Forecasting Global Generation of Obsolete Personal Computers

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Electronic waste (e-waste) has emerged as a new policy priority around the world. Motivations to address e-waste include rapidly growing waste streams, concern over the environmental fate of heavy metals and other substances in e-waste, and impacts of informal recycling in developing countries. Policy responses to global e-waste focus on banning international trade in end-of-life electronics, the premise being that e-waste is mainly generated in the developed world and then exported to the developing world. Sales of electronics have, however, been growing rapidly in developing nations, raising the question of whether informal recycling in developing countries driven by international trade or domestic generation. This paper addresses this question by forecasting the global generation of obsolete personal computers (PCs) using the logistic model and material flow analysis. Results show that the volume of obsolete PCs generated in developing regions will exceed that of developed regions by 2016–2018. By 2030, the obsolete PCs from developing regions will reach 400–700 million units, far more than from developed regions at 200–300 million units. Future policies to mitigate the impacts of informal recycling should address the domestic situation in developing countries.

1.0. Background

Electronic ownership is increasing around the world in both developed and developing countries. At the same time rapid and sustained technological development in the industry has led to rapid obsolescence and decreasing lifetimes. Increased ownership and rapid obsolescence combine to lead to rapidly growing volume of unwanted electronics (commonly known as electronic waste or e-waste), a stream managed in a variety of ways including storage at home, reuse, recycling, exportation, incineration or storage in landfills.

Environmental concerns regarding the management of e-waste is increasingly on policy agendas at local, national, regional, and global levels. Environmental impacts include exposure to toxic materials, particularly due to informal recycling practices in the developing world. In informal recycling sites, wires are pulled from electronics, collected, and burned in open piles to remove casings and recover resaleable copper, generating emission of dioxins, furans and other pollutants. Circuit boards are treated to extract copper and precious metals using acids and cyanide, polluting local water systems. NGOs and media reports have shown serious environmental impacts from informal recycling in China, India, Ghana, Nigeria, and other locations (*1–4*). Scientific studies in Guiyu (in China) have confirmed that informal recycling does lead to serious pollution (*5*, *6*).

Investigations of informal reuse and recycling sites revealed that processed e-waste mainly comes from the developed world (data on several cases of international transboundary movements of e-waste are shown in Supporting Information (SI) Section S7) (*7*, *8*). The informal recycling problem is primarily viewed as an issue of transboundary movements of waste (*9*, *10*). The main policy solution to informal recycling in the public discourse is banning international trade, the argument being that stopping international trade in e-waste should in turn stop informal recycling (*7–16*).

At the international level the main relevant policy is the Basel Convention, a multilateral environmental agreement controlling trade of wastes classified as hazardous (*10*). Some categories of e-waste not intended for reuse are classified as hazardous. The Basel Convention requires prior notification between signatories when trading wastes classified as hazardous. There is also a proposed amendment to the Convention, the Basel Ban, which forbids international trade in all the materials categorized by the Convention as hazardous. This amendment has not been ratified.

Partly in response to concerns over informal recycling, a number of countries have implemented bans or restrictions on imports of e-waste. In 2000 and 2002, China introduced legislation that prohibited the import of e-waste (*11*). India, Indonesia and Vietnam have also decided to prohibit import of e-waste (*12*). There is currently a bill under consideration in the U.S. Congress, H.R. 2595, which restricts certain exports of e-waste from the U.S (*13*). The question of when end-of-first-life electronics should be considered as used electronics versus e-waste is complex. Different countries take different positions on this issue. Indonesia has banned the import of used TVs, radios, and other second-hand equipment, while Thailand requires that the imported used electronics should not be more than three years old. The Philippines requires prior notification and consent before used electronics enter the country. India is relatively liberal, and used computers up to 10 years old may enter into the country as donations (*12*). Some countries such as Peru allow imports of e-waste (*14*). Recent U.S. environmental certification schemes for electronics recycling aim to ban (*15*) or restrict (*16*) the exports of end-of-life electronics.

It is worth recounting the primary drivers of international trade in end-of-life electronics. One driver is the reuse market. Demand for electronics is high but many in the developing world are still unable to afford new devices. This demand combined with low labor cost for refurbishing lead to a vigorous electronics reuse market in developing countries. A recent article by Kahhat and Williams showed that at least 87% of imported end-of-life computers went to reuse as opposed to recycling in Peru (*14*). A second driver is material recycling. A used desktop PC for example contains U.S.$16–18 of materials (*14*). Low wages, high demand for raw materials, and poor environmental controls in the developing world result in recycling running a net profit. On the exporter side, high wages and low demand for used electronics in developed countries imply that electronics collection and recycling runs a net cost (e.g., U.S.$5–40 for a PC) (*17*). Electronics collection recycling policies in the developed world therefore require

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financing mechanisms such as recycling fees paid by consumers or by making manufacturers financially responsible (*17*). There is a thus financial motivation for collectors in developed countries to export to the developing world.

For trade control policies to mitigate the environmental impacts of informal recycling two conditions must be met. One condition is that such trade policies must be effectively enforced. There are clearly governance challenges to implementing trade controls, as evidenced by repeated failures in practice. Although banned since 2002, the import to China of e-waste apparently continues much as before policies were implemented (*18*). Only 60% of e-waste is recycled under existing national systems in Europe, and despite an export ban, it is thought that the remaining 40% is exported to Asia or Africa (*19*).

The second condition for trade bans to work is that they must effectively cut off the supply of e-waste to informal recyclers. This effectiveness is predicated on the assumption that the main source of e-waste is imports from the developed world. Even if it is true today, markets for electronics in the developing world have been growing rapidly. This rapid growth combined with large population leads to the question of how rapidly the domestic generation of e-waste is growing in developing world.

2.0. Case Study: Geospatial Distribution of Obsolete Computer Generation

To address the issues raised in Section 1.0 we forecast the generation of obsolete personal computers (PCs) in the developed and developing worlds. The scope of products considered to be "e-waste" depends on the definition but often includes consumer electronics such as computers, cell phones, televisions, and audio/video equipment. We focus on PCs, mainly desktops (control unit + monitor), laptops and notebooks, but excluding servers. One argument to focus on PCs is that the high content of precious metals and high demand for used machines imply that PCs are particularly attractive to informal recyclers.

The parameter studied is the number of obsolete computer systems with the intent to characterize the "need" for proper recycling. Computers and recycling systems continue to evolve, however. For example the share of laptops in the market continues to increase and the electronics industry is in the midst of a transition toward lead-free solder. The impacts of informal recycling are complex. Study of the evolving relationship between computer design and recycling systems is beyond the scope of this article, we simply use numbers of obsolete systems as a proxy for potential impacts. We do assert that whatever design emerges for the PC of the future, informal recycling should still be avoided. Informal recycling of a PC even with all toxics removed will still cause impacts due to emissions (e.g., stripping chemicals, combustion products) from extracting valuable metals (*9*).

Using data on historical stock and sales in different regions, PC sales and generation of obsolete PCs are forecasted for the next two decades using the logistic function. The logistic function displays an S-shaped behavior and has been found to empirically describe the diffusion of a range of technologies ranging from mobile phone, home electric appliances, to computers. Frank used the logistic model to forecast diffusion of wireless communications in Finland (*20*). Combining the logistic model with materials flows analysis (MFA) enables estimation of the generation of obsolete/discarded devices (*21*). Using this approach, Yamasue estimated the number of discarded home electric appliances in Japan (*22*). Yang and Williams recently applied the model to forecast generation of obsolete computers in the U.S (*21*). At the regional level Streicher-Porte and collaborators applied MFA to assess obsolete PC processing in the informal sector in Delhi, India (*23*).

Our analysis is the first attempt to explore global trends in e-waste generation, trends clearly pertinent in guiding public response to e-waste. In the course of conducting this case study, we also explore methodological issues in the application of the logistic model. The logistic model has two parameters, which describe the height (carrying capacity) and steepness (growth rate) of the "S". The developing world in particular is far from reaching its asymptotic carrying capacity, posing a challenge for reasonable statistical fitting of the model. We address this challenge through a bounding analysis which considers three scenarios: upper, baseline as well as lower carrying capacity, to identify trends which are insensitive to the choice of bounds. In addition we deal with lack of data on lifespan in different regions by developing a method to determine computer lifespan from stock and sales data.

3.0. Data/Methods

3.1. Data Sources. Most estimates regarding the installed base of PCs are derived from data on shipments (e.g., the number of PCs sold each year) in a given country. A primary data source is the database developed by the United Nation's (UN) International Telecommunication Union (ITU) which lists PC stocks and penetration rate in individual countries (*24*). The statistic includes PCs, laptops, notebooks etc., but excludes terminals connected to mainframe and mini-computers that are primarily intended for shared use, and devices such as smart-phones and personal digital assistants (PDAs) that have only some of the components of a PC (e.g., they may lack a full-sized keyboard, a large screen, an Internet connection, drives, etc.) (*25*). Using population data from UN population database (*26*) and U.S. Census Bureau (*27*), the historical penetration rate of PCs in these regions was calculated. Annual sales data was for new PCs was collected from consulting firms and sources such as eTForecasts, IDC, and the Computer Industry Almanac Inc (*28–30*).

3.2. Logistic Model. The logistic model has its roots in ecology in modeling population growth (*31*). The differential equation is

$$dN/di = rN(1 - N/K) \tag{1}$$

where N represents the penetration rate of PCs, r is the intrinsic growth rate, and K represents the carrying capacity, which is the maximum average number of PCs per person. The solution to eq 1 is

$$N_i = \frac{K}{e^{-(ri+C)} + 1} \tag{2}$$

where $C = \ln\,[N_0/(K - N_0)]$, N_0 refers to the initial penetration rate in reference time period 0, and i is the time passed.

The logistic model describes the penetration rate N and is defined by using the following equation:

$$N_i = St_i/Q_i \tag{3}$$

where St_i is the stock of computers in use and Q_i is the population.

3.3. Material Flows Analysis. To forecast generation of obsolete devices the logistic model needs to be combined with materials flow analysis (MFA). MFA is based on stock and flow model, in which time step changes in stock are determined by tracking additions (flows in) and subtractions (flows out) to stock (*32*). The relationship between stocks and flows is represented by

$$St_i = St_{i-1} + S_i - O_i \tag{4}$$

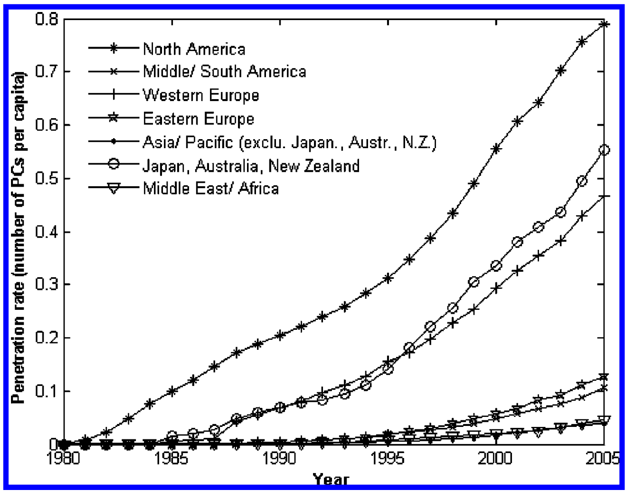

FIGURE 1. Historical computer penetration rate in different regions worldwide.

where St_i is the stock of computers in use in year i, S_i is the sales and O_i is the number of obsolete computers. The generation of obsolete computers O_i and sales S_i are related by the lifespan distribution L_j, which is the probability after j years that a new computer becomes obsolete. The equation

$$O_i = \sum S_{i-j} L_j \tag{5}$$

relates the lifespan L_j, sales S_i, and the number of obsolete computers O_i.

Different definitions of lifespan are possible, including (1) the purchase interval of new machines, (2) the length of time an individual or organization has the machine and (3) the period time between initial purchase of a computer and final end-of-life management. Here we choose lifespan as the interval from purchasing the computer to it leaving the active computer stock, meaning it has been disposed of or is in storage until final disposal. The reason for using this definition is because we fine-tune lifespan assumptions by ensuring consistency between separate data sources on stock and sales of computers (discussed further in Section 6.0).

4.0. Historical Penetration Rate and Sales of Personal Computers

In order to compare PC penetration rate and generation of obsolete PCs between developed and developing world, we divide the world into the following seven regions: North America, Middle/South America, Western Europe, Eastern Europe, Asia/Pacific (excluding Japan, Australia, and New Zealand), Japan/Australia/New Zealand, and Middle East/Africa. With the understanding there is a degree of variation within regions, North America, Western Europe and Japan/Australia/New Zealand are considered to be the developed world, Middle/South America, Eastern Europe, Asia/Pacific and Middle East/Africa are classified as the developing world. For more information, please see SI Section S8.

Figure 1 provides an overview of the historical PC penetration rates between 1980 and 2005 in the seven regions (*24, 26*). One can see that North America has the highest PC penetration rate during the past few decades, followed by Japan/Australia/New Zealand, Western Europe, Eastern Europe, Middle/South America, Asia/Pacific, and Middle East/Africa. Figure 2 shows computer sales trends between 1990 and 2008, indicating that North America held the largest percent share of PC market, followed by Western Europe, Asia/Pacific and Japan, Australia, and New Zealand (*28*). Asia/Pacific experiences the fastest growth of PC sales since 2000, with an annual growth rate of 16%. Developed regions have

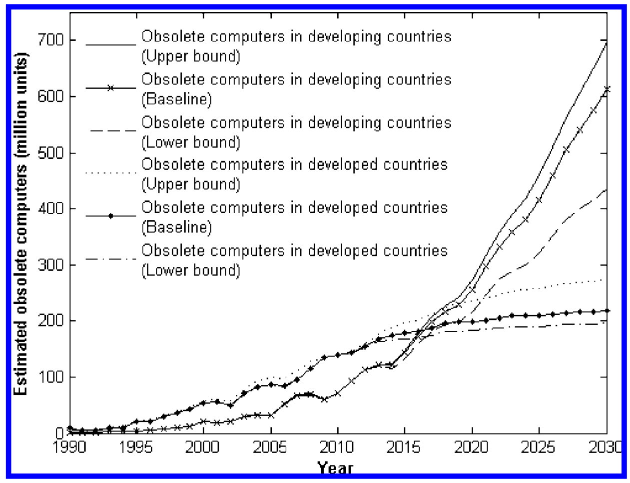

FIGURE 2. Historical PC sales in different regions worldwide.

slower annual growth rates in PC sales: North America has 9% growth, Western Europe 8%, and Japan/Australia/New Zealand 8%) (*29*).

Figures 1 and 2 indicate that the penetration rate in North America is rising rapidly, but the growth rates of PC sales are declining. A similar trend is occurring in Western Europe, Japan/Australia/New Zealand. The rest of the world is further behind in penetration rate and PC sales, and therefore has room for continued high growth, especially Asia/Pacific (Please see SI Section S1 for more information).

5.0. Forecasting Future Penetration Rates Using the Logistic Model

In this section future penetration rates are forecasted by fitting the historical penetration rates shown in Figure 1 with the logistic model, eq 1.

5.1. Bounding Analysis for Carrying Capacity. The logistic equation could in principle be fitted to the penetration rate in Figure 1 to empirically determine the rate of adoption and carrying capacity constants, *r* and *K*, respectively. As can be seen from Figure 1, however, the penetration of PCs continues to increase and has not yet passed through an inflection point. This indicates that from the perspective of the technological life cycle, diffusion of computers is still in its early stage. Statistical fits of the carrying capacity may not give reasonably accurate results (*33*). To address this problem, we use a bounding approach.

According to Yang and Williams (*21*), the upper bound for carrying capacity in U.S. is set by assuming every employed person has their own computer at work and that every person aged from 10 to 84 has their own personal computer for entertainment or other personal needs. The lower bound is set by assuming that only information workers have a computer at work and the penetration rate of computers in households equals to current penetration rate among wealthy families. They estimated that the upper bound of carrying capacity should equal to 1.3 units per capita, and the lower bound should equal to 1.0 unit per capita.

While the upper and lower bound on the U.S. depends on the age structure and labor force of a society, there is no compelling forecasting technique suggesting a long-term age/work force structure for other countries. We approach this challenge using a scenario approach, including scenarios which disfavor future generation of obsolete PCs in the developing world relative to the developed. Three scenarios are set for carrying capacity, including upper bound, baseline, and lower bound. We assume that 1.3 units per capita is upper bound for all regions (every country follows the North America's economic path), and 1.0 is the baseline carrying capacity for all regions (one computer per person, the current

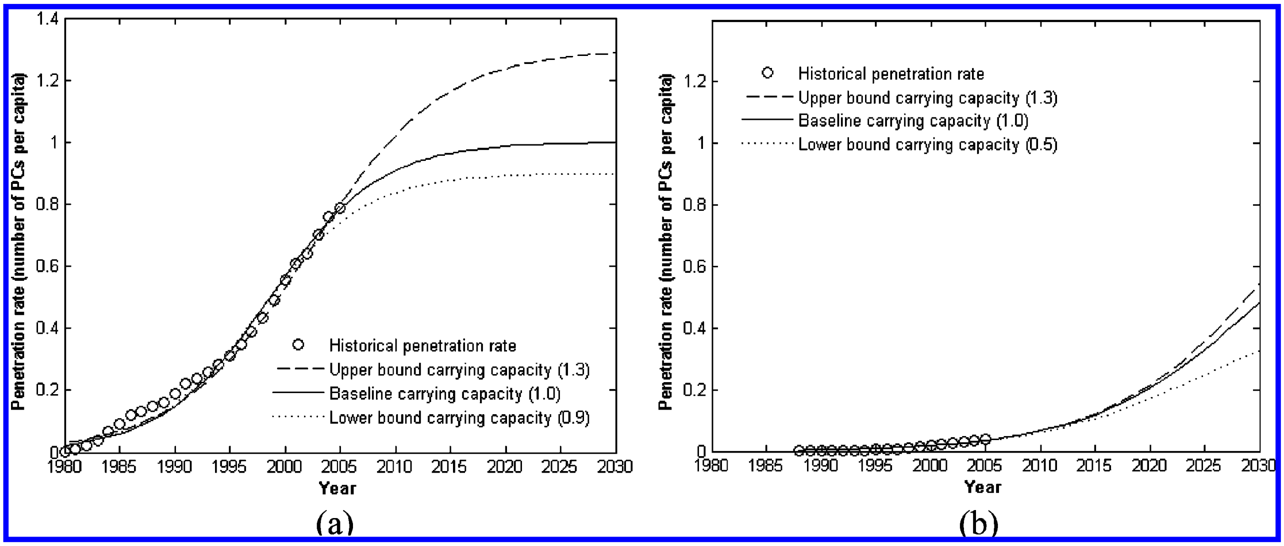

FIGURE 3. Forecasting of computer penetration rate in (a) North America; (b) Asia/Pacific (excluding Japan, Australia, and New Zealand).

TABLE 1. Lifespan Distribution in Different Regions Worldwide

regions	average lifespan (years)	distribution (years)					
		6	5	4	3	2	1
North America	3.8		40%	25%	15%	15%	5%
Middle/South America	5.35	55%	25%	20%			
Western Europe	4.4		65%	15%	15%	5%	
Eastern Europe	4.8	25%	50%	10%	10%	5%	
Asia/Pacific	4.9	10%	70%	20%			
Japan, Australia and New Zealand	4.35		50%	40%	5%	5%	
Middle East/Africa	5.75	75%	25%				

penetration rate at U.S.). To account for the possibility that some regions may be limited in long-term development, we set different lower bounds for each region: 0.9 for North America, 0.8 for Western Europe as well as Japan/Australia/New Zealand, 0.6 for Eastern Europe and Latin America, and 0.5 for Asia Pacific and Middle East/Africa. These lower carrying capacity assumptions do not represent actual potential for long-term growth, rather are intended to explore the sensitivity of e-waste generation to significantly lower carrying capacities in the developing world.

5.2. Fitting Results. The results of fitting penetration rate and bounding values of the carrying capacity for North American and Asia/Pacific regions are shown in Figure 3. North America will come very close to the point of long-term equilibrium in 15–25 years, but Asia/Pacific will need double this time. (For penetration rates and fitting errors for the other five regions, please see SI Section S2).

6.0. Forecasting PC Sales and Generation of Obsolete PCs

6.1. Lifespan Distribution. We now turn to the question of data available related to lifespan. There is no general database listing PC lifespan in all seven regions. However, we can assume the initial values by referring to lifespan data in leading countries in these regions. The U.S. reportedly has a 4-year average lifetime for computers (*34*). Researchers estimated that the average lifetime in Japan is 4–5 years (*35*). Following research by Yang and collaborators on e-waste in China (*36*), the initial value lifetime of PCs in China is set at 5 years.

To generate lifespan distributions for the seven regions, we use the values from the previous paragraph as initial values for different regions. We then iteratively determine the values of lifespan Lj which best matches the stock data points, Stj, with sales, Sj via eqs 4 and 5, by using least-squares analysis. The details of this method are discussed in SI Section S5. The resulting lifespan distributions are shown in Table 1.

6.2. Forecasting Generation of Obsolete Computers. The next step is to translate computer penetration rates to prospective sales and generation of obsolete computers. This requires using the lifespan distributions in Table 1 and population projections. For population, the medium variant scenario from the U.N. Population Statistics Division is employed to project the population from 2009 to 2030 (*26*). Converting from the penetration rate to stock data and computer sales data by applying the lifespan distributions, we obtain the generation of obsolete computers.

Fitting results for North America and Asia/Pacific shown in Figure 4 indicate that the PC sales and obsolete PCs will level off by the year 2030 in North America, but continue to rise dramatically in Asia/Pacific. (For results for the other five regions as well as developing and developed worlds, please see SI Sections S3 and S4).

Using forecasting results for all seven regions, forecasts for PC sales and obsolete PCs in developed and developing world are shown in Figure 5. From this figure one can see that the number of obsolete PCs generated in developing countries will exceed that of developed countries in the near future. The crossover point is insensitive to the scenario, occurring between 2016 and 2018, depending on what combination of upper, and baseline or lower bound cases. The generation of obsolete PCs in the developing world will rise dramatically after that the crossover. By 2030, the numbers of obsolete PCs in developing regions will double that of developed regions, with 400–700 million units in developing regions and 200–300 million units in developed regions.

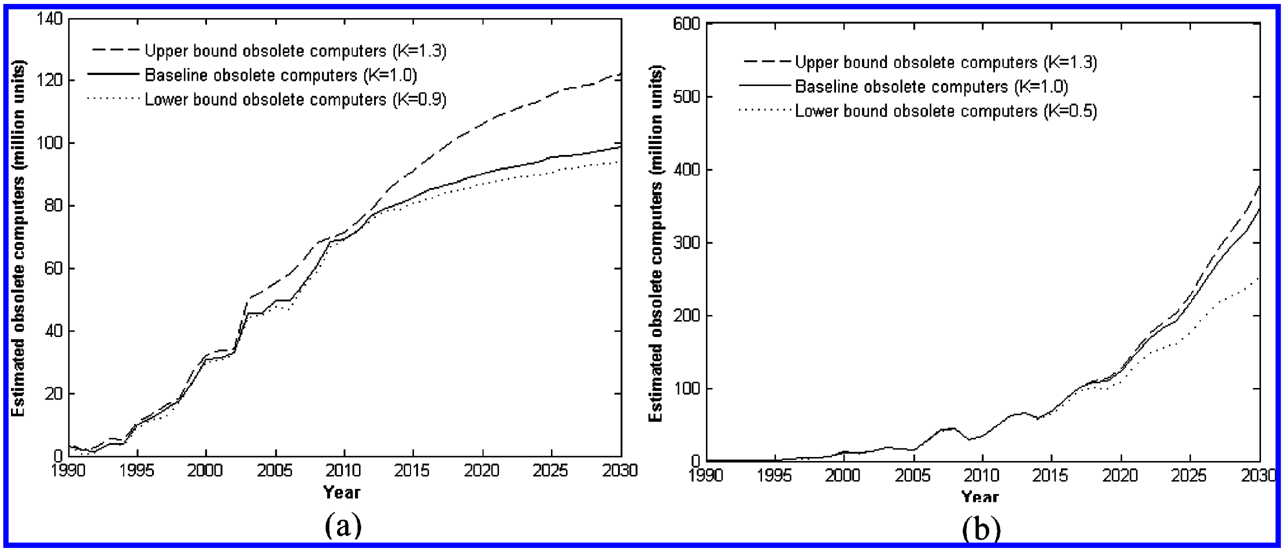

FIGURE 4. Forecasting of generation of obsolete computers in (a) North America (b) Asia/Pacific (excluding Japan, Australia, and New Zealand).

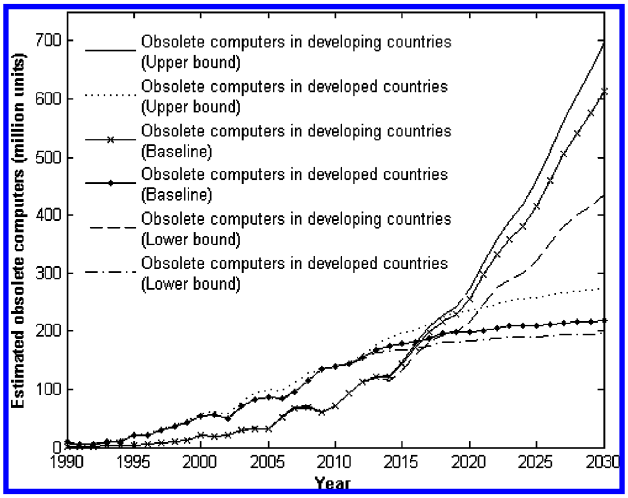

FIGURE 5. Forecasting of generation of obsolete computers in developed and developing world.

To briefly discuss uncertainty, note that the crossover point is insensitive to even pessimistic assumptions of long-term adoption of computers in the developing world. A second uncertainty is that due to lack of data, trade in used computers is not included in the computer sales data. In SI Section S6 we undertake sensitivity analysis of results to increased used computer trade and find that it causes a slight increase in generation of obsolete computers in the developing world.

7.0. Policy Implications

Assuming the forecast is robust, the results shown in Figure 5 have profound implications for international e-waste policy. The prevailing assumption that trade is the main driver of informal recycling will soon become obsolete. In fact, considering that more e-waste in the developed world is being recycled domestically due to take-back/recycling policies, it is possible that informal recycling of e-waste may already be dominated by domestic sources in the developing world.

There are several implications for international e-waste policy. The first is reconsideration of the goals of e-waste trade restrictions. By itself a global trade ban on e-waste partially mitigates impacts of informal recycling, but leaves the bulk of the problem untouched. In addition, trade restrictions have negative economic and social consequences. On the economic side bans reduce the supply of used electronics, eliminating refurbishing jobs in the developing world (*9*). Used computer markets also contribute to mitigating the digital divide by enhancing access to information technology to low income people in developing world (*9, 14*). Trade restrictions can play a role to ensure countries receive equipment appropriate their needs and capabilities, but should be part of a larger suite of policies aimed at solving the problem of informal recycling.

The second policy implication of these results is that environmental impacts of informal recycling need to be directly and explicitly addressed. One approach is command and control: Informal recycling practices are banned and local or national environmental authorities enforce the ban through putative measures. This success of command and control requires strong governance down from national to the local level, lacking in some developing countries. Command and control efforts in China, for example, have yet to succeed (*37*). Despite official bans on importation of e-waste the trade reportedly continues much as before (*7–10*). China has made significant investments in domestic electronics recycling systems. These formal systems have failed to collect sufficient equipment because the informal sector offers superior economic incentives to those disposing of products (*37*).

Economic instruments are another approach. The idea is to provide financial incentives to channel equipment from informal to formal processing. A specific proposal, the “collection point” model, fixes market prices for select parts resulting from the disassembly process which result in environmental damage when recycled informally (such as circuit boards) (*9, 38*). The price is set such that dismantlers profit slightly more to deliver parts to collection sites rather than process by informal recycling. Collection points 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 goal is to mitigate environmental impacts while maintaining reuse, profitability, and employment in the sector.

Whatever policy framework is used to address informal recycling it is likely that net financial injections into the system will be needed. If an agent (nation, organization or individual) disposes of a device with limited reuse potential it is reasonable to assert that that funds be set aside to ensure proper recycling at its ultimate end-of-life. One way to operationalize this idea is to require that recycling deposits be paid on equipment at purchase, deposits which follow the device through its life cycle tracked by radio frequency identification devices (RFIDs) (*17*).

The above lays out an impressionistic view of future policy directions to address informal recycling. It is not within the scope of this article to explore these ideas in depth. Our central assertion is that the new structure of global e-waste generation discovered here combined with economic and social considerations, call for a serious rethinking of e-waste policy. We believe there are unexplored opportunities to mitigate informal recycling while enhancing economic and social benefits. Researchers and policy-makers need to work to develop and realize new solutions.

Acknowledgments

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Supporting Information Available

Additional Figures for PC penetration rate and obsolete PCs forecasting. This material is available free of charge via the Internet at http://pubs.acs.org.

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