RCRA Toxicity Characterization of Discarded Electronic Devices. *Environ. Sci. Technol.* **2006**, *40*, 2721–2726.

(27) SWANA. The Effectiveness of Municipal Solid Waste Landfills in Controlling Releases of Heavy Metals to the Environment, Solid Waste Association of North America Applied Research Foundation, Silver Springs, MD, Nov (Revised) 2004.

(28) Vann, K.; Musson, S.; Townsend, T. Factors affecting TCLP lead leachability from computer CPUs. *Waste Manage.* **2006**, *26*, 293–298.

(29) SAIC. Characterization and Evaluation of Landfill Leachate. Draft report prepared by Science Applications International Corporation, Arlington, VA, for the US EPA, Sep 2000.

(30) Kjeldsen, P.; Barlaz, M. A.; Rooker, A. P.; Baun, A.; Ledin, A.; Christensen, T. H. Present and Long-Term Composition of MSW Landfill Leachate: A Review. *Crit. Rev. Environ. Sci.Technol* **2002**, *32* (4), 297–336.

(31) United States Environmental Protection Agency. Mercury Emissions from the Disposal of Fluorescent Lamps: Final Report, Washington, D.C., **1997**.

(32) Rowe, R. K. Long Term Performance of Containment Barrier Systems. *45th Rankine Lecture Geotechnique.* **2005**, *55* (9), 631–678.

(33) Bonaparte, R.; Daniel, D.; Koerner, R. *Assessment and Recommendations for improving the Performance of Waste Containment Systems, Report No. CR-821448-01-0*; Environmental Protection Agency: Washington, D.C., 2002.

(34) *NUS Corporation. Summary of data on municipal solid waste landfill leachate characteristics*. Prepared for the U.S. EPA: Washington, D.C., 1988.
(35) *Committee to Assess the Performance of Engineered Barriers. Assessment of the Performance of Engineered Waste Containment Barriers;* National Research Council, National Academies Press: Washington, D.C., 2007; 134 pages.
(36) Basel Action Network (BAN). The Digital Dump: Exporting Re-use and Abuse to Africa. Media Release Version, 2005, http://www.ban.org/Library/TheDigitalDump.pdf (accessed Aug 24, 2007).
(37) Gullet, B. K.; Linak, W. P.; Touati, A.; Wasson, S. J.; Gatica, S.; King, C. J. Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations. *J. Mater. Cycles Waste Manag.* **2007**, *9*, 69–79.
(38) United States Environmental Protection Agency. National Recommended Water Quality Criteria, Office of Water-Office of Science and Technology (4304T), 2006.
(39) World Health Organization (WHO). Environmental Health Criteria 205: Polybrominated Dibenzo-p-dioxins and Dibenzofurans. 1998.
(40) Wong, C. S. C.; Duzgoren-Aydin, N. S.; Aydin, A.; Wong, M. H. Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. *Environ. Pollut.* **2007**, *148* (1), 62–72.
(41) Wong, C. S. C.; Wu, S. C.; Duzgoren-Aydin, N. S.; Aydin, A.; Wong, M. H. Trace metal contamination of sediments in an e-waste processing village in China. Environ. *Pollut.* **2007**, *145* (2), 434–442.
(42) Deng, W. J.; Louie, P. K. K.; Liu, W. K.; Bi, X. H.; Fu, J. M.; Wong, M. H. Atmospheric levels and cytotoxicity of PAHs and heavy metals in TSP and PM2.5 at an electronic waste recycling site in southeast China. *Atmos. Environ.* **2006**, *40*, 6945–6955.
(43) Leung, A. O. W.; Luksemburg, W. J.; Wong, A. S.; Wong, M. H. Spatial Distribution of Polybrominated Diphenyl Ethers and Polychlorinated Dibenzo-p-dioxins and Dibenzofurans in Soil and Combusted Residue at Guiyu, an Electronic Waste Recycling Site in Southeast China. *Environ. Sci. Technol.* **2007**, *41* (8), 2730–2737.
(44) Li, H.; Yu, L.; Sheng, G.; Fu, J.; Peng, P. Severe PCDD/F and PBDD/F Pollution in Air around an Electronic Waste Dismantling Area in China. *Environ. Sci. Technol.* **2007**, *41* (16), 5641–5646.
(45) Yu, X. Z.; Gao, Y.; Wu, S. C.; Zhang, H. B.; Cheung, K. C.; Wong, M. H. Distribution of polycyclic aromatic hydrocarbons in soils at Guiyu area of China, affected by recycling of electronic waste using primitive technologies. *Chemosphere* **2006**, *65*, 1500–1509.
(46) Allenby, B. R. Infrastructure in the Anthropocene: Example of Information and Communication Technology. *J. Infrastruct. Syst.* **2004**, *10* (3), 79–86.
(47) Baskaran, A.; Muchie, M., Eds.; *Bridging the Digital Divide: Innovation Systems for ICT in Brazil, China, India, Thailand and Southern Africa*; Adonis & Abbey Publishers Ltd.: London, UK, 2006; 256 pages.
(48) Osin, L. Computers in Education in Developing Countries: Why and How? *Educ. Technol. Ser.* **1998**, *3* (1), 1–14.
(49) Williams, E.; Hatanaka, T. Residential computer usage patterns in Japan and associated life cycle energy use, in 2005. *Proceedings of the IEEE International Symposium on Electronics and the Environment*, Piscataway, NJ, 2005; pp 177−182.
(50) Tong, X.; Wang, J. Transnational Flows of E-Waste and Spatial Patterns of Recycling in China. *Eurasian Geogr. Econ.* **2004**, *45* (8), 608–621.
(51) Luening, E. Used PC market surging. CNET News.com, March 31, 1998, March 31, 1998; http://news.com.com/2100−1001−209684.html (accessed Aug 24, 2007).
(52) Dyrwal, J.; Rodriguez, J.; Moreno-Guzman, J. ReVAMP IT: A study on the international used computer resale opportunities, Washington, D.C., Kogod School of Business at American University, 2000; http://www.american.edu/carmel/jd1000a/index.html.
(53) Lynch, J. Personal communication, 2007.
(54) Ingenthron, R. Personal communication, 2007.
(55) Keafe, C. Where haves meet wants, Jan 2002; www.dealer-scope.com.
(56) My-Com PC Web. 2001 market for used computers at 830,000 units (in Japanese), Aug 22, 2002, http://pcweb.mycom.co.jp/news/2002/08/22/23.html.
(57) Japan Electronics Industry Development Association (JEIDA), White paper on personal computers 2000−2001(in Japanese), Tokyo, 2001.
(58) Escherich, M. *Thriving Secondary PC Market Puts Old PCs to Good Use*. Gartner Research: Stamford, CT, 2005.
(59) International Association of Electronics Recyclers (IAER), 2006. IAER Electronics Recycling Industry Report, 2006 Update, Albany, NY.
(60) eTForecasts. Worldwide PC Forecast 1990−2007, eTForecasts, Arlington Heights, IL, 2002.
(61) Jain, A. E-waste Management in India (Current Status and Needs), Presentation given at the Creation of Optimum Knowledge Bank for Efficient e-Waste Management in India, N. Delhi, India, May 8, 2006.
(62) Williams, E.; Hatanaka, T. Residential computer usage patterns, reuse and life cycle energy consumption in Japan. Procedings of the 2005 ACEEE Summer Study on Energy Efficiency in Industry, July 2005.
(63) European Commission, Directive 2002/96/EC of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE), Brussels, Belgium, 2003.
(64) Gibson, J.; Tierney, K. Electronics Waste Management and Disposal Issues and Alternatives. *Environ. Claims J.* **2006**, *18:4*, 321–332.
(65) European Commission. Directive 2002/95/EC of the European Parliament and of the Council on the restriction of the use of certain hazardous substances in electrical and electronic equipment, Brussels, Belgium, 2003.
(66) US Environmental Protection Agency. Solders in Electronics: A Life Cycle Assessment, EPA744-R-05-001, Aug 2005.
(67) Ku, A.; Ogunseitan, O.; Saphores, J.-D.; Shapiro, A.; Schoenung, J. Lead-free solders: Issues of toxicity, availability and impacts of extraction. Paper presented at the Proceedings of the 53rdIEEE Electronic Components and Technology Conference (ECTC), May 28 2003, New Orleans, LA.
(68) Griese, H.; Muller, J.; Reichl, H.; Somi, G.; Stevels, A.; Zuber, K. H. Environmental assessment of lead free international systems. Proceedings of the Symposium on Lead Free Interconnect Technology, SMTA, Boston, MA, June 13−14, 2000.
(69) Secretariat of the Basel Convention-United Nations Environment Programme, Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, 1992; http://www.basel.int/text/con-e-rev.pdf (accessed Aug 24 2007).
(70) Selin, H.; Van Deveer, S. Raising Global Standards: Hazardous Substances and E-waste Management in the European Union. *Environ.: Sci. Policy Sustainable Dev.* **2006**, *48* (10), 6–18.
(71) Tong, X. Global Mandate, National Policies, and Local Responses: Scale Conflicts in China's Management of Imported E-waste. Proceedings of the IEEE International Symposium on Electronics and the Environment, May 10−13, 2004; pp 204−207.
(72) Chisholm, M.; Bu, K. China's e-waste capital chokes on old computers, Reuters News Service, Jun 11, 2007. http://www.reuters.com/article/latestCrisis/idUSPEK148230.
(73) *Fundacion Telefonica. DigiWorld-America Latina 2007*; Ariel S. A., Ed.; Primera Edicion: Madrid, España, 2007.
(74) Iles, A. Mapping Environmental Justice in Technology Flows: Computer Waste Impacts in Asia. *Global Environ. Politics* **2004**, *4* (4), 76–107.
(75) Kim, J-H. Crisis in Asian Environmental Justice-Focused on the Transboundary Movement of E-wastes in Northeast Asia. Proceeding of the Second NIES Workshop on E-waste. Nov 23, 2005 pp 91−103.
(76) Mala Bard, S. Global Transport of Anthropogenic Contaminants and the Consequences for the Arctic Marine Ecosystem. *Mar. Pollut. Bull.* **1999**, *38* (5), 356–379.
(77) Thomas, V. Product Self-Management: Evolution in Recycling and Reuse. *Environ. Sci. Technol.* **2003**, *37*, 5297–5302.
(78) Matsumoto, M.; Fujimoto, J. A study on the potential of ICT on realizing environmentally sustainable society. *Proceedings of the 4th Asiatic International Conference*, Selagor, Malaysia, July 2007.
(79) Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). CERCLA Priority List of Hazardous Substances, 2008; http://www.atsdr.cdc.gov/cercla/ (accessed Apr 3, 2008).
(80) London Metal Exchange, Market Data, 2008; http://www.lme.co.uk/dataprices.asp (accessed Mar 31, 2008).
(81) Johnson Matthey. *Platinum 2004*; Johnson Matthey Plc.: London, U.K., 2007.
(82) eTForecasts. PCs In-Use Reached Nearly 1B in 2006, eTForecasts, Arlington Heights, IL http://www.etforecasts.com/pr/pr0907 (accessed Apr 3, 2008).

ES702255Z