Plans to distribute the next billion computers by 2015 creates lead pollution risk

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Abstract
Major computer and software companies, along with governments and philanthropic organizations have embarked on ambitious plans to put computers in the hands of more than one billion new computer users over the next five to seven years in untapped markets in emerging economies. The most frequently proposed solution to overcome the electricity shortfall in communities where new computer users will be located is to use rechargeable lead-acid batteries to provide primary and back-up power for computers. This paper calculates the lead emissions from battery manufacturing and recycling that will result if independent market projections to greatly expand the number, geographic, and socioeconomic distribution of computer users are realized. By examining several possible scenarios, we estimate that between 1,250 and 2,300 kilotonnes of lead -- between four and seven times the weight of the Empire State Building -- could be released into the environment in the developing world to provide power to computers sold through 2015. Increased lead exposure has a negative impact on children's neurological development as measured by reduced school performance and on standardized tests. In order to realize the educational achievement and economic development benefits of reducing the "digital divide" proponents will need to encourage improvements in lead battery production and recycling in targeted markets.

Keywords: Electronic Waste; lead acid battery; lead pollution; Uninterruptible Power Supply; computer market

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1. Introduction

Personal computers have revolutionized the way people communicate, educate, and conduct business. For a large portion of the world's population, the personal computer is used on a daily basis to interact with individuals and access information from around the globe. This technology is opening educational opportunities for many and allowing businesses to make more informed and strategic decisions. The most obvious environmental cost of this revolution has been the proliferation of electronic waste (e-waste) as computers become obsolete on frequent cycles, yet still contain high levels of toxic materials. This e-waste has been poorly managed with much of it ending up in low wage countries where it is crudely recycled leaving significant contamination in its wake. As a result, many governments are drafting robust protocols to improve the collection, recycling, and disposal of e-waste [1, 2].

Market analysts have estimated that, in 2007, the world population of connected computers exceeded one billion. These billion computers have mostly gone to individuals in higher income economic strata, with some market penetration into lower income and rapidly industrializing countries, such as China and India. Major computer manufacturers have embarked on ambitious plans to sell and connect the "next billion" computers over the next five to seven years [3]. For example, Paul Ottelini, CEO of Intel Corporation, introduced the "World Ahead Program", in a speech at the World Congress on Information Technology in 2006. The program targets markets that have little access to computers with low cost devices that will enable increased access to information and educational opportunities. Simultaneously large philanthropic efforts are being launched to donate or sell low cost computers to schools and individuals in these same underserved populations. Table 1 provides a partial list of major initiatives aimed at getting computers in the hands of the lowest income groups in developing countries. This list does not include the government initiatives to bridge the digital divide by providing innovative financing, grants, and tax incentives to bring more computers within reach of the poorer households [3].

No comprehensive tally of public, private and philanthropic efforts has been attempted, but private investment in marketing computers could dwarf that of the other sectors.

Table 1: Partial List of Efforts to Promote Computer Usage in Developing Countries

Organization	Program	Financial Commitment	Notes
AMD	50 X 15	Unknown	Goal to reach 50% of the world population by 2015. For-profit program targets high growth markets like India, China and Russia. Program does not give out grants or partner with NGOs; model is customer centric.
Intel	World Ahead	$1 billion	Systems will be made in the country where they are sold e.g. in India Intel has created three computing systems for the regional market, this includes a community PC that works on car batteries when the power runs out.
HP	e-inclusion	$1 billion	Includes HP Garage venture fund, targeted to HP customers in the developing world. Will enlist 1 million partners by establishing several major alliances with organizations and individuals already in the e-inclusion program. They also want to start "'on-the-ground' initiatives that provide social and economic benefits to people around the world, representing at least 1000 rural communities."
Inter-American Development Bank	1:1 (one on one computing)	$3 million	Made a $3 million dollar grant for a pilot project to distribute XO laptops (made by OLPC) in Haiti.
Microsoft	Flexgo	$25 million dollars in software donations	Program allows low income users to pay for computers with a pay-as-you-go model.
MIT Media Lab	One Laptop per Child (OLPC)	$10 million dollars, includes $ 2 million dollars from Google and $ 2 million from Rupert Murdoch	Program relies on participating governments buying laptops at very large scales. According to the organization's estimates it requires $30 billion dollars each year to reach its goal of providing all two billion children in the developing world, between 6-16 years old with a laptop, this also includes the infrastructure cost.
Gates Foundation	Global Libraries	$70 million	Works in countries emerging from poverty to help public libraries provide free access to computers connected to the Internet.
Green WiFi	Green WiFi project	Unknown, being funded by OLPC	Provides solar powered Internet access in developing communities where electric power is unreliable or non-existent. One key feature of this product is a lead battery used to store solar power.

One of the challenges of reaching this intended market of new computer users is the lack of reliable electricity supply. The solution initially proposed during Mr. Ottelini's speech, which has been repeated and piloted since, is to market computers that are designed to be powered by rechargeable lead-acid batteries (LAB). Since LAB technology, commonly used in automobile, marine, and backup power applications is universally available and relatively inexpensive, this solution has some merit from a market perspective. If users are in an area with intermittent electricity, the battery is a component in a back-up uninterruptible power supply (UPS). If users are in an area with no electricity, the computer and router operate on battery power until the battery is depleted, and then it is transported to a nearby location on the electricity grid or a distributed power source, like a gasoline/diesel generator for recharging. Photovoltaic solar and wind power sources are also suggested as alternatives for powering these computers, but these technologies, when employed in rural areas of developing countries are also reliant on LABs.

Until now, there has been little discussion of the potential environmental consequences of the predicted increased demand for LABs for this purpose. Developing countries where these LAB powered computers will be marketed have limited recycling infrastructure and most of the batteries consumed in these countries are melted down and sold for scrap by the informal sector or in highly inefficient small smelters. The lack of sufficient large-scale collection and environmentally sound recycling in these countries contributes to the degradation of public health and extensive environmental contamination.

The marketing of the next billion computers in conjunction with lead batteries opens up a new source of electronic waste. As more computers and routers begin to use LABs as promoted by computer industry leaders and philanthropic organizations, the lead emissions from the production and recycling of the battery will far exceed the amount of all other toxic materials combined in the computer. This paper uses independent market projections coupled with electricity penetration data to develop several scenarios of computer distribution in locations with intermittent or no grid electricity supply. We estimate potential lead losses to the environment from batteries used in this expanded computer market, assuming that current independent market projections are accurate and expressed goals of industry and philanthropic organizations are realized. While it is difficult to estimate worldwide computer adoption by geographic and economic strata, this paper presents the potential consequences of initiatives to provide computers to those without electricity. Some recommendations will be made to mitigate these potential impacts, while still facilitating increased access to computers and the Internet.

2. Methodology

This paper quantifies total lead emissions for new computer users based on independent marketing projections conducted by others [4] and backed by statements from organizations aimed at delivering computers to the poorest economic strata. These country-specific market projections are matched with country specific electricity access throughout the world. Emission rates are based on aggregate production efficiencies of the lead industry throughout the world, reported by Mao and Dong et al. [5]. Because of the dominance of China in market projections for new computer users, we rely heavily on China's lead industry environmental performance to *illustrate* lead pollution pathways, but we rely on worldwide data to calculate country or region-specific loses. China is particularly important because it also accounts for over one-third of the projected new computer users. **Error! Reference source not found.** illustrates the framework of analysis, linking market projections, electricity access, low-income computer access campaigns and environmental impacts.

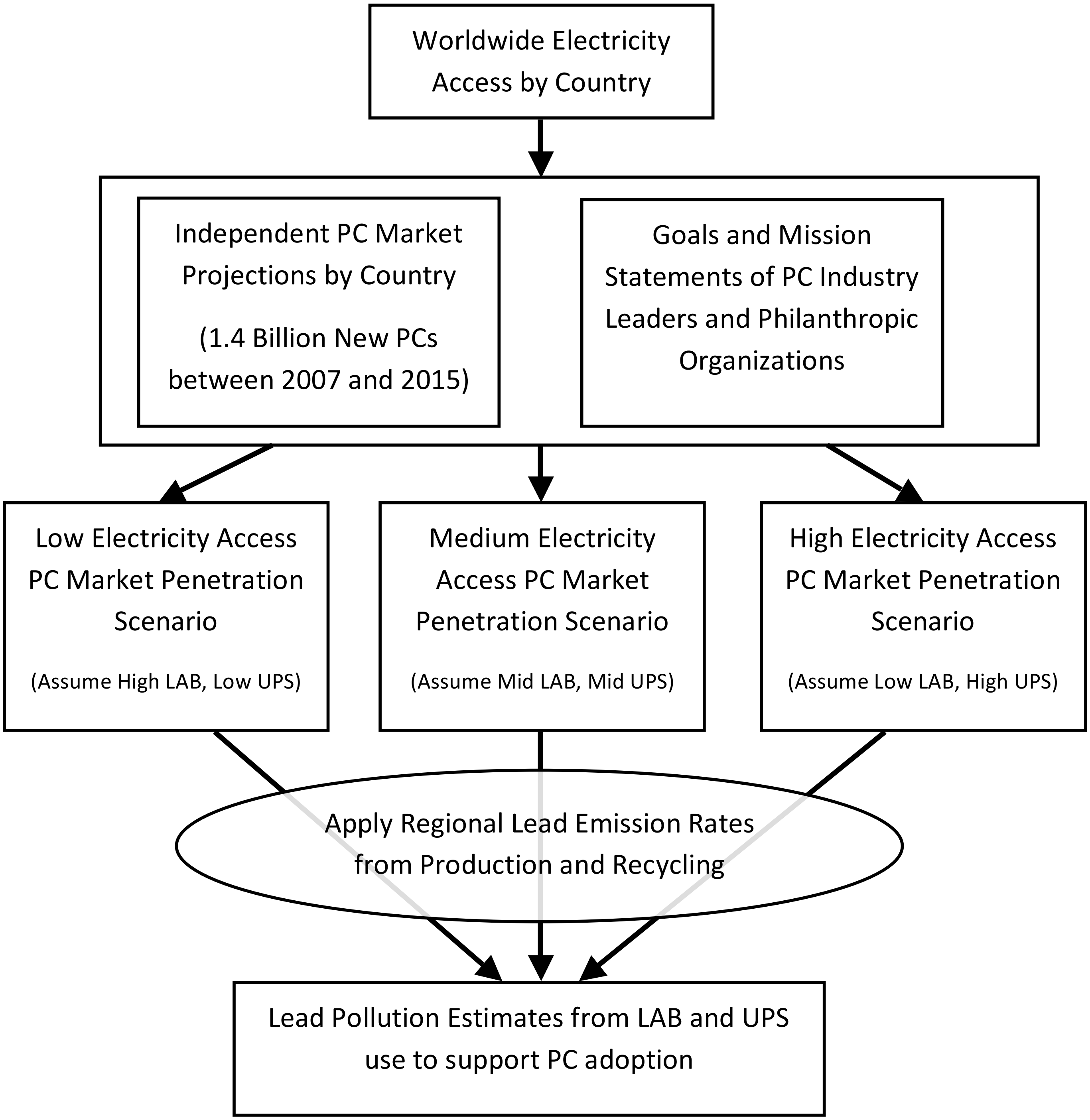

Figure 1: Framework for Analysis of Lead Pollution to Support PC Adoption

For emissions rates we rely extensively on those published by Mao and Lu et al. [7], Mao and Yang et al. [8], and Mao and Dong et al. [5], who identify pollution and loss rates of various processes in the production of LABs throughout the world. From these sources we estimate pollution rates during the lifecycle of a LAB based on inputs and outputs from each process, including mining, concentrating, smelting, manufacturing, and disposal.

3. Lead Pollution

Ironically, one of the largest predicted negative impacts from the proliferation of lead batteries for this purpose is on the educational opportunity and intellectual function of the very population targeted by these marketing plans and philanthropic programs. At even relatively low-level exposures, lead is a neurotoxin demonstrated to reduce school performance, lower standardized test scores (e.g. IQ) and thereby reduce lifetime earning capacity. Such impacts may be particularly detrimental to countries seeking economic development through expansion of the service economy.

Airborne lead emissions come from primary smelters, battery manufacturing facilities, and secondary smelters where batteries are recycled. Lead from these sources are inhaled and can be ingested as these particles settle in dust and soil. Water emissions and soil contamination from mining, smelting, manufacturing and recycling operations are also significant sources of exposure. Small scale operations where batteries are melted are the most common way to process used batteries in developing countries.

3.1. Lead Pollution Rates

Emission of lead through the battery life cycle can be quantified using a number of methods, including input-output models or environmental emission monitoring. Lead emission rates can be relatively low for facilities in developed countries, on the order of 3-5% of the lead mass in a battery over the entire production process [7, 10]. While this may seem small, it can amount to tonnes of emissions as exemplified in the annual Toxic Release Inventory in the U.S. where batteries consume over 80% of all lead production. Lead emissions from the most recent Toxic Release Inventory (TRI) amount to 202 kilotonnes in 2006, where the majority of that release is on-site land disposal [11]. The situation is more alarming in the developing world because of low quality ore, antiquated technology, and unregulated production. Loss rates vary greatly depending upon the manufacturing and recycling technology employed. For example, the most efficient manufacturers and recyclers lose less than 5% of the lead content of the battery. However, it is estimated that more than 50% of the weight of the battery may be lost to the environment in typical backyard recycling operations in the developing world [9, 12, 13].

A LAB's lifecycle consists of four sub-processes: 1) processing and refining primary or secondary lead, 2) manufacture of the battery, 3) use of the battery, and 4) disposal or recycling. The lead refining process includes crushing ore and concentrating lead metals from the ore through a series of chemical reactions. The concentrate is sintered and finally smelted in a blast furnace. The metal produced by the smelting process is refined, resulting in output of nearly pure lead. Secondary smelting relies on used batteries and recycled scrap but operates in a similar manner. The loss rates of highly efficient large scale secondary lead smelting are about twice that of primary smelting, but secondary lead does not require concentrating, resulting in lower overall emission rates than when using mined ore as raw material. Lead is also lost during the manufacture of batteries. Additionally, some lead scrap is a byproduct of the battery manufacturing process and enters the secondary lead input stream in the future production of batteries. Finally, a small percentage of used batteries are not recycled and enter the waste stream in the form of solid waste.

China's aggregate emission rates for production processes derived from Mao and Lu et al. [7] are estimated, including losses from primary concentration, primary smelting, manufacture, and secondary smelting. On average, primary concentration has a loss rate of 16.2% of the input lead mass, primary smelting loses 7.2% of the input mass, manufacture loses 4.4% of the input mass and secondary smelting loses 13.6% of the input mass; all emitted to the environment in the form of solid, liquid, or gaseous emissions.

Battery recycling releases significant lead emissions. In China's case, aggregate battery recycling losses are 13.6% of its lead mass to the environment during the secondary smelting process, compared to 7.2% during the primary smelting process. This is due to the low efficiency in secondary smelting operations. However, because secondary lead does not have to go through the concentration process, recycled batteries do not experience an initial 16% loss from the concentration processes, so recycled batteries could be seen as "cleaner" than those produced from virgin material. Informal backyard recycling has even larger loss rates and much of the resulting material is often sold to formal sector secondary smelters that reprocess the metal to produce lead that is required for high quality battery manufacturing.

Models of material flows have been developed to estimate lead losses to the environment throughout the global lead sector (not limited to batteries) in the year 2000 [5, 15]. The results are less precise than previous country-specific estimates [7, 8], but provide consistent environmental loss rate estimates for all continents. Table 2 shows their estimated lead loss rates for *production* and *manufacturing* processes of the lead battery industry. The losses are in the form of tailings, slag, and environmental emissions. These rates do not include any disposal losses, assuming that battery recycling rates approach 100 percent. Notably, Mao and Lu et al. [5, 15] carefully account for imports and exports in this global model.

Table 2: Regional Environmental Lead Loss Rates (metric tonnes) derived from Mao et al. 2008 [15]

	India	Japan	USA	Africa	Asia	Middle East	Latin America	Europe
Total Inputs	154	307	1940	281	1992	260	544	1802
Total Products	136	276	1813	204	1628	237	454	1673
Total Environmental Losses	15	23	91	75	320	19	85	94
Loss Rate (% of Inputs)	9.6%	7.5%	4.7%	26.6%	16.0%	7.2%	15.5%	5.2%
Loss Rate (% of Product Outputs)	10.9%	8.4%	5.0%	36.7%	19.6%	7.9%	18.6%	5.6%

Emission rates in the lead production and product manufacture sector vary considerably over the world, with relatively lower rates in developed regions, including the U.S. and Europe. In contrast, African average loss rates exceed one third of the mass of the final product. In Asia, the average loss rate approaches 20 percent of the final product. With region-specific loss rates, one can project lead losses in locations where batteries will needed for the next billion computer users.

4. Lead Demand and Electricity Supply for Computers

The United Nations [16] estimates that 1.6 billion people are without electricity constituting one quarter of the world's population. Moreover, despite trillions of dollars in infrastructure investment, 1.4 billion people will still lack electricity in 2030. Most of these people are in rural areas in Asia and Sub-Saharan Africa. Beyond those that have no access to electricity, there is a range of backup power supply types that can serve computer users where electricity supply is unreliable. The battery supply needs depend on the type of computers and routers developed and marketed, as well as the demographic of the end users.

Lead batteries are either linked directly as a power supply to a computer (or server) or can be employed as a component in an Uninterrupted Power Supply (UPS) device, which is plugged into an outlet. UPS systems can operate on standby in the event of a power outage or online in a continuously operating mode and provide short-term power to avoid sudden shut down resulting in data loss. The later systems are also sometimes referred to as “invertors” although both types utilize equipment to convert DC electricity from batteries to AC power. We use the term UPS to cover all types of systems for uninterruptible backup power.

The global market for UPS systems is currently over $7 billion dollars per year and growing at approximately 20 percent per year [17]. In India where electric power supplies in even the largest urban areas are extremely unreliable, 60% of all new PCs are sold with UPS systems [18]. Very large lead batteries are also used by businesses, schools, and industry for backup power, especially for computer equipment and servers that cannot be shut down even momentarily.

4.1. Computer Demand

The geographical distribution of areas without electricity or experiencing shortages corresponds with market projections for computer technology adoption in developing countries. These market projections are consistent with stated philanthropic and corporate goals for expanding computer users. For example, Intel is focused on those in middle and lower income strata with virtually no personal computer market penetration as shown in Figure 2 [3]. Marketing plans for selling the next billion computers acknowledge the need to expand outside major urban centers in the more developed countries which would be necessary to reach a sufficient number of those who have yet to adopt this technology.

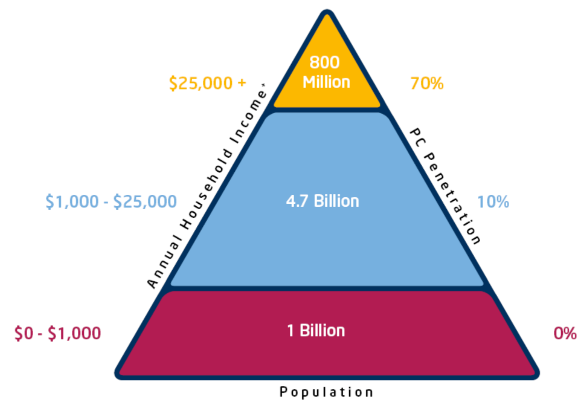

Figure 2: Computer Market Penetration (from Intel 2007 [3])

This paper makes no attempt to test marketing assumptions or the likely success of philanthropic goals for distributing computers in developing countries. Rather, we rely on market projections from independent analysts [4] and reported market strategies without critically evaluating their probability for success. Independent personal computer market projections for 2015 suggest that 1.4 billion additional computer users will be connected to the Internet by 2015 compared to the base year of 2007 [4]. As markets in developed countries are saturated, expansion in Europe and North America is predicted to be modest. Of these 1.4 billion new computer users, 880 million will be in the Asia-Pacific Region. **Error! Reference source not found.** shows the geographic distribution of the predicted PC market, with the majority of growth occurring in industrializing countries of Asia, primarily China and India.

In addition to supplying computers to those who have not yet owned them, there are plans underway to supply these new users with inexpensive Internet connections. As there is a consensus that many of the new users will be located in areas off the electricity grid, plans call for introducing WiMax broadband connections to this population. These efforts, being promoted by for-profit and non-profit programs, are expected to rely on solar technology with lead storage batteries to run an interconnected web of local servers. These programs have already been field tested in Brazil, India and other countries.

Efforts are also underway to make computers available to those who cannot afford to own one outright. For example, in India the most popular program that has been implemented is to set up computer kiosks in rural centers. Many of these locations are powered by lead batteries re-charged from solar systems or generators. The second largest lead battery company in India is even involved in promoting these kiosks. Some marketing plans such as Microsoft's Flexgo program allow users to buy the computer over time with metered usage.

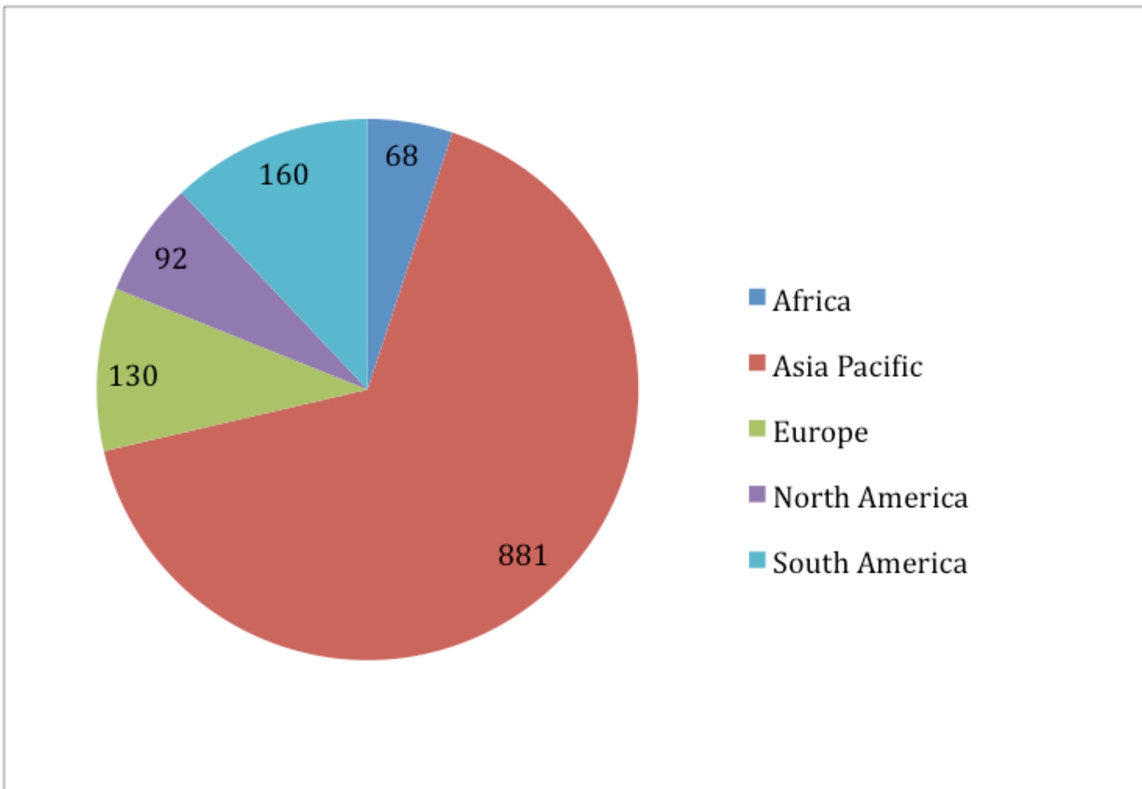

Figure 3: New PC Adoption by Region-2007-2015 (millions) derived from Yates 2007b [4]

4.2. Electricity Supply

The geographic distribution of PC market growth throughout the world is overlaid on the populations throughout the world without electricity to estimate the number of purely battery powered PC's and the number that will be reliant on lead batteries for backup power. The International Energy

Agency [19] provides country-specific estimates of the population unserved by electricity. Electricity availability rates are extracted in the 67 countries included in the PC forecast by Yates [4] (see Figure 4).

The pattern that clearly emerges is that most of the new computer growth will occur in Asia where the majority of the world's population without electricity is located[c]. Furthermore, market expansion is planned primarily in rural and semi-rural areas in countries where electricity coverage is even more limited and sporadic. This strong association between projected users and areas without adequate electricity is why Intel and other promoters of expanding the reach of this technology have implemented plans to address this limitation. It is worth noting that Africa and Asia, the world's largest future computer markets, have the world's poorest environmental performance in the lead production sector, with loss rates of 36.7% and 19.6%, respectively.

[c] Although Africa also has large populations without electricity, it is a significantly smaller projected computer market.

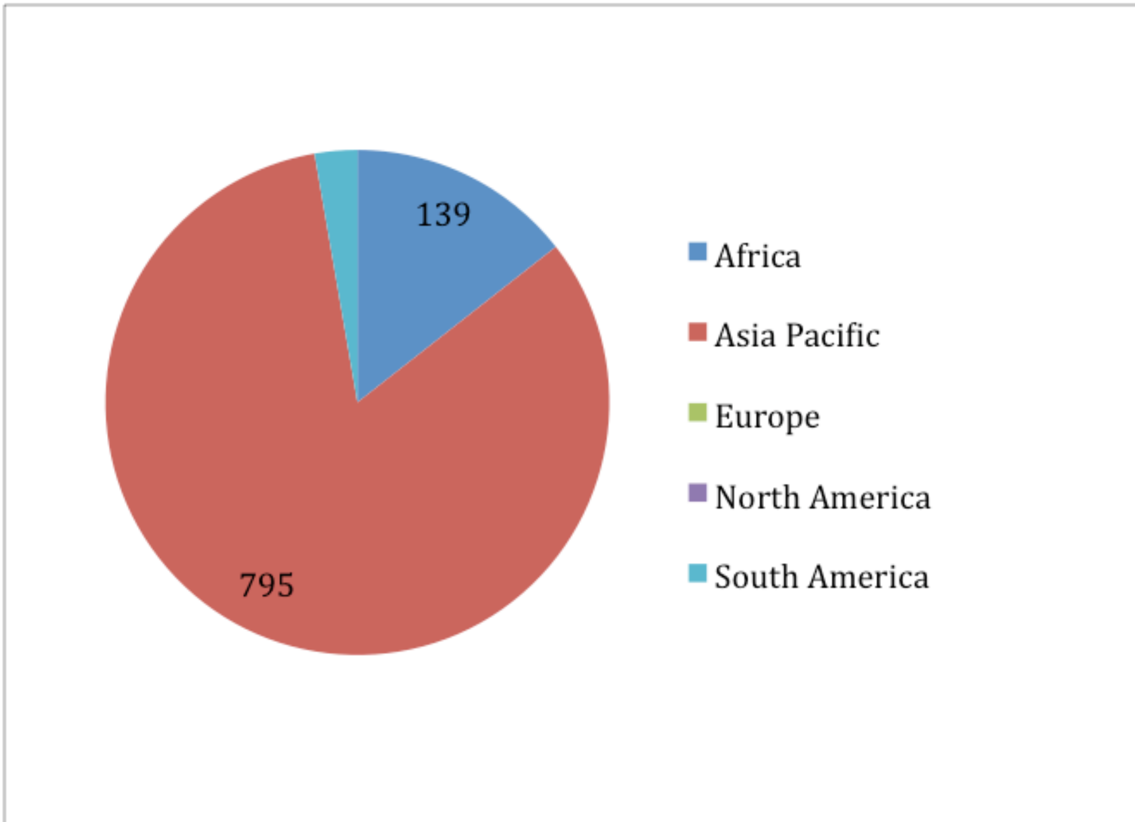

Figure 4: Population Without Electricity by Region-2005 (millions) derived from United Nations 2005 [16]

Disaggregating these data shows that some 500 million new computer users will be in China, a country where over 99% of the residents have access to electricity according to IEA estimates. It is expected that almost all of these new computer users will have access to grid electricity. On the other hand, only 54% of India's population, who are expected to adopt 150 million PC's by 2015, has access to electricity. This leaves a potentially large PC market without electricity.

4.3. Lead Acid Battery and Uninterruptible Power Supply Adoption

Lead acid battery demand comes three sources: 1) to provide primary power when the user is off grid; (2) for back up power when intermittent power is available; and (3) power needed for reliable internet connectivity. There are still over four billion people with access to some electricity, but without computers. It is possible that almost all of the next billion computers could be absorbed by populations with electricity (except in a couple of African countries where estimated national PC adoption rates exceed electricity availability rates). This is unlikely however given the stated plans of technology companies and major donor organizations (Table 1) to heavily invest in efforts to introduce computers to the lowest income strata in rural areas of developing countries. We expect that a large portion of the new recipients will be either entirely without electricity or only have access to unreliable electricity. From these two datasets, we assume different adoption rates by those with and without electricity to estimate lead battery use and environmental impacts.

Based on the available data sources, marketing projections, and the claims of those promoting computer adoption, we developed three scenarios for LAB demand from new computer users. From disaggregate country-level data; we estimated the percentage of the new user population that would be entirely without electricity. The first scenario assumes that public and private efforts will have minimal impact in bridging the “digital divide” and therefore only 25% of the new computers (109 million) would be adopted by those without electricity, while the other 75% would be adopted by those with electricity. The next scenario assumes that the 1.4 billion computers adopted by 2015 will be equally distributed over the computer-less population in each country, regardless of electricity access. For example this assumption suggests only 1% of the approximately 500 million computers in China would go to those without electricity, since only 1% of China’s population is without electricity. Summing across all countries covered by Yates [4] indicates that 154 million computer users will rely on batteries as a primary power supply under this model. A third scenario assumes that public and private investment would be largely successful in bridging the “digital divide” and 75% of the new computer users (258 million) would be those without electricity, while 25% of the demand would be filled by those with electricity.

Global lead losses are calculated as follows (for one scenario):

$$PbEmission^{LowLABScenario} = \sum_i \left[\left(\min(25\% PC_i, P_i^{noElectric}) \times n \times M_{LAB}^{Pb} + \max(75\% PC_i, PC_i - P_i^{noElectric}) \times p_{UPS} \times m \times M_{UPS}^{Pb} \right) \times e_i \right]$$

where; $PbEmission^{LowLABScenario}$ is total worldwide emissions. PC_i is the number of PCs projected for nation *i*, $P_i^{noElectric}$ is the population of nation *i* without electricity, n is the number of LABs needed per PC that is primarily reliant on LAB power, M_{LAB}^{Pb} is the mass of lead in a LAB to support one PC, p_{UPS} is the proportion of PCs that will use a UPS system, m is the number of UPS replacement batteries needed over the life of a PC that uses a UPS system, M_{UPS}^{Pb} is the mass of lead in a UPS to support one PC, and e_i is the loss rate of lead production and recycling in nation *i* expressed as a percentage of the output lead mass.

The estimated number of computers that will be used with primary LABs is shown in **Error! Reference source not found.**. These scenarios identify a range of possible lead pollution values that could reasonably be expected based on industry statements and market reports.

There is significantly less information on the population without *reliable* electricity, which likely far exceeds those without *any* electricity. Computer users without reliable electricity still require some alternative source for uninterrupted power for computer equipment and Internet connectivity. This is already the case in much of the developing world where power supplies are suffering from rapid increases in demand for electricity, antiquated infrastructure, and poor planning. As electricity demand is expected to increase greater than capacity in many parts of the world, we can anticipate these trends to continue. The situation is likely to grow considerably worse as efforts to address climate change are putting more pressure on countries to limit the use of coal and other highly polluting power sources.

Error! Reference source not found. shows the assumed primary battery power requirements, coupled with assumptions of UPS demand. The demand for UPS systems is inversely related to LAB adoption, since those computers using primary power LAB's do not require UPS systems. The number of UPS systems estimated for each scenario was derived as follows. All major computer markets in industrializing countries (primarily those in Asia and Africa) are assumed to have intermittent power supply. With the exception of China, we assume that among all computers that have access to electricity from the grid, 60% (the rate observed in India) will utilize a UPS. In addition, we do not include any UPS systems for the servers that will be required for Internet access. Since China constitutes over one-third of new PC users, country-specific UPS market data were used to estimate that only 2.5% of new computers are being equipped with UPS systems [17, 20].

Table 3: Lead Emissions from LAB and UPS Use for the Next 1.4 Billion Computers (2007-2015) derived from Mao et al. 2008 [15], Yates 2007b [4], and Frost and Sullivan 2007 [17]

Scenarios	Computers Requiring LAB (no electricity) millions	Computers Requiring UPS (intermittent electricity) millions	Lead Loss LAB (kt)	Lead Loss UPS (kt)	Total Lead Loss (kt)
Scenario 1: 75% of new computers are distributed to those with electricity first	109	324	**827**	**423**	***1,250***
Scenario 2: Computers are distributed equally, independent of electricity access	154	282	**1,197**	**368**	***1,565***
Scenario 3: 25% of new computers are distributed to those with electricity first	258	234	**1,994**	**303**	***2,296***

4.4. Lead Losses from Computer Use

Given that primary power LABs, used to power a computer or community server, weigh 17 kg on average and 60-70% of the weight is lead [5, 10], the total lead requirement is about 12 kg per battery.

An example of estimated environmental losses is presented in **Error! Reference source not found.**, using the loss rates derived from Mao and Lu et al. [7].

Table 4: Lead Loss from 12kg Lead Content Battery During Production and Disposal in China derived from Mao et al. 2006 [7]

	Process Losses (kg)	
Lead Acid Battery Recycle Rates	**90%**	**100%**
Concentration (Primary)	1.4	1.2
Smelter (Primary-Virgin Material)	0.5	0.5
Smelter (Secondary-Recycled Scrap and Used Battery)	1.0	1.1
Manufacture	0.6	0.6
Total Emissions	***3.5***	***3.4***
Battery Disposal Loss	***1.2***	***0.0***
Total Losses	***4.7***	***3.4***

In this example, with an assumed 100% recycling rate, 3.4 kg of lead are lost during the production processes to produce a battery containing 12 kg of lead, or a loss rate of 28% of the final battery lead content. Under lower recycling rate assumptions, more lead is lost during the production processes due to more reliance on virgin lead resources and disposed lead entering the solid waste stream. Because battery use will most likely be highly dispersed throughout rural areas, the probability of efficient and formal recycling practices could be low, resulting in lower recycling rates overall and higher overall pollution rates.

Exacerbating the problem, most deep-cycle LABs experience heavily degraded performance after about 300 discharge-recharge cycles, and most require replacement every 2-3 years. It is unclear how long the computer replacement cycle will be in developing countries, but it will likely be significantly longer than the current replacement cycle of 4-5 years in the developed world [4]. This indicates that each computer would require between two and four batteries over its lifetime. Utilizing reported efficiencies for Asia's battery manufacturing and recycling operations, between 4.8 and 9.6 kilograms of lead would be released to the environment over the lifetime of each computer reliant on battery power with an assumed 100% recycling rate.

Although UPS systems vary for home and office environments, all contain small lead batteries, for short duration backup power applications. Based on a small survey, residential UPS systems contain between 2 and 4 kilograms of lead. Considering Asia again and using the same recycling infrastructure that is outlined above with a 100% recycling rate, an average UPS system with 3 kg of lead would emit 0.60 kg of lead over its lifetime. UPS systems are generally guaranteed for 3 years, implying that a computer will require two UPS systems (or at least one UPS battery replacement) over its usable life.

While these emission rates may seem small individually, when scaled up to the possible demand of computers in the developing world, the aggregate releases are significant. We assume that three LABs are required for each fully battery powered computer over its usable life and two UPS systems (or replacement battery) are required for each computer with intermittent supply over its life. **Error! Reference source not found.** shows the lead losses of the next 1.4 billion computers projected by Yates [4] with the LAB and UPS assumptions outlined in Section 4.4.

These extraordinarily high lead emissions will redefine the way we view e-waste for the coming billion computers. For perspective, CRT monitors (which are quickly being replaced by LCD monitors in the current computer market) contain only 1.2 kg of lead, but have been the subject of several efforts attempting to minimize the entry of this lead into the municipal waste stream [21, 22]. Even under the best recycling scenarios, using batteries as power supplies will release approximately four times the lead waste into the environment per computer, compared to CRT monitors.

4.5. Discussion

To put the calculated lead losses into perspective, the environmental releases estimated for the next 1.4 billion computers are an order of magnitude higher than the annual lead emission levels in the U.S. as reported by the Toxic Release Inventory [11], or between four and seven times the weight of the Empire State Building. These losses only account for new computer sales that will occur through 2015 and not any of the impacts for equipment currently in use. On average, we estimate that the planned distribution of computers in developing countries will result in 0.9 to 1.6 kilograms of lead emissions per computer. At the same time, these estimates do not account for lead emissions from batteries that will be used for transportation, photovoltaic solar systems, Internet connectivity, and other purposes related to distributing the next wave of computers.

Our assumptions outlined above and the market projections provided by others, come with considerable uncertainty. There are four primary areas where alternate inputs could impact our findings:

(1) This paper relies on future computer adoption patterns from third-party market projections. To the extent that those projections are overly optimistic, then the estimates reported here may overestimate future lead emissions. Although companies have pledged to put computers in the hands of those in the lower economic stratum in more rural areas throughout the developing world, this concept has not yet been fully tested.

(2) The market projections that we rely on do not delineate the proportion of desktops, laptops, and even smaller netbooks that will be distributed in the future. There is some evidence that PC's designed for the developing world will be designed and perform very differently than current PC's [23]. The One Laptop Per Child (OLPC) initiative for instance allows AC and DC recharging capability, allowing the laptops to be recharged with grid electricity, solar systems,

generators or lead acid batteries. Although these segments have different power requirements and battery capacities, all must be recharged or powered from an external source. The extent to which backup power systems are needed is less clear without knowing more about the mix of computers that will be distributed.

(3) Many of the power sources and lead batteries used for computers will also be shared with electrical devices including televisions, mobile phones or additional computers. Since lead acid batteries deteriorate based on the number of discharge/recharge cycles, these multiple uses are likely to contribute to shorter battery lives and more recycling. Battery life can also be affected by extreme temperatures and other factors.

(4) Much of the estimated loss is due to small-scale battery manufacturing and recycling activities that are highly inefficient. We rely on recent estimates of recycling efficiencies reported in the literature. If current trends continue, rapidly increasing demand for lead batteries will likely prompt more informal recycling that is very difficult to control or regulate. Therefore we assume that manufacturing and recycling efficiencies will remain constant. If governments or other eco-labeling incentives are successful at initiating universal collection programs and encouraging improvements in manufacturing and recycling, this can reduce lead emissions from the batteries used for the next billion computers.

Furthermore, competing technologies for connecting to the Internet may displace demand for computers and reduce lead battery consumption. Portable phones and personal digital assistants (PDAs) may have greater market penetration and delay computer adoption in these emerging market countries where demand for computers is projected to be the greatest.

Our assumptions concerning the life cycle of these new computers and associated LABs may also introduce some bias in our calculations of lead emissions. We know that poor quality LABs that are commonly sold in developing countries have a considerably shorter life span than new branded products. At the same time, consumers in developing countries may be more inclined to keep computers for many more years before seeking a replacement. Therefore our assumption of three replacement LABs per computer and one replacement per UPS can greatly underestimate lead battery consumption and emissions over the computer life cycle. Also if one were to account for backup power provided by larger UPS systems that are common in schools, offices and other commercial applications, this may also significantly increase emission estimates.

While lead loss rates are high in industrializing countries, it should be noted that human exposure pathways vary based on mode of lead emissions into the environment and with characteristics of the exposed population. For instance, airborne lead emissions in an urban area would presumably have much higher public health impacts than fugitive emissions and soil contamination from mine tailings around a rural lead mine. Airborne lead also contributes to exposures over many years after it settles in dust and soil [24].

There are generally insufficient data in the aggregate to rank the importance of competing exposure pathways resulting in overexposures to lead in any given population. Even the absorption of airborne lead will vary greatly by particle size. The most dangerous forms are the smallest fumes generated from heating lead as required for smelting, battery manufacture, and recycling activities [25]. Lead can also be introduced into the ecosystem by poorly engineered water and mine tailing treatment facilities [26-29]. In most cases, half to three quarters of the environmental emissions are in the form of tailings at the mine site. These tailings, if properly contained, pose limited health risks, though developing country mines generally do not follow international best practices on tailing treatment.

Newer smelting technologies with improved environmental controls are being adopted and future increases in the price of lead may spur improvements in efficiency to lower the predicted loss rates over time. However, improvements that would result from developing a larger-scale recycling sector will require consolidation that is only achievable with national level collection systems that have not yet been adopted in most developing countries.

New battery technology including lithium ion and other battery chemistries may displace some of the lead-acid batteries required during the same time frame we used to calculate loss rates. The adoption of these alternatives will likely be governed more by price than any other factor and therefore are unlikely to capture a significant market share of the projected new computer users. As other battery intensive sectors (such as the electric vehicle industry) gain momentum, advanced battery technologies could become more cost effective, but prices are unlikely to sufficiently drop in the projected timeframe for computer adoption. In addition, lithium ion batteries pose different challenges in that currently there is no recycling infrastructure that can convert today's diverse battery chemistries into useable stock for making new batteries.

5. Recommendations

While this paper does not suggest limiting computer introduction into poor communities in developing countries, it does demonstrate that widespread use of LAB powered computers, servers and UPS systems is going to increase the magnitude of lead emissions under the proposed scenarios. While we can expect some environmental improvements particularly in new LAB recycling facilities, existing recyclers may continue to operate at less than optimal efficiencies for years. In addition, developing countries still face difficult challenges addressing emissions from the informal recycling sector which can still continue to grow along with the expanding market. Since the demand for lead batteries spans many industrial sectors, the computer industry could join efforts with automotive, industrial, and energy sectors to improve the environmental performance during manufacturing and the recovery of lead batteries.

Lead batteries can be manufactured and recycled with far fewer emissions. Programs to encourage improvements in the manufacturing of lead batteries can be adopted by businesses, governments and donors involved in promoting computer technology. Preferred purchasing programs can provide incentives to companies that reduce environmental lead emissions and take back used batteries for environmentally sound recycling. Independent third-party certification has been introduced to reward battery manufacturers that meet minimum standards. The Better Environmental Sustainability Targets (BEST) certification allows companies that demonstrate compliance with specific performance measures in an annual audit to place an eco-label on lead batteries.

In order to reduce the predicted negative environmental impacts associated with the significant increase in LAB consumption dedicated to computer technology in developing countries, there will also need to be more formal collection mechanisms for used batteries to justify the investment necessary for more efficient recycling plants. Collection systems must provide consumers with an incentive to return used batteries so that they will be processed only at formal battery recycling facilities. This is difficult to achieve without regulation calling for tax incentives, mandated deposits, or refunds since large-scale collection and recycling requires costly pollution controls and higher transportation costs. Without these measures, the informal sector, with loss rates near 50 percent, will continue to capture a significant share of used batteries for processing.

Governments can mandate battery take-back mechanisms with deposits or purchase discounts. Deposit systems require consumers to pay a set amount at the point of purchase that would be refunded at the end of the battery life if it is returned to authorized retailers or collection centers. Purchase discount programs work with a similar incentive except battery manufacturers or retailers are required to pay a bounty in the form of a discount that would apply to the purchase of a replacement battery. Both deposit and purchase discount programs will only work to capture a larger share of used batteries from the informal sector if the mandated fee or deposit is set at a higher rate than what is being offered by competing collectors.

The producer responsibility model that is gaining momentum in response to the growing problem of e-waste would require battery manufacturers to provide financial incentives and infrastructure to recover and track the collection and recycling of lead batteries. In developed countries there has been considerable successes in implementing these programs not only with lead batteries, but also for beverage containers, other types of batteries, and e-waste [1, 30, 31]. Alternatively, in order to mitigate the negative externalities associated with LAB production and recycling, the government could develop a tax, targeted at all LABs. The tax revenue could then be used for large-scale battery collection, and educating the lead industry to encourage improvements in environmental performance.

Simultaneously, improvements in electricity access and improved efficiency of the electric power sector can also significantly reduced demand for LABs. Improved efficiency could allow more reliable electricity supply where demand exceeds supply, reducing the requirements for UPS systems. Finally, computer power management improvements, along with more energy efficient technologies, could significantly reduce the power requirements, and thus LAB size requirements.

Furthermore, those businesses and donors advocating the adoption of computer technology to low income and rural communities in developing countries must take responsibility for purchasing batteries from companies that meet environmental emission standards and collect used batteries for formal sector recycling. This responsibility may be contractually shifted to vendors supplying this equipment but, it must be accounted for at the project planning phase. Given the larger goals expressed by both philanthropic and private businesses active in this market, it is beholden upon them to also make investments to ensure that lead loss rates are reduced by promoting more efficient lead battery manufacturing and recycling. Without accounting for the potential increases in lead pollution expected from these activities, the education and economic development goals of these programs will never be fully realized. Benefits of narrowing the “digital divide” will be offset by increasing the gap in educational opportunity caused by more prevalent and higher lead exposures.

Computers that are connected to the internet and in the hands of the lower income groups in developing countries have the potential to educate and empower a population that has had little access to educational and global information systems in the past. Though the initiatives put forth by technology companies and philanthropic organizations are noble, there must be more consideration given to the scope of lead pollution that we predict will be created by the next billion computer users. The marketing and donation of computers and servers that are powered by LABs, without concern for how batteries are manufactured or recycled is alarming and is likely to result in significant increases in lead poisoning in the same populations targeted for computers.

References

1. Kierkegaard, S., *Charging up the batteries: Squeezing more capacity and power into the new EU Battery Directive.* Computer Law and Security Report, 2007. **23**(4): p. 357-364.
2. Widmer, R., et al., *Global perspectives on e-waste.* Environmental Impact Assessment Review, 2005. **25**(5): p. 436-458.
3. Intel, Financing the Next Billion PC Users: Financing Government Assisted PC Purchase Programs. 2007.
4. Yates, S., Worldwide PC Adoption Forecast, 2007-2015. 2007b.
5. Mao, J., J. Dong, and T.E. Graedel, *A multilevel cycle of anthropogenic lead: I. Methodology.* Resources, Conservation and Recycling, 2008. **52**(8-9): p. 1058-1064.
6. International Lead and Zinc Study Group, Lead and Zinc Statistics-Monthly Bulletin. 2007.
7. Mao, J., Z.W. Lu, and Z.F. Yang, *The Eco-efficiency of Lead in China's Lead-Acid Battery System.* Journal of Industrial Ecology, 2006. **10**(1-2): p. 185-197.
8. Mao, J., Z. Yang, and Z. Lu, *Industrial Flow of Lead in China.* Transactions of Nonferrous Metals Society of China, 2007. **17**(2): p. 400-411.
9. Hoffmann, U. and B. Wilson, *Requirements for, and benefits of, environmentally sound and economically viable management of battery recycling in the Philippines in the wake of Basel Convention trade restrictions.* Journal of Power Sources, 2000. **88**: p. 115-123.
10. Lave, L.B., C.T. Hendrickson, and F.C. McMichael, *Environmental Implications of Electric Cars.* Science, 1995. **268**: p. 993-995.
11. US EPA, 2006 Toxic Release Inventory Public Data Release. 2008. http://www.epa.gov/tri/tridata/tri06/index.htm. 03/27/2008
12. UNEP, Basel Convention Training Manual-National Management Plans for Used Lead Acid Batteries. 2004.
13. Hoffmann, U., A Review of the Options for Restructuring the Secondary Lead Acid Battery Industry, in Particular the Smaller Battery Recyclers and Secondary Lead Smelters and the Informal Sector, with a View to Enhancing Their Environmental Performance and Improving Health Standards. 1999. http://www.unctad.org/trade_env/test1/publications/battery2.pdf. , Accessed 8-11-2008
14. China Data Online, *China Yearly Industrial Data*. 2007.
15. Mao, J., J. Dong, and T.E. Graedel, *A multilevel cycle of anthropogenic lead: II. Results and discussion.* Resources, Conservation and Recycling, 2008. **52**(8-9): p. 1050-1057.
16. United Nations, The Energy Challenge for Achieving the Millennium Development Goals. 2005.
17. Frost and Sullivan, World UPS Markets. 2007. www.frost.com. Accessed March 1, 2008
18. Singh, A., *Branded Players Shine in Indian UPS Market*, in *Express Computer*. 2004.
19. International Energy Agency, World Energy Outlook 2006. 2006.
20. Market Avenue, 2008 Report on China's UPS Market. 2009. http://www.marketavenue.cn/upload/ChinaMarketReports/REPORTS_1058.htm. Accessed February 23, 2009
21. US EPA, Life Cycle Assessment of Desktop Computer Displays: Summary of Results. 2002. http://www.epa.gov/dfe/pubs/index.htm#comp.
22. Macauley, M., K. Palmer, and J.S. Shih, *Dealing with electronic waste: modeling the costs and environmental benefits of computer monitor disposal.* Journal of Environmental Management, 2003. **68**: p. 13-22.
23. Yates, S., Designing PCs For The Third World-How Children And Education Will Redefine The PC. 2007a.

24. Tong, S., Y.E.v. Schirnding, and T. Prapamontol, *Environmental lead exposure: a public health problem of global dimensions.* Bulletin of the World Health Organization, 2000. **78**(9): p. 1068-1077.
25. Suplido, M.L., Ong, C.N., *Lead Exposure among Small-Scale Battery Recyclers, Automobile Radiator Mechanics, and Their Children in Manila, the Philippines.* Environmental Research Section A, 2000. **82**: p. 231-238.
26. Cappuyns, V., *Environmental impact of the former Pb-Zn mining and smelting in East Belgium.* Journal of Geochemical Exploration, 2005. **88**(1): p. 6-9.
27. Jung, G.B., et al. *Characteristics of Heavy Metal Contamination in Residual Mine Tailings Near Abandoned Metalliferous Mines in Korea*. in *18th World Congress of Soil Science*. 2006. Philadelphia, PA.
28. Dudka, S. and D.C. Adriano, *Environmental Impacts of Metal Ore Mining and Processing: A Review.* Journal of Environmental Quality, 1997. **26**(3): p. 590-602.
29. Dudka, S., M. Piotrowska, and H. Terelak, *Transfer of Cadmium, Lead, and Zinc from industrially contaminated soil to crop plants: a field study.* Environmental Pollution, 1996. **94**(2): p. 181-188.
30. Mayers, C.K., C.M. France, and S.J. Cowell, *Extended Producer Responsibility for Waste Electronics: An Example of Printer Recycling in the United Kingdom.* Journal of Industrial Ecology, 2005. **9**(3): p. 169-189.
31. Nixon, H. and J.-D.M. Saphorestra, *Financing Electronic Waste Recycling California Households' Willingness to Pay Advanced Recycling Fees.* Journal of Environmental Management, 2007. **84**(4): p. 547-559.