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# Making A Vicious Cycle Virtuous: Rare Earths As An E-waste Case Study

Stephanie Alarcón, MES
salarcon@upenn.edu

# MAKING A VICIOUS CYCLE VIRTUOUS: RARE EARTHS AS AN E-WASTE CASE STUDY

**Stephanie Alarcón, MES**

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Primary Reader: Stan Laskowski

Secondary Reader: Christina Dunbar-Hester

# EXECUTIVE SUMMARY

The problems with electronic waste are well-documented. In the US, 82% of discarded electronics are landfilled or incinerated, while 18% are sent to recyclers (US EPA, 2008b). However, weak e-waste regulations and enforcement in the US contribute to an environment where exportation is more economically viable than recycling.

These situations arise because the regulatory environment fosters a vicious cycle: recycling is expensive, because electronics are not designed for recycling, because recycling is not mandated. The author refers to this as the e-waste cycle and examines its various inputs and outputs.

However, citing the success of European Union electronic waste legislation, it is suggested that thoughtful regulation and meaningful enforcement can set in motion a virtuous cycle. Policy can nurture a market where electronics are designed for easy recovery of valuable metals and other substances, making electronics recycling a more lucrative enterprise, encouraging used electronics to flow out of waste deposits and into inputs for new manufacturing, thereby reducing dependence on mining and other high-impact industrial processes.

These principles are applied to an anomalous, but not unpredictable, rare earth element embargo that took place in late 2010. Through this example, it is shown that the importance of building a regulatory environment that fosters

electronics recycling, goes beyond harm reduction and virtuous cycles. It can be viewed as economic insurance against volatile global markets, and should be part of the US's overall technology strategy.

## Key Findings:

- Weakness in US regulations leaves the economy unequipped to make electronics recycling financially viable. Thus, e-waste recycling rates in the US are low.
- US failure to recycle electronic waste leads to environmental injustices and causes potentially valuable materials to flow to foreign scrap markets.
- Markets for certain critical minerals, particularly rare earths, are extremely polarized. US lacks reliable sources of several materials necessary for electronics manufacturing and the continued development of renewable energy products. It also lacks key intellectual resources like patents and rare earth engineering expertise.

## Recommendations:

- Strengthen and consolidate US e-waste regulations following successful models, particularly in the EU.
- Focus attention and investment on extracting critical minerals from “urban mines” including extant electronic waste, rather than strictly new mining projects.

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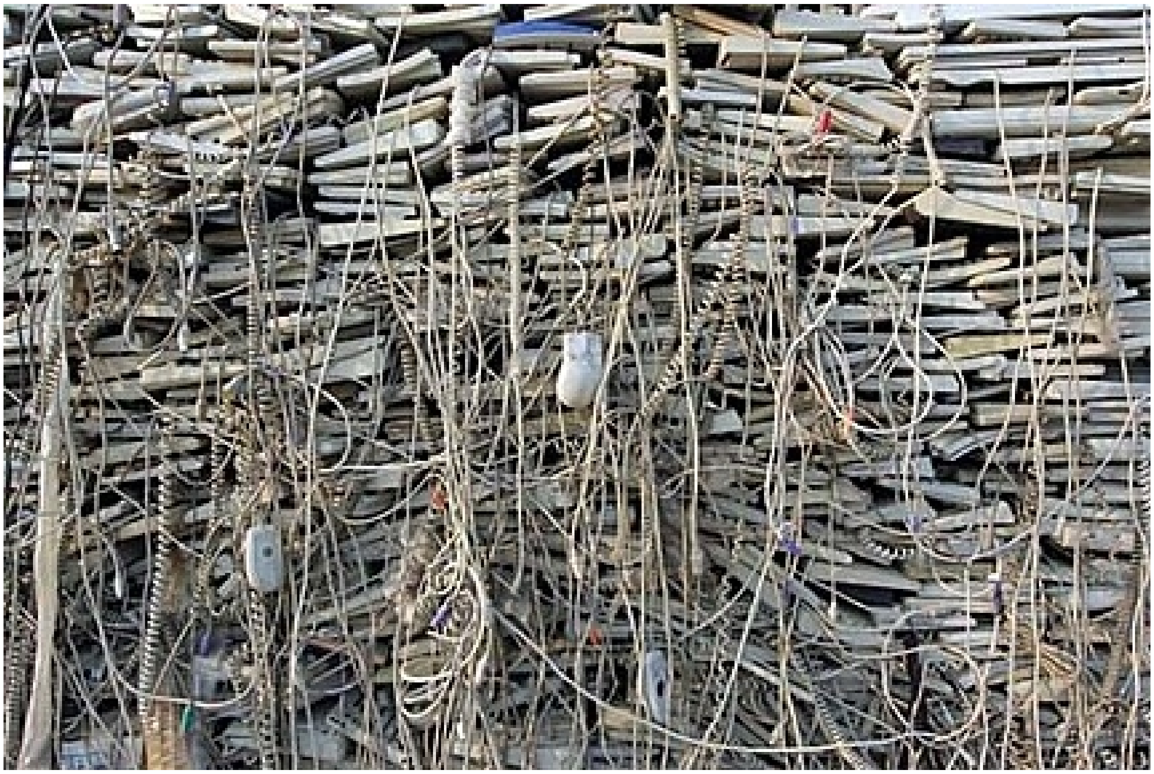

Figure 1.1: Pile of Computer Peripherals. © Greenpeace / Natalie Behring

## 1.1 Introduction

Electronic waste, also called e-waste or WEEE (waste electrical and electronic equipment), is any electrical or electronic device that has fallen out of use. It might be thrown away and destined for a landfill, sold for scrap or reuse, stored by the user in the home or workplace, or recycled into new products. Each year, as the number of devices in society increases, so does the amount of e-waste that must be processed. The tonnage of discarded computers, cellular phones, electronic children's toys, home appliances and so forth, are a clear reminder that despite the appearance of a “dematerialized” information economy that relies on the flow of data, the goods that make this system work are in fact quite material.[1]

What difficulties and opportunities lie in the growing stores of electronic waste? What harm arises from inappropriate e-waste processing and unjust distribution of environmental and labor impacts? What untapped economic potential exists in the “urban mines” of discarded electronics, and what systemic inputs can help us take advantage of it?

The first section of this paper will discuss what the author calls the e-waste cycle. This is a set of inputs, outputs, practices and missed opportunities that have made this potential economic and manufacturing resource into a source of toxins, environmental damage, and economic injustice. Special attention will be given to the regulatory environment, with a discussion of the success of European Union e-waste regulations. This example will be used to derive lessons about how regulation can turn a vicious cycle into a virtuous one, creating new markets and reducing harm.

The second section will apply this way of understanding electronic waste to a particular time period and family of industrial materials, specifically the

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[1] “Our point was, and is, simply that the amount of materials used to manufacture a computer chip these days is hundreds, if not thousands of times greater than the quantity actually embodied in the chip. This makes the weight of the chip a misleading indicator of the amount of materials used, and it means that people like Alan Greenspan and Frances Caircross who have cited microelectronics as an example of radical "dematerialization" have misunderstood the situation.” (Williams, Ayres & Heller, 2004)

impact of a brief but highly publicized embargo of rare earth oxides from the People's Republic of China in late 2010. The examination of this incident provides an opportunity to apply the principles discussed in section one to a specific situation and draw conclusions about how a virtuous cycle might have critical economic benefits.

## 1.2 A Typical User

Before delving into the various inputs and outputs that create the vicious cycle of electronic waste, it may be helpful to think through the example of a typical technology user and the life cycle of a consumer electronic product.

Imagine a user who has just bought a new computer. It may be her first, or perhaps she is replacing an older model that no longer meets her needs. Presumably, she shops for the fastest processor and largest hard drive that fits her budget. If she is eco-conscious, she may look for an energy-efficient model. When it gets to her home or workplace, she opens it up and puts the packaging in the garbage or out with the recycling. Even before she creates a user account, she has transferred waste from the manufacturer to her municipal waste system.

She uses the computer for several years, maybe three if she has processor-intensive needs and has to upgrade to do her work; maybe five to seven if her needs are more basic and the computer keeps working. On the advice of her IT department she puts the computer in power save mode when not in use, and tries not to print unnecessary documents. However, up to 81% of the energy used during the computer's lifetime was already expended during its manufacture, while the production of just a memory chip could demand 630 times the weight of the chip in fossil fuels and chemicals (Williams, Ayres & Heller, 2002).

At the end of the computer's life, she tries to decide on the best way to dispose of it. She knows that throwing it out with regular garbage is not the best choice because the metal in the computer is recyclable and toxins can leach out of the circuit boards in a landfill or pollute the air if incinerated. She considers donating the computer but decides against it. She has heard too many alarming stories about data theft (Puckett et al, 2005). Besides, if she donates it with only a little bit of life left, then the next person will have to find a way to dispose of it.

Now our user considers recycling. She calls a few electronics recyclers and is surprised to find that they charge about $10-$30 to take old computers.[2] Unclear on why she should pay to give away a computer, she eventually finds that her town sponsors an electronics recycling event every few months. This sounds like the perfect solution and she takes it to her municipal dump on the proper day.

At this point, as far as the user is concerned, the old computer is gone and headed to a facility that will turn it into scrap, destined to be made into something new later on.

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[2] Recycling prices fluctuate with scrap prices, but $10-$30 remains a reasonable benchmark. For example, see this Seattle electronics recycler. http://www.pcrecycle.net/prices.html

However, what is not clear to the user is that recycling a computer requires significant manual labor and sophisticated mechanical and chemical handling because the computer was designed for its use phase, not its disposal phase. That infrastructure is expensive, and the resulting scrap does not earn enough to pay for the processing. That may explain the fee that some recyclers charge.

How was her town able to offer free recycling? It is possible that the town contracted with a reputable recycler and paid for the service out of the taxpayer-funded municipal waste budget (Electronics TakeBack Coalition, 2010). In that case, her municipality--and therefore the taxpayers, including her--paid to dispose of both the original packaging and the computer itself. The manufacturer took no responsibility and was not given the opportunity to reclaim the waste to make its next line of products.

Another possibility is that, in order to save money, the town unknowingly contracted with a less reputable recycler. The company may claim to process waste using only the most secure data destruction techniques and the highest environmental standards, but the scrap market simply cannot support that level of service without charging a fee. It is possible that the company sells used electronics to a broker who brings them to an overseas market (Electronics TakeBack Coalition, 2010).

Where does a market exist for electronics discarded by users in the US?

Thriving second hand technology markets exist in the developing world, but overseas shipments are only cost effective on a large scale. So the recycler may sell an entire shipping container of electronics, assuring the broker that at least 75% of them were functional at the time of sale.

The broker cannot reasonably sift through an entire shipping container and verify that 75% of the shipment appears functional. When the container arrives at its destination, a partner brings the electronics to a nearby market and workers begin testing. They may find that only 50% or even 25% of the shipment works at all (Puckett et al, 2005). The rest is junk and goes to the local dump. Of the working devices, perhaps our example user's machine was found to work. Fortunately, she removed the hard drive just to be sure that her personal data could not be stolen. It is now in a closet with 3 other hard drives and an old cell phone.[3]

When the non-functioning electronics arrive at the dump, enterprising young people who know that they can sell some of the metals for scrap descend on the pile and start picking out valuable parts. One person collects power cords and throws them on a fire to burn off the vinyl jackets. When the acrid black smoke clears, what remains is a small pile of copper ready for the scrap market. Another person might be hired to pull out printed circuit boards, heat them over a small stove to melt the leaded solder and pick off the components, then soak the

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[3] "Of products sold between 1980 and 2007, approximately 235 million units had accumulated in storage as of 2007." http://www.epa.gov/osw/conserve/materials/ecycling/manage.htm

stripped board in a potent acid solution to dissolve the gold traces which can be reclaimed through a second chemical process. Someone else may use a hammer to break the screen of a cathode ray tube (CRT) monitor—including the lead curtain—to extract the copper yoke. These workers probably do not have access to personal safety equipment, and may be paid poorly for their efforts and personal risk (Puckett et al, 2002).

Meanwhile, the various carcinogens released when the cables were burned eventually settle into the soil, reaching nearby farms. Lacking proper disposal facilities, workers are forced to dump the spent acid solution into nearby waterways, the same ones used for fishing. The lead released from CRT monitors makes its way into the soil, water, and air, leading to health problems and neurological impacts, especially for children (Puckett et al, 2002).

This is almost surely not what the user envisioned when she attempted to dispose of her old computer properly. Even though her individual consumer decisions were conscientious, they were ensnared in a larger vicious cycle.[4]

## 1.3 The Electronic Waste Cycle

Our example user understood a basic principle of sustainability, which is that throwing something away at the end of its useful life is a missed opportunity to capture the resources it embodies. Not only does a discarded computer

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[4] For two excellent visual encapsulations of the complicated issues around e-waste, see “The Story Of Electronics” by Annie Leonard, creator of “The Story Of Stuff” (http://storyofstuff.org/electronics.php) and Good Magazine's E-Waste PSA (http://www.good.is/post/e-waste-psa-high-tech-trash/).

contain materials that can be reused, it also represents the energy that was expended to extract and assemble those materials. The energy "contained" in a product as a result of raw material extraction and manufacturing is called "embodied energy" (Costanza, 1980). A related concept is virtual water (also called embedded or embodied water[5]) which attempts to measure the amount of fresh water required to make a product (Allen, 2003).

The idea that the energy, water, and other resources that are invested in a product before it goes to market can and should be quantified, can be viewed as a corollary to the idea of "ecosystem services". This concept says that functions of nature provide services with massive economic value, such as food production, water supply and filtration, climate regulation and so on (Costanza et al, 1997).

A concrete example of the intersection of embodied resources and ecosystem services as it applies to electronic waste is the difference in energy intensity of aluminum mining versus aluminum recycling. Aluminum is used in electronics to make cases, heat dissipation devices, and other hardware. According to the International Aluminum Institute, recycling a given quantity of aluminum requires about 5% of the energy needed to extract the same amount from bauxite.[6] That means that recycled aluminum is 20 times less energy

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[5] John Anthony Allen coined the term "embedded water" in 1993, inspired by Israeli economists who had argued since the 1980s that the exportation of water-intensive produce was tantamount to exporting water from a semi-arid nation. Allen applied it to agricultural products, but the concept has since been extended to talk about water usage in other industries.

[6] http://www.world-aluminium.org/Sustainability/Recycling

intensive per product lifetime than newly mined aluminum. It is also less expensive in terms of ecosystem services because of the energy usage, soil disruption, and other ecological impacts of mining. Later we will investigate how this applies to other materials contained in e-waste.

When damages to the environment or to people occur outside of the formal economy, they are termed externalized costs. In economics, an externality is an impact of a commodity that is not captured in its price. A beneficial impact is called a positive externality, and a detrimental impact is called a negative externality. Externalities are viewed as economic inefficiencies because they indicate that a product's price is an incomplete representation of its value (Callan, 2007, p. 55). In the case of our example user, when her old computer was disassembled, some valuable materials were extracted but the process damaged human health and caused the loss of ecosystem services like availability of agricultural land and provision of potable water. Because these damages were not financially codified, they became externalized costs.

Externalized environmental costs that negatively impact people are examples of environmental injustice, such as the harm to human health and well-being mentioned above. Violent conflicts over mineral rights are also externalized costs and environmental injustices. For example, the term “conflict coltan” is used as shorthand for coltan mined in the Democratic Republic of Congo in areas under the control of fighters from Rwanda and Uganda (Ware, 2001). Coltan is a mineral that contains niobium and tantalum, which is used to make capacitors. Proceeds from the sale of coltan fund the ongoing conflict while displacing residents and compromising farmland and wildlife habitat. The similarity of the phrase “conflict coltan” to the well-publicized concept of “conflict diamonds”[7] is intended to draw attention to the seriousness and violence of the situation around this important industrial mineral.

Recycling transforms the one-way flow of materials from natural resources to landfill, into a cycle that reclaims materials and takes advantage of embodied energy. Instead of retiring both the object and all the energy that was used to derive it, recycling conserves some of those resources by putting them to a new use. Strong recycling infrastructure prevents the flow of electronics to places where they are likely to harm people and the environment, and supplies domestic scrap markets. Increasingly, recycling in general and e-waste processing in particular can be seen as not only the “right” thing to do, but also a way to conserve valuable material resources in domestic markets. As we will see, there is growing recognition that materials extracted from e-waste recycling may play a significant role in the future of electronics manufacturing.

Though the benefits of recycling electronics are well understood, the market is currently not equipped to make it financially viable because it externalizes the costs of not recycling. Recycling rates are low, because

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[7] The UN General Assembly defines conflict diamonds as “diamonds that originate from areas controlled by forces or factions opposed to legitimate and internationally recognized governments, and are used to fund military action in opposition to those governments, or in contravention of the decisions of the Security Council.” http://www.un.org/peace/africa/Diamond.html

recycling is expensive, because products are not designed for recycling, because recycling rates are low.  In other words, the US in particular is caught in a vicious e-waste cycle:  Products are not designed for disassembly because recycling is optional, so disassembly is expensive.

Well-designed regulations can induce virtuous cycles.  They can create markets from externalized costs (e.g., cap-and-trade programs[8]) and foster an even playing field valued by industry.  Regulations that require manufacturers to take back old electronics could trigger changes in product design that bring down the cost of disassembly, leading to an expanded market and greater business opportunities for recyclers.

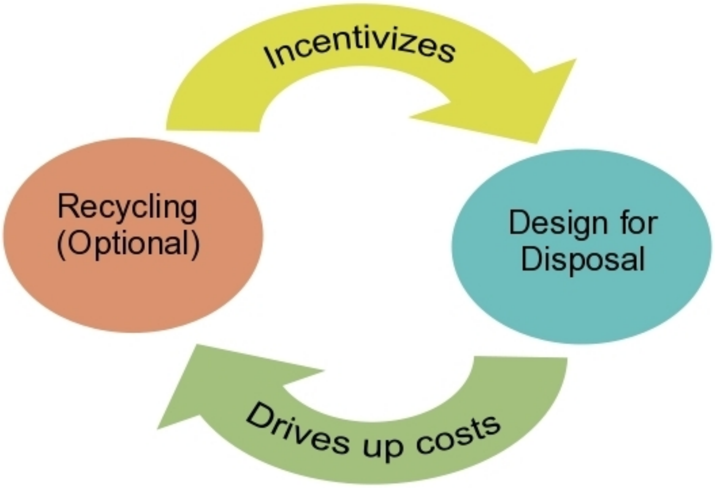

Figure 1.2: A vicious cycle: Optional recycling encourages design for disposal, which drives up the cost of recycling.

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[8] An EPA white paper examined the two largest price spikes in cap and trade markets in 2003 and 2006.  It found that the markets self-corrected and are usually fairly stable (US EPA 2009).  For a list of US EPA Clean Air Markets, see http://www.epa.gov/airmarkets/index.html

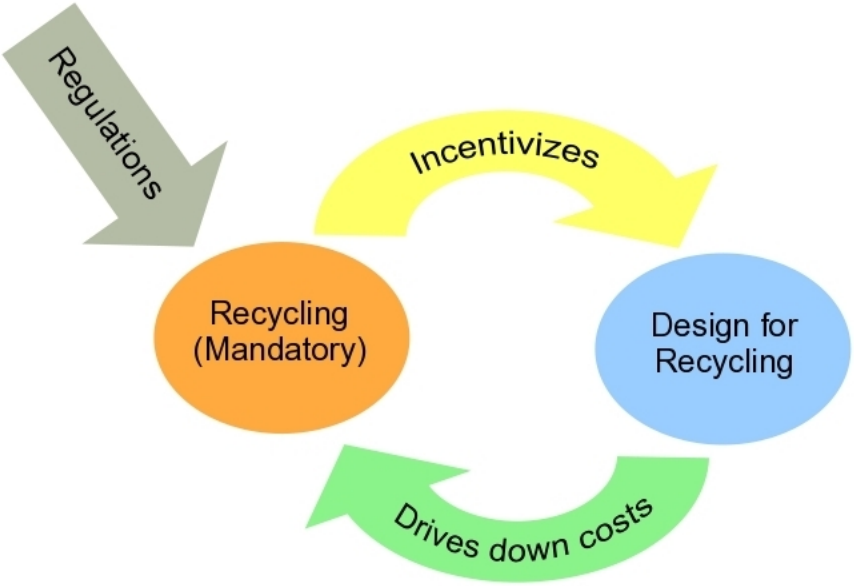

Figure 1.3: A virtuous cycle:  Mandatory recycling recognizes externalized costs and encourages design for the environment, which makes recycling more cost-effective.

The literature about how to interrupt the e-waste cycle consistently refers to several high-level concepts including recycling, product design, and regulation.

Recycling is often discussed as a panacea for the e-waste problem, but it is by no means a trivial proposition.  The need for sophisticated separation machinery and emission control means that electronics recycling is only economically viable under specific circumstances which are largely determined by global commodities pricing and local labor costs.  In other words, disassembly is too expensive and scrap is too cheap for e-waste recycling to thrive in the current US market.  This is evidenced by the fact that unsubsidized e-waste recycling costs money (the $10-30 estimate mentioned earlier) rather than earning money. Materials recovery is complicated by everything from the multitude of fasteners found in various gadgets to chemical commingling of substances. A more detailed discussion of these factors is to follow, but for this introduction it is sufficient to point out that electronics are generally not designed to facilitate disassembly and recycling.

Why are electronics designed this way, and what might cause that to change? Traditionally, electronics have been designed to reduce production costs and increase sales, without much consideration for what might happen at the end of their useful life. Furthermore, many electronics vendors influence the lifespan of devices either explicitly by making products that tend to break after a certain amount of time, or implicitly by pricing devices and support contracts to encourage the purchase of new products on a regular basis. These are examples of planned obsolescence, which The Economist defines this way:

> "Planned obsolescence is a business strategy in which the obsolescence (the process of becoming obsolete—that is, unfashionable or no longer usable) of a product is planned and built into it from its conception. This is done so that in [the] future the consumer feels a need to purchase new products and services that the manufacturer brings out as replacements for the old ones". (2009)

It specifically mentions software and microprocessors as examples of products designed so that new versions make old versions obsolete, encouraging purchase of the new product. More supporting examples will be discussed in the section entitled "Rethinking the E-Waste Life Cycle".

The profit motive behind planned obsolescence helps explain why companies often prefer to design products that are easier to replace than repair or upgrade. However, if responsibility for handling products at end-of-life fell to manufacturers instead of municipalities—in other words, if the cost of waste processing were internalized--the costs associated could profoundly impact product design.

This is the concept behind manufacturer take-back, also called product stewardship or extended producer responsibility (EPR). Advocates believe that if it were legally required and/or financially advantageous to design for easy upgrades or safe recycling (also referred to as design for the environment), companies would change their design standards to be more sustainable. The Electronics TakeBack Coalition, a vocal promoter of e-waste recycling, asserts that EPR is

> “the policy tool to promote sustainable production and consumption of consumer electronics (all products with a circuit board). EPR will improve the next generation of solid waste and toxic materials policy, promote the manufacture of cleaner computers and curb the flow of toxic electronic waste by pushing manufacturers to take responsibility for their waste, internalizing its cost in corporate bottom lines, and phasing out the use of hazardous substances[9].”

The coalition's stance is not a radical one, and in fact a take back scheme is featured prominently in European Union e-waste legislation. Regulations and enforcement can play a critical role in increasing efficiency by curtailing practices

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[9] http://www.electronicstakeback.com/about-us/

that are prone to externalizing costs. As we will see in a later section, EU legislation and international treaties have set a baseline for reducing toxicity in electrical and electronic products, and have increased recycling rates. Many entities from activist organizations to the Government Accountability Office (GAO, 2008) have called for stronger e-waste regulations in the US. Some are interested in EPR and sustainable design, while others want to limit exports or expand the definition of hazardous waste. However, they have in common a belief that the market has not and will not properly internalize costs and break the e-waste cycle without regulation. This claim will be explored in the section entitled "The Role of Regulation" that summarizes e-waste management from international treaties to state laws.

As we have started to see, the components of the e-waste cycle are important and inter-related largely because of the way capital flows in the global economy. For example, planned obsolescence is economical for manufacturers because they externalize the cost of their waste, while the scrap industry internalizes the cost of its operations through environmental permitting and pollution control mechanisms. Meanwhile, scrap prices are too low to make e-waste recycling viable in the US partly because foreign markets drive down the cost of the same materials by externalizing the impacts of mining and pollution from poorly regulated recycling facilities. Because waste and raw materials are inexpensive in terms of price but expensive in terms of environmental degradation, public health, and quality of life, there is little economic incentive to build sophisticated recycling facilities, and great incentive to export e-waste to places with lax environmental regulations and poor working conditions. The e-waste problems in such places have been exacerbated by growing domestic markets for electronics as business becomes more global. Because there are few facilities to extract valuable substances from electronics, there are few sources of competitively priced recycled materials for electronics; and so on.

In other words, in a global economy with inconsistent economic efficiencies and environmental externalities, recycling is performed where it is most financially viable. When recycling is expensive in one place, products flow to other places where it can be done more cheaply.

## 1.4 Contents And Quantities Of E-Waste

Electronic waste can be thought of as any discarded object that uses electricity or electromagnetism to perform its core function. Exact definitions differ from place to place for the purposes of local regulations, but this guideline is similar to an EU definition that is widely used. Some common examples are discarded computers, cell phones, printers and fax machines, televisions, and computer monitors. Less obvious items include electronic children's toys, microwave ovens, radios and stereos, control systems from cars, and a great number of consumer appliances.

Quantifying electronic waste is a difficult task (Williams, 2005). Since waste is viewed as valueless, it is not tracked or measured carefully.

Furthermore, one product can be partly disassembled and end up in more than one waste stream. It might be classified as either municipal or industrial waste, and toxic or non-toxic depending on the point in the product's life cycle at which the waste is discarded, or who throws it away. Finally, there is enough variation in how waste is defined from country to country that comparing totals from each country can be complicated. For example, US Environmental Protection Agency (EPA) measures “major appliances”, “small appliances” and “selected consumer electronics” as distinct waste types, while the EU WEEE directive quantifies those types of waste but considers them all part of the WEEE definition.

A common method for estimating e-waste quantities is to multiply sales data by the projected lifetime of a product (US EPA Office of Solid Waste, 2008b). By this method, it is estimated that Americans own an average of 24 electronic devices per household, resulting in about five to eight million tons of e-waste per year, or three billion units between 2003-2010 (Grossman, 2006, p. 146). Furthermore, US EPA estimates indicate that over 235 million old, broken, or obsolete devices were stored in people's homes between 1980 and 2007 (US EPA, 2008a). Grossman cites a 2004 US EPA bulletin which claimed that the US government discarded about 10,000 computers per week, not including the postal service or military (p. 146).

Currently, electronic waste only constitutes about 2% of municipal waste in the US, but it is the fastest growing municipal waste stream. US EPA estimates that about 82% of electronic waste ends up in landfills or incinerators

(US EPA, 2008b), from which toxins can leach into soil and groundwater or escape into the air. The remaining 18% is sent to recyclers. According to the Basel Action Network, recycling industry sources estimate that 50-80% of that is exported, not recycled, most commonly to nations in Asia and Africa (Puckett et al, 2002). This is consistent with a US EPA finding that 77% of televisions and CRT monitors collected in 2005 were sent abroad at end-of-life for resale, refurbishing, or glass recycling (US EPA, 2008b).

WEEE is also on the rise in the European Union. In 2005, the EU27 nations produced an estimated 8.3-9.1 million tons of waste electronics. That number is expected to grow by about 2.5% per year, reaching 12.3 million tons in 2020 (Huisman, Magalini, Kuehr & Maurer, 2007).

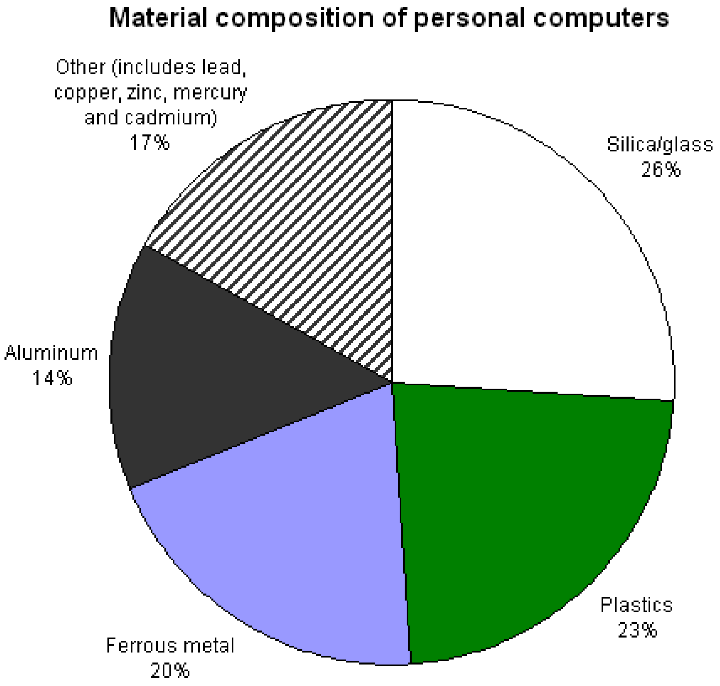
Electronic waste is generally seen as a problem created in developed nations and exported to developing nations, but one projection indicates that the number of obsolete computers in developing nations will exceed those in developed nations by 2018. By 2030, developing nations might have twice as many obsolete computers as developed nations (Yu, Williams, Ju & Yang, 2010).

| Country | Total E-waste Generated tonnes/year | Categories of Appliances counted in e-waste | Year |
|---|---|---|---|
| Switzerland | 66042 | Office & Telecommunications Equipment, Consumer Entertainment Electronics, Large and Small Domestic Appliances, Refrigerators, Fractions | 2003 |
| Germany | 1100000 | Office & Telecommunications Equipment, Consumer Entertainment Electronics, Large and Small Domestic Appliances, Refrigerators, Fractions | 2005 |
| UK | 915000 | Office & Telecommunications Equipment, Consumer Entertainment Electronics, Large and Small Domestic Appliances, Refrigerators, Fractions | 1998 |
| USA | 2158490 | Video Products, Audio Products, Computers and Telecommunications Equipment | 2000 |
| Taiwan | 14036 | Computers, Home electrical appliances (TVs, Washing Machines, Air conditioners, Refrigerators) | 2003 |
| Thailand | 60000 | Refrigerator, Air Conditioners, Televisions, Washing Machines, Computers | 2003 |
| Denmark | 118000 | Electronic and Electrical Appliances including Refrigerators | 1997 |
| Canada | 67000 | Computer Equipment (computers, printers etc) & Consumer | 2005 |

***Table 1: E-waste generation in selected countries (Source: Williams, 2005)***

## 1.5 Valuable And Toxic Contents

E-waste contains certain rare and valuable mineral products. Contact circuitry contains precious, semi-precious, and highly recyclable metals like copper, gold, platinum, nickel, cobalt, tungsten, and molybdenum (USGS, 2001; Grossman, 2006, p. 59). Cases and displays contain aluminum, ferrous metals, plastics, glass and silica (Environment Canada, see chart below). Capacitors are made with tantalum, whose dwindling reserves are a concern to electronics manufacturers (Grossman, 2006, p. 45). Tantalum in turn is a product of the mineral coltan, whose geopolitical significance in the Democratic Republic of Congo was previously discussed.



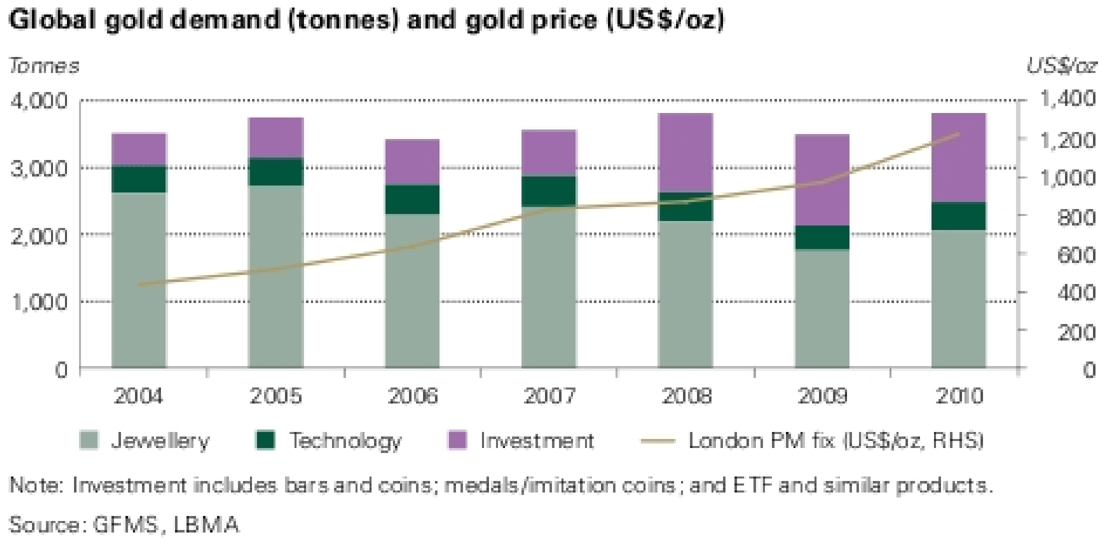
**Source:** Environment Canada.

Figure 1.4: Material composition of personal computers. Source: Environment Canada

Because electronic waste contains pre-extracted mineral goods, it can be thought of as an “urban mine” or “anthropogenic ore”. The United Nations Environment Programme uses the term anthropogenic to describe “metal stocks in society, already extracted, processed, put into use, currently providing service, or discarded or dissipated over time” and calls recycling “'mining above ground' or “urban mining'” (Graedel, 2010). Extracting recyclable materials from e-waste is process-intensive, but the waste contains valuable substances at concentrations much higher than those found in nature. For example, according to a United States Geological Survey (USGS) report, 200,000 tons of ore and waste were extracted for each ton of gold mined in 1998 in South Africa where underground mines are the norm, whereas the ratio was 2.6Mt waste per ton of gold in the US where most gold comes from surface mines (Butterman & Amey, 2005, p. 43). The Earthworks.org “No Dirty Gold” campaign condensed government and industry measurements into an estimate that the production of an eighteen karat, 0.333 ounce gold ring generates about 20 tons of mining waste (No Dirty Gold, accessed Apr. 2, 2011). A USGS fact sheet reports that one ton of used circuit boards is richer in gold than seventeen tons of average gold ore; some estimates indicate that depending on geologic conditions, circuit boards may be 40-800 times richer in gold than ore (USGSas, 2001).

Figure 1.5: Fimiston Open Pit Gold Mine (Kalgoorlie Super Pit), Western Australia. Image courtesy of www.superpit.com.au

Yet, the materials that go into new electronics overwhelmingly come from the mining industry. Even though gold is extremely recyclable, only about 30% of the world's gold products are made from scrap. As a precious metal, most of the world's gold goes into static uses like jewelry, coins and bars. But while demand for gold jewelry and investment instruments have shifted over the last decade, demand for gold in technology has hovered around 11.5%. At the same time the price of gold has more than quintupled (Ong, Street, Palmberg, Artigas & Grubb, 2011; see chart from World Gold Council below). Thus, even though a large proportion of gold is fixed in non-industrial uses like jewelry and investments, the total value of the gold used in electronics—and therefore potentially available for reclamation--continues to rise. This indicates that there is investment opportunity in reclaiming gold from technology products.


Global gold demand (tonnes) and gold price (US$/oz)

Note: Investment includes bars and coins; medals/imitation coins; and ETF and similar products.

Source: GFMS, LBMA

Figure 1.6: Global Gold Demand and Price, 2004-2010. Courtesy of World Gold Council

Why, then, are recycling rates for electronics so low, particularly in the US? The answer comes down to two factors: disassembly costs and scrap prices. Scrap prices are too low to cover the cost of infrastructure and permitting required for proper handling in the US. A frequently cited estimate from the Basel Action Network claims that recycling costs in China are about one-tenth of those in the US (Puckett et al, 2002). This can be explained largely by differences in environmental protection standards and labor costs.

Most electronics recycling is labor-intensive. Disassembly is complex, highly variable from product to product, and difficult to automate (Iles, 2004). For example, the method for opening the case of a PC, laptop, or cellular phone varies from model to model, meaning that the first steps of disassembly are often necessarily manual processes. The various toxins in electronics further complicate disassembly. E-waste frequently contains metals which are classified as hazardous under the Resource Conservation and Recovery Act (RCRA) such as lead, mercury, and cadmium (USGS 2001, see table below). Electronics also contain non-metal materials that are potentially carcinogenic or harmful to human health like polyvinyl chloride (PVC), polychorinated biphenyls (PCBs[10]), and brominated flame retardants (BFRs). Proper and complete electronics recycling typically requires high safety standards, air pollution scrubbers, and on-site wastewater recovery systems.

| Metals in computers classified as hazardous under RCRA | |
|---|---|
| Antimony | Cobalt |
| Arsenic | Lead |
| Cadmium | Mercury |
| Chromium | Selenium |

*Table 2: RCRA classified metals in PCs (Source: USGS, 2001)*

By contrast, electronic waste contains another valuable resource that is

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[10] Not to be confused with printed circuit boards, also PCBs

dangerously easy to extract: data. Many hard drives are not properly erased before disposal, and some recyclers who claim to provide this service in fact do not. This leaves the previous owner vulnerable to data thieves who are skilled in retrieving sensitive, personal, and even classified data (Puckett et al, 2005). The costs incurred by companies, governments and consumers due to data theft from e-waste are difficult to estimate and constitute another externalized cost.

The gap between the value of substances embodied in electronics and the difficulty of extracting them is a direct result of design and life cycle decisions. Electronics are built with consumer use in mind, not disposal, disassembly, or re-use and recycling. If easy recycling were a prominent design parameter, features might include modularization, standardized fasteners and attachment hardware, and consistent labeling to indicate how to take the device apart most safely and efficiently. Broadly, the concept of planning products to maximize the ability to repair, reuse and recycle while minimizing toxic substances and processes is referred to as design for the environment, which will be discussed in more depth in the section entitled “Rethinking the E-Waste Life Cycle”.

## 1.6 Environmental And Economic Justice Impacts

At the start of this paper, we considered a hypothetical but typical e-waste pipeline. In our example, disassembly was performed by freelance workers in the developing world who used techniques that put their safety, health, and local environment at risk. In the previous section we saw that the low cost of recycling in China relative to the US drives the exportation of e-waste. Similar price differences exist between the US and other developing nations. There is value in the waste but not enough to make its extraction worthwhile in richer nations, and trans-boundary movement of e-waste is variably restricted and enforced. Thus, e-waste tends to flow to places where labor is cheap, income is scarce, and environmental regulations and enforcement are weak. It is routinely disassembled by untrained freelance workers under dangerous conditions, without proper disposal of unwanted parts and chemicals (Puckett et al, 2005). In other words, the regulatory environment and economic circumstances around electronic waste make it a prime candidate for environmental injustice.

In 2002, one industry estimate claimed that 10.2 million computers would be exported from the US to Asia just that year (Puckett et al, 2002). The same year, the Basel Action Network (BAN) released “Exporting Harm”, an exposé film about back yard e-waste processing in Guiyu, China, which is a major center for electronics dumping. It shows children playing near piles of old electronics, next to adults who use hammers to smash through the leaded glass and lead curtain of CRT monitors to get to the copper yoke. It shows workers desoldering circuit boards over makeshift coal stoves without masks, and dissolving gold from circuit boards using aqua regia (hydrochloric and nitric acids) with no gloves.

There is footage of a researcher dipping a pH test strip into a river and watching it read near zero, a result of dumping used aqua regia. Residents say that only about a year after e-waste deliveries started arriving in Guiyu, the local water became undrinkable. Sediment samples from the local Lianjiang River revealed chromium levels at 1338 times the level considered safe by USEPA, and lead at 212 times the concentration considered hazardous waste by the Dutch government. Two water samples taken in 2000 and 2001 were found to have lead levels at 2400 and 190 times the level declared safe by the World Health Organization (Puckett et al, 2002, p. 22).[11] Local residents do not eat food grown in the city, where there is soil so polluted that it is considered hazardous.

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[11] While the *Exporting Harm* report presents a good summary of toxicity concerns in Guiyu, there are numerous peer-reviewed articles that provide greater detail. For example, see “Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China ” (Wong et al, 2007, Environmental Pollution 148 (2007) 62e72); “Export of toxic chemicals: A review of the case of uncontrolled electronic-waste recycling” (Wong et al, 2007, Environmental Pollution 149 (2007) 131e140); and “High levels of heavy metals in rice (Oryza sativa L.) from a typical E-waste recycling area in southeast China and its potential risk to human health ” (Fu et al, 2008 Chemosphere 71 (2008) 1269–1275).

Figure 1.7: E-waste by a river in Guiyu, China. Courtesy of BAN

These dangers to human health and the environment are only part of the story. A second BAN film, “Digital Dump”, explored the second hand electronics market in Lagos, Nigeria. Along with similarly dangerous disassembly, the film looked at the effect of electronics imports on local markets. The situation they described was similar to the depressive effect of used clothing imports on textile markets, which has lead to restriction or bans in many countries (US Dept. of Commerce, accessed 4/24/2011). Similarly, the flood of old electronics slated for resale in West Africa has crippled local technology entrepreneurs. There is tremendous technical expertise in Lagos, but technicians have little opportunity to develop local products because of fierce price competition from imports. Many of the imports are sourced through donation and recycling drives in the global north, meaning that the previous owners may have no concept of how their old electronics might impact a foreign market.

These two films made the unjust impacts of e-waste highly visible around the world and paved the way for many more exposés by reporters for *Frontline*, *60 Minutes*, and *National Geographic*. Because of decades of legacy electronics that already exist, the devastating effects of electronic waste on people, environments, and markets are likely to persist for a long time even if immediate changes are made to design, manufacturing, and disposal practices.

In the discussion about the e-waste cycle, conflict surrounding coltan mining was introduced as a negative externality and environmental injustice. Violent conflicts between mining companies and residents opposed to gold mining are well-documented (Martinez-Alier, 2001). However, another mineral conflict has come to light in recent months. In southern China, farmers who live near rare earth deposits suffer the threat of violence as gangs vie for control over illegal mining. The ore in this area is non-radioactive, easy to process, and very lucrative. This makes the area a target for black market “miners” who fetch prices that “can rival drug money” for nothing more than a bag of earth dug up from the lanthanide-rich farmland (Bradsher, Dec. 29, 2010).

A comprehensive discussion of the environmental justice implications of mining is beyond the scope of this paper, but should be included in any mineral extraction cost-benefit analysis. The cost of litigation alone demands it, and the human impact of displacement and contamination are important externalized costs.

## 1.7 Rethinking The E-Waste Life Cycle

Throughout this discussion, the idea of shifting product design to facilitate recycling has come up more than once. There are several concepts and methodologies that can empower product designers to make electronics with a lower environmental impact, by helping them identify low-toxicity raw materials and design products with a longer lifespan and lower recycling cost. They include ideas like pollution prevention, design for the environment, life cycle assessment, and material input calculations.

First, we will return to the concept of planned obsolescence and investigate two examples of how it works in the electronics industry. Typical support contracts for certain electronics indicate that they are designed with a particular life span in mind. In the author's experience as an IT professional, desktop and server equipment often remains viable for five to seven years or even longer, depending on the availability of replacement parts and the capacity of older machines to keep step with new software demands. However, server support contracts tend to span three to five years, meaning that when the vendor declares that the equipment has reached “end of life”, the cost of maintaining a repair contract goes up. Support schedules for vendors like Dell, HP and Oracle (which purchased Sun Microsystems in 2009) bear this out, as do many reports on server useful life and total cost of ownership (TCO). For example, a Gartner report on the useful life of network equipment found that end-of-life support offerings are one of two "primary inhibitors extending the useful life of older network equipment" from the average seven year useful life that is seen in the field, to a three or four year support cycle (Fabbi, 2010).

Another familiar example of vendor-driven life cycle expectations is the pricing structure of subsidized cellular phones. Commonly, cell phone customers who maintain a contract with a provider are offered a hardware upgrade, or new subsidized phone, every two years. However Wilson (2006) found that the average life span of a cellular phone dropped from 4.5 years in 1992 to 2 years in 2005. This finding is not consistent with the expectation that technology should improve as it matures. It is reasonable to suggest that this decrease in expected life span arose from a combination of pressure from manufacturers to sell new products, and pressure from consumers who desire new features.

However, is it necessary to replace an entire phone, computer, or even television in order to implement an upgrade? Can a healthy business model be based on longer lasting products with modular upgrades? Can devices be built that are both durable and easy to recycle? What sorts of design innovations can bring about the biggest environmental benefit at the lowest cost?

Methodologies that help designers look at a product's entire life cycle from raw materials to disposal, or better, to recycling or reuse, can begin to address these questions.

Pollution prevention refers to the idea that rather than managing environmental damage after it happens, pollution can be avoided through thoughtful product design and industrial processes. For electronics, pollution prevention might include practices like standardization and modular design that enables easy snap-in upgrades.

Pollution prevention might incorporate the principle of design for the environment (DfE). DfE suggests criteria like low toxicity, more efficient use of energy, water, and materials, and consistency in assembly so that any manufacturer can recycle any other manufacturer's old goods. In their research to define a comprehensive set of DfE principles, Telenko, Seepersad and Webber identified the following key guidelines: sustainability of resources; healthy inputs and outputs; minimal use of resources in production and transportation phases; efficiency of resources during use; appropriate durability of the product and components; facilitation of disassembly, separation, and purification (2008). US EPA manages several Design for the Environment initiatives for a broad range of products including electronics. One program analyzes chemical products for safety and allows those that meet its criteria to display a US EPA logo, similar to its Energy Star program.[12]

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[12] See US EPA's Design for the Environment program for household and commercial products: http://www.epa.gov/dfe/

Life cycle assessment (LCA) is an idea that goes back at least to the 1960s (Curran, 1996). It takes pollution prevention a step further by examining the inputs and outputs of a product throughout its lifetime. Gutierrez, et al define LCA as “an iterative process for assessing the consumption of resources, the creation of waste, and the occurrence of environmental impacts throughout the life cycle of a product, process, or activity.” (2010) LCA might consider factors like how much water, energy, or materials are required to make a product (US EPA 2006)[13]. Many LCA methodologies exist, but one particularly notable innovation is the move from “cradle to grave” LCA (which itself was a significant improvement over traditional design guidelines) to “cradle to cradle” LCA. Both methods start by looking at raw materials and resource inputs, and follow a product through end-of-life and disposal. The key distinction is that the latter also considers recycling, and finally re-use in a new product.

This kind of comprehensive analysis is ideal for curtailing the flow of e-waste at the source. Taking into consideration the potential end-of-life costs and hazards helps designers make products that fuel a virtuous cycle of pollution prevention by both reducing demand for new raw materials and reducing waste. Life cycle analyses require a significant investment of time and expertise but they can bring to light opportunities to cut costs, especially if manufacturers have an incentive or a requirement to internalize the cost of the end-of-life processing of their products.

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[13] See also ISO 14040 and ISO 14044.

Thus far, we have mostly discussed might happen under required take-back schemes. However, companies might prefer a take-back scheme for business reasons. In her book *High Tech Trash*, Elizabeth Grossman quotes HP environmental strategies executive Kevin Farnam's view of manufacturer take-back. “Ideally, from the manufacturer’s point of view, they’d like to get their own stuff back. ... If we get everyone’s stuff back there’s no incentive to design more easily recyclable stuff. ... But it’s not unachievable. The payoff would be in manufacturers designing more recyclable products with more recyclable content.” If a company could count on reclaiming most of the products it sells, Grossman argues, it would have a predictable source of materials and it would know exactly what it contained (p. 227).

## 1.8 The Role Of Regulation

By now, we have seen that electronic waste proliferates and causes unnecessary harm in the absence of incentives to recycle and design for the environment. It is clear that the US market as it currently exists is not equipped to support recycling. This amounts to a missed opportunity for waste management companies in the US that would welcome the business if it were economically viable. According to the Electronics TakeBack Coalition, electronics recyclers in the US are operating under capacity, unable to compete with export prices. They report that some US facilities can do circuit board pre-processing, but none is equipped for final smelting. The one lead smelter that exists in the US lacks the machinery to process the leaded glass found in CRT monitors (2010).

Regulations could change the e-waste landscape in the US. Grossman quotes industry officials who cite the influence of EU regulations on their own operations, as well as the need for a “level playing field” to ensure fair competition. In 2004, the director of environmental affairs for the Electronic Industries Alliance (EIA) told Grossman, “U.S. manufacturers are involved in pilot projects and voluntary programs to increase the use of recycled materials and for shared responsibility at end of product life. Today we want to take care of the entire program at a national level and we need legislation to make a level playing field.” In a talk at the 2004 E-Scrap conference, the president of EIA said “A while ago industry was taking an NRA-like approach—an over my dead body approach—but that’s changed enormously with the EU directives.” (p. 155)

The regulatory and enforcement environment that surrounds e-waste is highly variable. From international treaties to voluntary programs, a number of approaches address different aspects of the issue with varying success and consistency. The precedent set by EU e-waste legislation is particularly informative for the US.

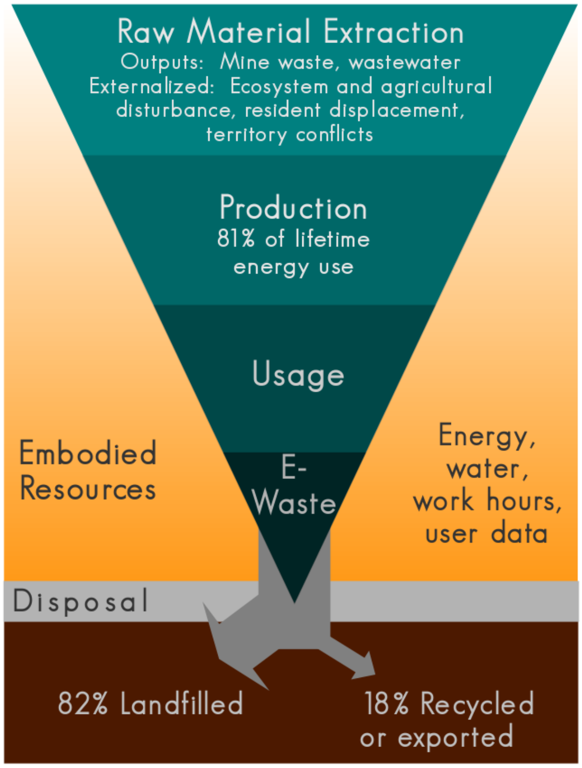

Figure 1.8: One way flow from raw materials to waste with limited recycling

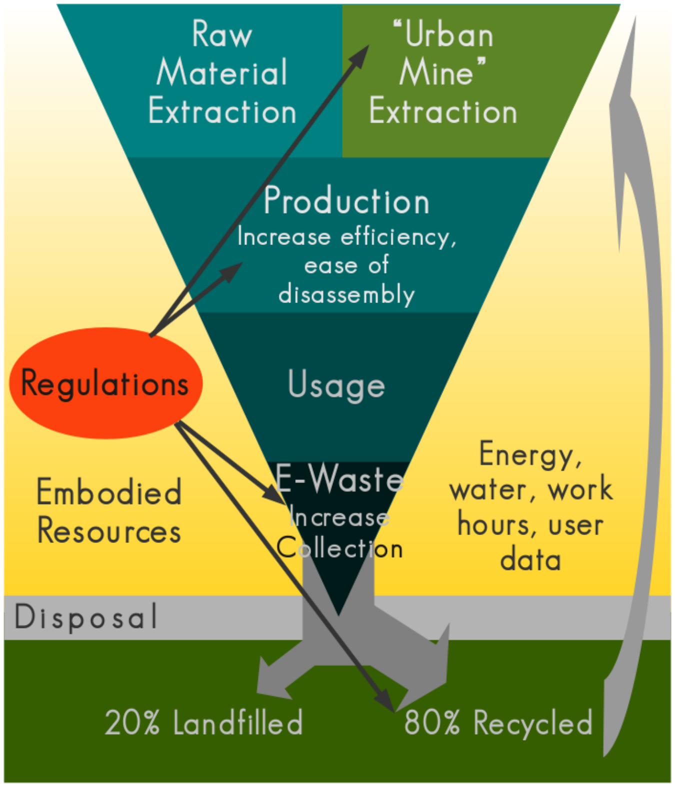

Figure 1.9: Regulatory inputs can induce a virtuous cycle

At the international level, the strongest policy instrument is the Basel Convention. It covers generation, management, and transboundary movement of hazardous materials. In particular, it requires any nation that exports toxic substances to have prior written permission from the importing nation. The 1992 treaty has been ratified by 172 countries; the US is a signatory but has not ratified the treaty.[14]

In 2003, the EU implemented two strong directives that have had a palpable impact on design, manufacturing, and collection of e-waste. The WEEE

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[14] See parties to the Basel Convention at http://www.basel.int/ratif/convention.htm

(Waste Electrical and Electronic Equipment) directive[15] ensures that manufacturers are responsible for disposal, while the RoHS (Restriction of Hazardous Substances) directive[16] bans the use of some toxic substances, and mandates a continuous review process to retire dangerous substances and implement less-toxic or non-toxic alternatives as they become available. The directives are regularly reviewed and updated to keep them current and effective.[17] The WEEE directive set the stage for changes in the way EEE producers design their products, by forcing them to consider the disposal and re-use portions of the product life cycle. One far-reaching impact of RoHS has been the reduction of toxic substances in electrical and electronic devices worldwide. Many manufacturers who operate globally have found that is it more cost effective to update all their production lines than to have separate lines for the European market versus the rest of the world (Grossman, 2006, p. 243). According to a 2008 review of the WEEE directive, compliance is not yet complete but collection rates for different types of WEEE range from 16% to 65%, compared to an 18% collection rate in the US (Huisman, Magalini, Kuehr & Maurer, 2007). There are many variables that make it inappropriate to compare these rates at face value, but the difference is great enough to warrant further analysis. A different WEEE review found that the cost of compliance, including training, data collection and obsolete components, was about twice as high as

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[15] http://ec.europa.eu/environment/waste/weee/index_en.htm

[16] http://ec.europa.eu/environment//waste/rohs_eee/index_en.htm

[17] See 2008 Review of Directive 2002/96 on Waste Electrical and Electronic Equipment Study No. 07010401/2006/442493/ETU/G4

technical costs like capital expenditure, research and development, and operations (Bogaert et al, 2008). One interpretation of this finding is that there is great opportunity to lower the financial burden of regulations by finding ways to lower the cost of compliance.

In the US, the only federal restriction on e-waste exportation is the CRT Rule proposed by US EPA in 2002, meaning that CRT monitors are the only type of e-waste that the US restricts. The rule requires any party that wishes to export waste CRTs to alert US EPA, which then obtains consent from the importing nation and forwards it to the exporter. Without this consent, it is illegal to export CRTs for recycling.

However, it is possible to gain permission to export CRTs as long as they are intended for reuse. This provision is often exploited as a loophole, and the law is commonly ignored altogether. Several reporting teams, including a team featured on *Frontline*, have produced investigative journalism pieces that follow illegal e-waste shipments around the world, demonstrating the weakness of the rule. Enforcement resources are limited and many shipments enter foreign ports illegally with no tracking, notification or consent.

CRTs, with their high lead content, constitute a large and problematic portion of e-waste worldwide, but many parties, including the US Government Accountability Office (GAO) have criticized the limited scope and efficacy of the CRT Rule. In 2008, GAO delivered a report to Congress whose title aptly summarized its message: “Electronic Waste: Harmful U.S. Exports Flow Virtually Unrestricted Because of Minimal EPA Enforcement and Narrow Regulation”. In it, GAO found that the rule had limited scope and weak enforcement, and that companies regularly sidestepped it. They recommended ratifying the Basel Convention, working with Customs and Border Protection for better control over illicit exports, and covering more electronics under hazardous waste regulations.

GAO's hazardous waste recommendation refers to an interesting aspect of US environmental law. Electronics contain several substances that are listed as hazardous under RCRA, yet electronics are only considered hazardous waste under certain conditions. If a company wants to dispose of electronics, they are considered hazardous waste and thus are prevented from being incinerated or disposed of in municipal landfills. However, if an individual wants to discard the same electronics, they are not considered hazardous (USGS, 2001). This system attempts to regulate the largest and most dangerous sources of hazardous waste while reducing the regulatory burden on individuals. However, it undercuts the importance of preventing hazardous materials from entering the municipal waste stream.

In response to increasing pressure on municipal landfills--and in the absence of an overarching federal law--25 US states have passed producer responsibility laws[18]. However, state laws do not all have the same

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[18] Source: Electronics TakeBack Coalition. See Appendix B for state-by-state comparison.

requirements. A 2011 report on Texas' Computer TakeBack law showed that although manufacturers are required to make recycling free, convenient, and appropriate for the state's collection needs, their collection rates were much lower than in some other states. Recycling rates went up 60% from 2009 to 2010, but overall rates remained relatively low. Additionally, only four manufacturers picked up 92% of the recycling burden, signaling an uneven playing field for industry. The report found that three key omissions in the law held back recycling rates: "1) collection goals and recycling targets, 2) convenience and access standards, and 3) a disposal prohibition (Texas Campaign for the Environment, 2011)." The Electronics TakeBack Coalition maintains a table comparing features of state EPR laws, included as Appendix B. The chart below shows state-by-state per capita e-waste collection in some states that have EPR laws.

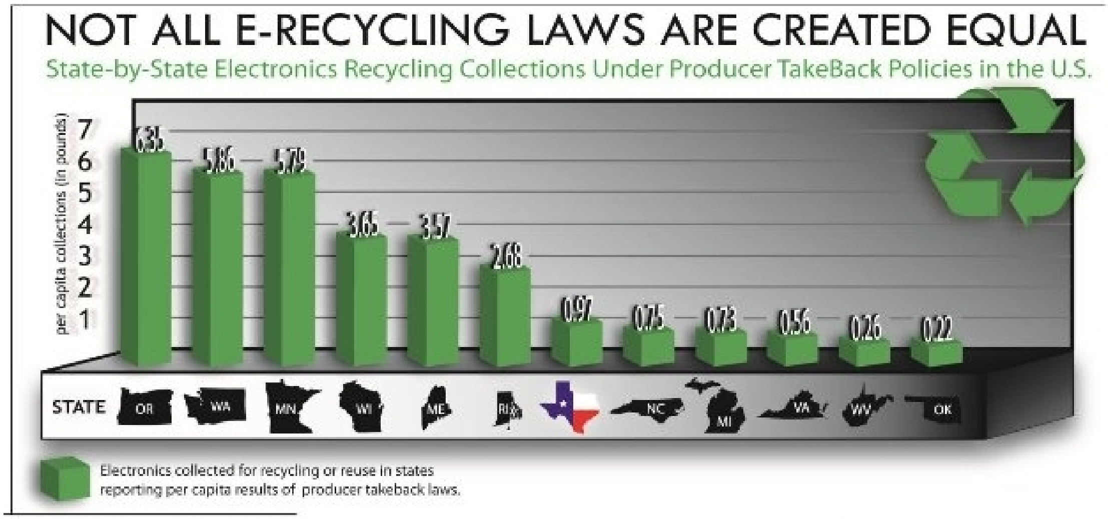

Figure 1.10: E-waste collection per capita in some states with EPR laws. Courtesy of Texas Campaign for the Environment

State laws do seem to be setting in motion some important changes, but having 25 sets of rules creates a confusing and inefficient EPR landscape. Grossman (2006) warned that “without action at the federal level, manufacturers are looking at the potential of fifty different sets of regulations within the United States, plus those coming from Europe and elsewhere” (p. 155), and her prediction seems to be coming true. A 2006 study by the National Center for Electronics Recycling looked at requirements in just four states and found that the overhead required to administer four separate programs instead of one amounted to $25 million of “dead weight”.

Some retailers accept e-waste for recycling, allowing customers to bring old electronics to stores for disposal. The electronics chain Best Buy offers this service regardless of where the product was purchased. This provides a convenient collection point for customers who are motivated to dispose of electronics properly. Effective collection is a key feature of successful e-waste programs, but it alone does not trigger the kind of systemic change that is necessary.

Finally, voluntary programs have been developed to provide guidance on a number of issues, and are of use to companies that wish to promote themselves as players in the “green” marketplace. For example, US EPA's Design for the Environment program is geared toward producers who seek to implement environmentally sensitive product development. E-Stewards.org provides strict auditing measures for facilities voluntarily seeking certification as responsible recyclers. Developed under an EPA grant and managed by the Green Electronic Council, EPEAT (Electronic Product Environmental Assessment Tool) is similar to the EPA Energy Star program. It aims to provide a consumer guide to electronics, using an IEEE public standard to rate products based on their environmental impact. Voluntary efforts can be a useful tool when the incentives to participate exist, but they weaken under financial strain. Their effect is generally not consistent enough to produce market-wide change.

Many groups have called for meaningful regulation and enforcement. Naturally, activist groups such as the Electronics TakeBack Coalition, Silicon Valley Toxics Coalition, and the Basel Action Network are vocal in their demands for strong legislation and enforcement. Some US state governments have called for federal measures to eliminate the overhead required to manage individual programs. This would create an even playing field to combat pressure from manufacturers who threaten to do business in a neighboring state with more lenient laws.

However, even manufacturers have joined in the call for regulation. Without a consistent regulatory environment, companies that try to act in good faith may find it difficult to compete with companies that make no effort to reduce toxic load or take responsibility for disposal. Furthermore, regulations can open up new business opportunities. If electronics recycling were mandated in the US, it would create a market for advanced and innovative recycling machinery.

As the market stands now, there are very few facilities to recycle electronics in the US, and this creates a resource void for domestic electronics manufacturers who want to build their products with recycled materials. This puts domestic manufacturing at a disadvantage in the growing "green" marketplace.

## 1.9 Research Needs And Recommendations

Further research is needed for the following topics:

- Development of safe and cost effective in-field e-waste processing

  Informal recycling of legacy electronics will continue to harm human health and the environment for many years to come. Field deployable methods of e-waste separation are needed as part of a harm reduction strategy. These methods must be low cost, easy to implement, and result in financial benefit to the user that is comparable to traditional methods. This work should be done in accordance with appropriate technology best practices, i.e., in consultation with practitioners and with cognizance of local needs, norms, expertise and materials.

- Better and more open ways of measuring waste

  Waste quantification is complicated and error prone. Seek ways to measure and track waste more accurately and openly.

- Comparison of state e-waste legislation

Perform a comprehensive state-to-state comparison of existing e-waste laws. Discover which measures are most effective and how to modify them to apply to all states effectively. Report on least effective measures as lessons learned. Use the results to inform possible federal legislation.

- Discover how WEEE and RoHS translate to the US context

Compare waste production and management in the US and EU. Identify portions of WEEE and RoHS directives that would work in the US, as well as barriers to implementation and any incompatible methodologies that could complicate management and measurement.

- Compare cost and environmental impact of mining and recycling

Perform a comprehensive cost-benefit analysis that compares the up-front and operational costs and productivity of permitting and building new mines for various materials required by the electronics industry, to the same costs and productivity for recycling facilities intended to extract the same materials from anthropogenic stocks. Compare environmental impacts and attempt to quantify the dollar value.

- Identify market inefficiencies in negative externalities

Study key externalized costs associated with electronic waste and analyze how they do or do not indicate economic inefficiencies. Compare externalities in different geographic locations to identify inconsistent economic and regulatory environments and whether they lead to unfair advantages or burdens, either economic or environmental.

Main recommendations:

- US Congress and EPA should implement GAO recommendations

  Extend the CRT rule and the definition of hazardous waste to cover potentially hazardous products; ratify the Basel Convention so the US can operate under a larger regulatory umbrella appropriate for the international nature of the issue; collaborate with US Customs to label and track exported electronics.

- US should review existing state laws and implement the most effective measures at the federal level

  Implement the most effective regulatory instruments among the existing 25 state e-waste laws at the federal level to increase compliance and decrease confusion and inefficiency for manufacturers, governments and consumers.

- US should adopt key provisions from the WEEE and RoHS directives

Pass legislation that requires extended producer responsibility, design for the environment, and the phase-out of toxic substances. Where incompatibilities are found, legislation should emphasize making fewer provisions that are similar to EU directives rather than more requirements that differ significantly. An emphasis on consistency with EU rules where possible will boost efficiency and lower cost of implementation by providing manufacturers with a set of rules with which they already comply if they do business in the EU.

# 2 CASE STUDY: RARE EARTH ELEMENTS IN 2010

The previous portion of this paper established a baseline understanding of the key issues around electronic waste. This section will turn its attention to a moment in time that illustrates many of the interconnected issues. A brief embargo of Chinese rare earth minerals in 2010 provides an opportunity to study the complexities of the e-waste cycle in the context of this one unusual--but not unforeseeable—incident. The highly publicized interruption to the flow of rare earth elements (REEs) necessary for electronics manufacturing brought to light a suite of issues including the geopolitics of commodities, the challenges in sourcing materials for electronics, and the important role that recycling regimens could play in provisioning those materials.

In September and October, 2010, shipments of rare earth minerals from China to Japan ceased for several weeks following a diplomatic dispute between the two nations. Toward the end of the unofficial embargo, shipments to the US and Europe were also halted. This sudden choke point in the flow of rare earths caused price spikes and a flurry of media coverage about China's dominance of the rare earth market.

The incident was a highly visible example of monopoly and the volatile market forces that underpin high-tech manufacturing from cell phones to wind turbines. However, the situation that lead to the worldwide shock had been building for over two decades. The embargo provides a snapshot of the connected issues discussed in part one of this paper. It is informative about the importance of diversified sources for material and intellectual resources, the failure of the global market to provide diversification in this case, the role of recycling in planning for the future of electronics manufacturing, and the role of regulations and policies in encouraging recycling and reliable sources of raw materials.

## 2.1 Rare Earths In Industry

Rare earth elements include the fifteen elements in the lanthanide group plus yttrium and scandium (U.S. Geological Survey Minerals Yearbook, 2000). They have a broad range of properties from permanent magnetism to luminescence to high electrical conductivity (Eckert, 2010). One of the most well-known industrial applications is neodymium magnets. Made from an alloy of neodymium, iron, and boron, “rare earth magnets” as they are known, are used in computer hard drives, generators and motors, wind turbines, audio speakers, and even jewelry and children's toys.

Currently, many REEs have no substitutes. For example, according to a study by the National Research Council, erbium (Er) is the only substance suitable for enriching or “doping” the glass in fiber optic cables. Erbium's unique optical properties amplify the light transmitted through cables to increase signal strength and clarity over long distances (National Research Council, 2008, p. 131). Other rare earths are used in lighting products, catalytic converters, and batteries (US DOE, 2010, p. 25). Industries that depend on REEs include electronics, renewable energy, automotive parts, telecommunications, and medical equipment manufacturing.

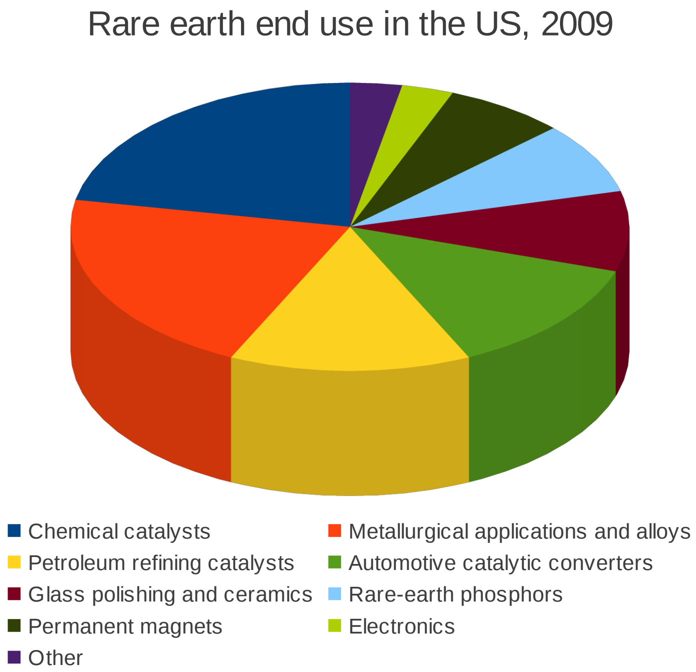

Figure 2.1: Rare earth end uses in the US, 2009. Source: USGS Mineral Commodity Summaries, 2011

Rare earth prices have risen dramatically in recent years, up twelvefold in two years according to The Sydney Morning Herald (FitzGerald, 2011). A *Technology Review* report from October, 2010 stated that worldwide REE demand was also on the rise, expected to jump from 125,000 tons in 2010 to 225,000 tons or more by 2015 (Bourzac, 2010). However, prices have been trending upward for decades. The chart below shows historical prices per metric ton for rare earth oxides in unadjusted and 1998 adjusted dollars[19]. Between 1979 and 2009, unadjusted prices jumped over 700%, from a low of $1,870 per ton in 1981 to $13,600 per ton in 2008. USGS price data from 1900-2009 are included as Appendix C.

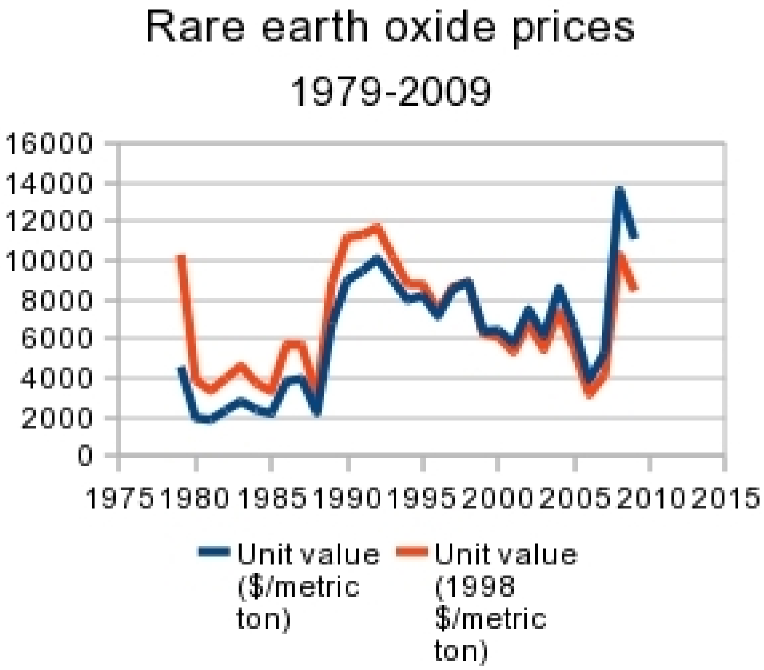

Figure 2.2: REO Prices 1979-2009. Data source: USGS, 2010

Several recent studies have attempted to enumerate the importance of rare earths to industry and national defense. In the 2008 report *Minerals, Critical*

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[19] "Unit Value ($/t) : Unit value is the value in dollars of 1 metric ton (t) of REO apparent consumption. Unit value was estimated for the United States in actual dollars by a weighted average of imports and exports. Data were not available for 1900–21.
Unit Value (98$/t) : The Consumer Price Index conversion factor, with 1998 as the base year, is used to adjust unit value in current U.S. dollars to the unit value in constant 1998 U.S. dollars. Data were not available for 1900–21. " Source: USGS Rare Earth Statistics. Last modified Nov. 16, 2010. See Appendix C.

*Minerals and the US Economy*, the National Research Council compiled a "criticality matrix" which classified non-fuel minerals according to the likelihood of a disruption in the supply chain and the impact it would have in the US. It found rare earths to be critical, as well as platinum group metals, indium, manganese, and niobium (p. 15). The US Department of Energy (DOE) used a similar methodology and found five rare earths and indium to be critical for renewable energy (DOE p. 6). The National Defense Authorization Act for Fiscal Year 2010 required a report on REEs in the defense supply chain. To assist the Department of Defense (DOD) in its evaluation, USGS published a summary of rare earth deposits in the US in which it asserted that domestic REE resources are "modest and of uncertain value " (p. 1). That report showed that other materials with a high risk index for the US (high probability of threat and high impact of supply disruption) include bauxite and alumina, tin, titanium, and tungsten (p. 16). As of April, 2011, the full DOD report, originally due in September, 2010, had not been published.

## 2.2 Geologic Occurrence And Global Production

While once thought to be rare, REEs are actually rather abundant. According to USGS data, the most abundant REE, cerium (Ce), occurs in the Earth's crust at a concentration of about 60 parts per million, similar to copper. The two most rare REEs, thulium (Tm) and lutetium (Lu) are 200 times more abundant than gold (USGS Fact Sheet, 2002).

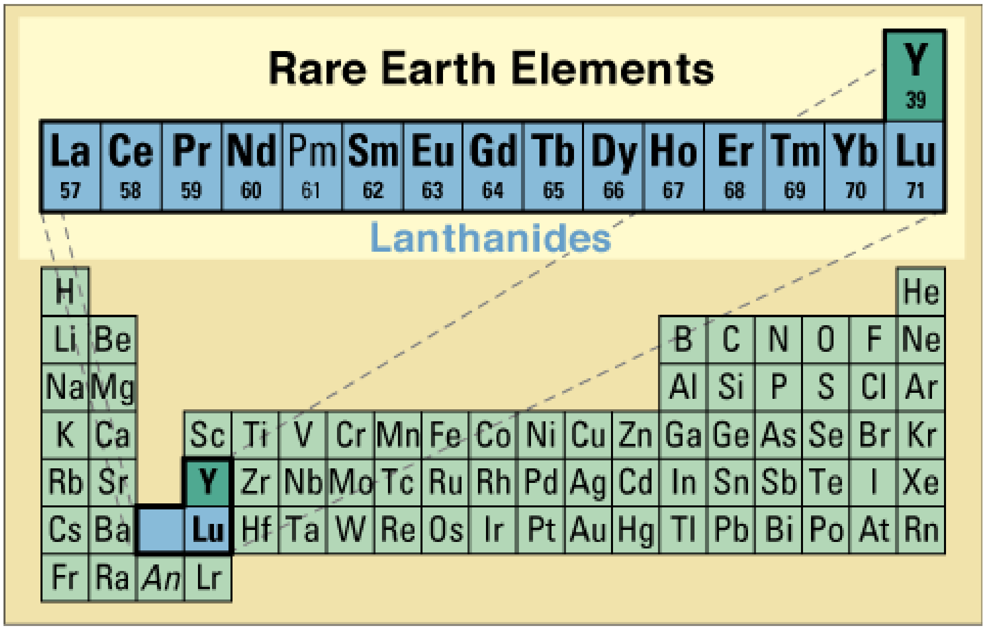

Figure 2.3: Periodic table with rare earths highlighted. Image courtesy of USGS

Despite their relative abundance, there are limited known reserves of REEs in extractable concentrations. The elements in this group occur as intermingled oxides in mineral deposits such as monazite and bastnäsite (USGS 2011, pp 128). According to a *New York Times* report from October, 2010, the global rare earths market was worth about $1.5 billion in 2009, which is relatively small compared to other mining enterprises (Tabuchi, Oct. 4, 2010). Rare earth oxides (REOs) seldom occur in high enough concentrations to make them economically viable as a primary mining product. Instead, generally they are extracted as byproducts or co-products of other elements like titanium and iron. Currently, about 44% of global REO production is a byproduct of iron mining at the Bayan Obo mine in Inner Mongolia (USGS, 2010, p. 11).

Rare earth oxide deposits are known to exist in the United States, China, Argentina, Brazil, India, Russia and a few other countries. During the second half of the 20th century, the US was the leading producer of rare earth elements. However, starting the 1980s China became a major producer. By 2002 rare earth mining in the US had ceased following the termination of mining operations at the Unocal/Molycorp Minerals mine in Mountain Pass, CA, though the facility continued to refine oxides that had already been mined (USGS Fact Sheet, 2002). Today, China mines between 95-97% of the world's rare earth oxides (USGS, 2011).

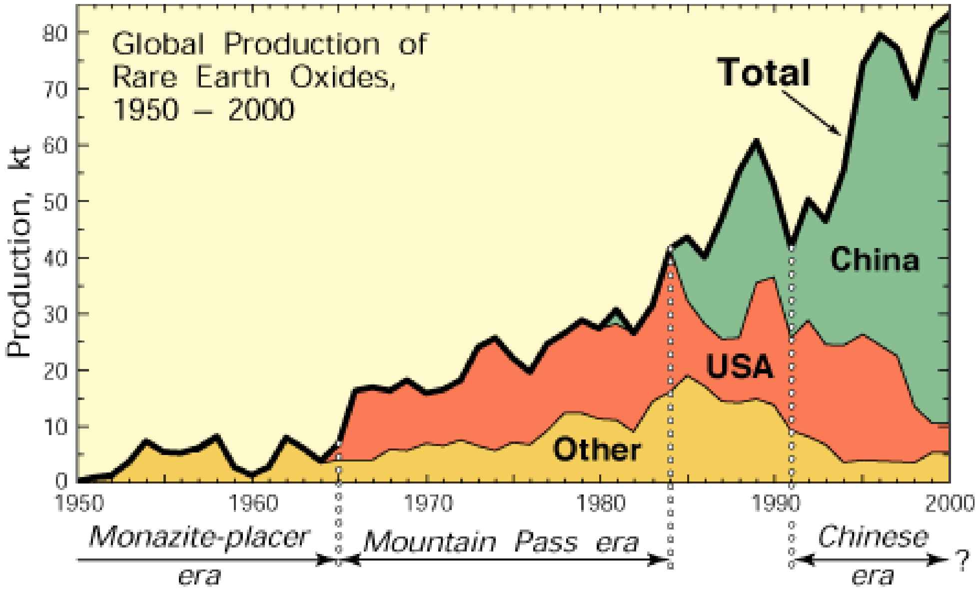

Figure 2.4: Global Production of Rare Earth Oxides, 1950-2000. Source: USGS, 2002

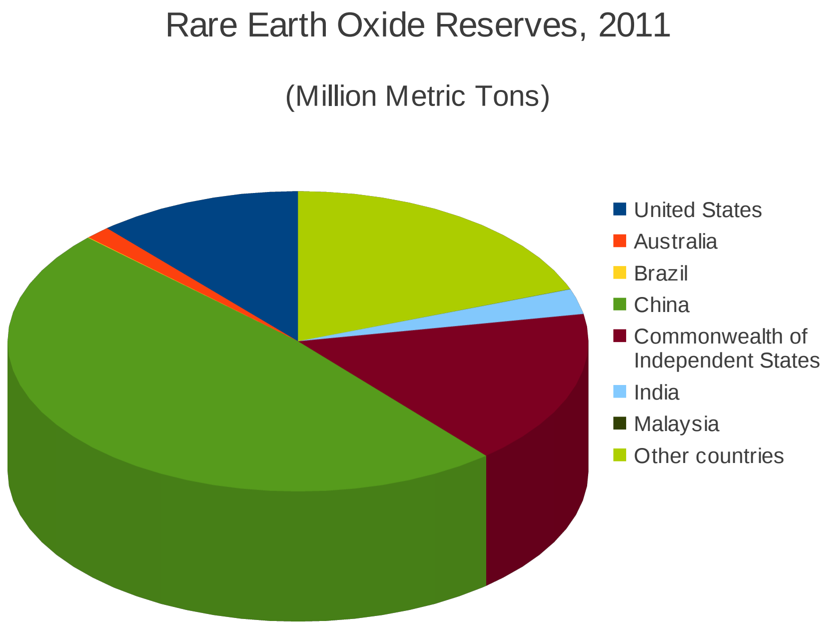

Figure 2.5: Rare earth oxide reserves by country. Data source: USGS Mineral Commodity Summaries, 2011

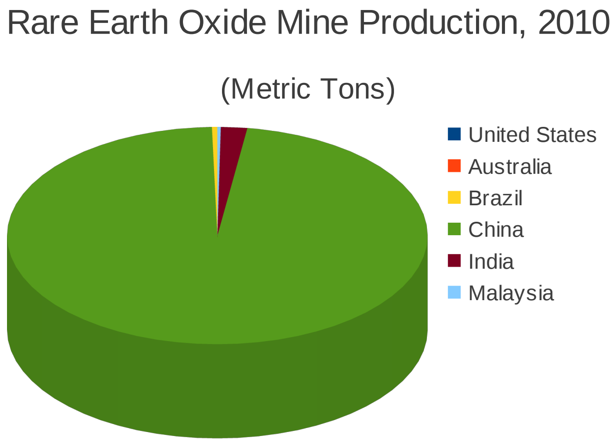

Figure 2.6: Rare earth oxide mine production, 2010. Data source: USGS Mineral Commodity Summaries, 2011

REEs are grouped into light and heavy types according to their atomic weight. Light rare earths are more abundant worldwide than heavy ones, but not necessarily more in demand. Consequently, mines with extractable concentrations of heavy REEs are at an economic advantage. Proposed REE production in the US includes sites with only trace amounts of heavy rare earths. However, demand may change over time and could be satisfied by “reliable trading partners” like Australia and Canada (USGS 2010, p. 23).

## 2.3 Challenges In Rare Earth Production

Rare earth extraction and refinement are environmentally intense processes. Because the elements are chemically similar, separating them can require processing them in solvents and boiling acid repeatedly (E. Schelter, personal communication, April 18, 2011). At the Bayan-Obo mine in Inner Mongolia near Batou, China, rare earths undergo acid digestion thousands of times, according to *Scientific American* (2010). Specifically, a US EPA mineral processing document on rare earths indicates that preparation of monazite and bastnäsite ores requires digestion in sulfuric and hydrochloric acids heated to 140-220°C, followed by “fractional crystallization and precipitation, solvent extraction, ion exchange, and reduction (US EPA, updated 2008).”

In practical terms, a rare earth processing plant generates several high impact environmental outputs such as enormous amounts of wastewater which might be highly acidic, laced with toxic metals, and if the ore contains thorium, radioactive. Molycorp Chief Technology Officer and chemist John Burba told *Scientific American* that in its final days, the Unocal/Molycorp mine at Mountain Pass produced 850 gallons of wastewater per minute (2010). Extraction at Mountain Pass officially ceased in 2002 under pressure from both low-priced Chinese competitors and permitting problems following a history of intense water usage and toxins in evaporation ponds. US EPA involvement at the site goes back to at least 1989.[20]

Bringing new sources of rare earths to production is a difficult, time-consuming process. In a report from April, 2010, the Government Accountability Office cited industry estimates that “rebuilding a U.S. rare earth supply chain may take up to 15 years and is dependent on several factors, including securing capital investments in processing infrastructure, developing new technologies, and acquiring patents, which are currently held by international companies.” USGS (2010) supported this view by reporting that a selection of mines around the world took between five and 50 years to develop, including two advanced REE projects in Australia. A comparison of metal mines in the US showed lag times of up to 20 years from the start of permitting to production. Eight out of the seventeen experienced long delays because of litigation (USGS 2010, pp 22-23).

Infrastructure is not the only long-term investment required to bring new

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[20] See letter from US EPA Office of Solid Waste and Emergency Response to Charles J. Umeda (San Bernardino Deputy District Attorney), 1998, RO 14205

rare earth sources online. They also require technical expertise in mining and separation technology, which has declined in the US since it stopped extracting rare earths according to experts from the National Mining Association and the Ames National Laboratory, quoted in *Technology Review* (Bourzac, 2010). In its report on US REE deposits, USGS complained that "the lack of mining industry exploration of REE deposits in the last few decades is paralleled by a low level of geological research," and asserts that national and global mineral resource assessments can lead to more discoveries (USGS 2010, p. 23). Finally, the National Research Council argues that resource availability depends on educated professionals, whose numbers have fallen in recent years. It recommends government intervention to help fill the gaps in expertise:

> "Finally, the committee found that well-educated resource professionals are essential for fostering the innovation that is necessary to ensure resource availability at acceptable costs with minimal environmental damage. The infrastructure for adequate training of professionals to service the mineral and materials sectors has declined substantially over the past few decades in almost all industrialized countries. The current pipeline of training in the United States does not have enough students to fill the present or anticipated future needs of the country in terms of mineral resource capabilities in the private sector, the federal government, [and] academic institutions, particularly if critical minerals are to be part of the government's mineral data collection, analysis, and dissemination program. While market responses may eventually cover some of the apparent gap between the short-term demand for workers and the supply of new hires, the time lag of market responses, the very large number of anticipated workforce openings, and the need for technology innovation entail larger commitments than the market alone is able to address and suggest the need for government engagement in the matter of professional training." (National Research Council, 2008, pp. 13-14)

Furthermore, intellectual property resources and patent rights are needed.

In its April, 2010 report to Congress, GAO found that as early as 2003, the Air Force’s Materials and Manufacturing Directorate had looked into the lack of intellectual property rights to produce rare earth magnets in the US (US GAO, 2010).

## 2.4 China's Market Dominance And 2010 Embargo

During the period when the US scaled back and eventually terminated rare earth mining, production in China was on the rise.  Currently, 95-97% of the world's supply of rare earth oxides comes from China, although it is home to only about 37% of the world's reserves (Bradsher, Oct. 29, 2010).  In the 1990s and 2000s, competitive pricing among Chinese suppliers created incentives for Western manufacturers to buy their rare earths from China, driving almost all other global sources out of business.

In the past year, there has been a flurry of media coverage of price spikes caused by restricted exports from China.  The publication of China's new export quotas every six months is consistently greeted with anticipation and followed by intense commentary in the financial and tech sectors.  However, China has been reducing its export quotas for rare earths since 2005.  Since the Chinese government distributes these quotas among a small number of official exporters, the recipients often sell their exportation rights, which adds overhead and drives up prices even more (Bradsher, Oct 28, 2010).  Over the years, this has encouraged manufacturers to relocate their operations to China since domestic sale is less restricted. Some believe that China's export quotas (which also apply to products like grains, fuel, and other metals, as reported in a semi-annual publication of restricted and prohibited goods) may be a violation of World Trade Organization rules which frown upon export quotas of any kind (Bradsher, Oct. 29, 2010).

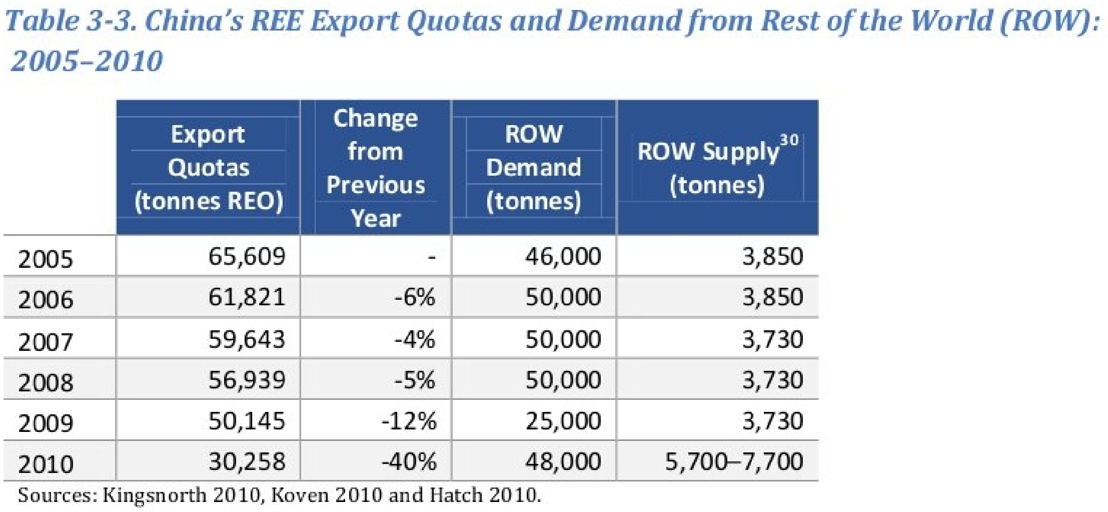

*Table 3-3. China's REE Export Quotas and Demand from Rest of the World (ROW): 2005–2010*

| | Export Quotas (tonnes REO) | Change from Previous Year | ROW Demand (tonnes) | ROW Supply[30] (tonnes) |
|---|---|---|---|---|
| 2005 | 65,609 | - | 46,000 | 3,850 |
| 2006 | 61,821 | -6% | 50,000 | 3,850 |
| 2007 | 59,643 | -4% | 50,000 | 3,730 |
| 2008 | 56,939 | -5% | 50,000 | 3,730 |
| 2009 | 50,145 | -12% | 25,000 | 3,730 |
| 2010 | 30,258 | -40% | 48,000 | 5,700–7,700 |

Sources: Kingsnorth 2010, Koven 2010 and Hatch 2010.

Figure 2.7: China's REE Export Quotas. Reproduced from DOE, 2010

Chinese law calls for free trade in general, but allows exceptions for exports that cause environmental damage or whose limited reserves call for conservation. These are the official reasons that China gives for limiting rare earth exports, and as such, they are reasonable. However, the economic benefits of restricting exports to a monopolized market are not to be ignored. The *New York Times* cites a Xinhua report in which the vice chairman of Inner Mongolia, Zhao Shuanglian, points out that moderating production and reducing exports attracts foreign investors (Bradsher, Oct. 28, 2010).

In the context of declining export quotas and rising demand, an economic anomaly shocked the already-stressed rare earth market in late 2010. On September 21, shortly after a dispute over the Japanese capture of the captain of a Chinese fishing boat in disputed waters, rare earth exports to Japan halted. They resumed on October 28 as reported in the *New York Times*, but remained subject to scrutiny and delays. Officially, China reported that there was no federally mandated embargo against Japan. Spokespeople offered the explanation that the 32 authorized rare earth exporters may have decided to cease shipments independently, but this explanation is generally not seen as credible (Bradsher, Oct 28, 2010). In an action that some think was intended to make the embargo appear less diplomatically targeted, rare earth shipments to the US and EU halted a few weeks later (Bradsher, Oct 28, 2010). Shipments had returned to normal by late October but the incident sent a ripple through markets and the media. The embargo affected Japan more than the US and EU because the embargo only applied to partly-processed raw materials which Japanese industry relies on, and not the refined materials and finished products popular among US and European manufacturers.

This brief but dramatic event focused attention on the importance of rare earths to many industries, the scarcity of viable sources worldwide, and the challenges in diversifying those sources. The REE market responded strongly, with price increases of 600-700% according to Molycorp Chief Executive Mark

Smith (Eckert, 2010). In recent years, Molycorp had secured financing and started planning to re-open the Mountain Pass mine, so when speculative buying soon followed the embargo, Molycorp's stock prices tripled (Malone, 2010). An analyst for Byron Capital Markets told *Rare Earth Investing News* that the enthusiasm over some rare earths qualified as a bubble (Montgomery, 2010).

While the embargo took many by surprise, there had been indications that such a bottleneck was possible for some time. In its 2010 report to Congress, US GAO states that military officials in the Air Force and Navy had taken steps to address US dependence on rare earths from The People's Republic of China in 2003 and 2006 respectively. At the time of that report, GAO indicated that there could be cause for concern over the impact of the consolidated rare earths market on the defense supply chain. It stopped short of making predictions, reiterating that more information about the use of REE in specific defense applications was forthcoming in a report from DOD. However, as mentioned earlier, that report has yet to be released. Furthermore, Grossman makes reference to similar spike in the price of tantalum during the dot-com boom in 2000-2001 (p. 46). Thus, the impact of mineral price volatility that the electronics industry experienced during the 2010 embargo was not unprecedented.

As of this writing, REE prices continue an upward trend. MetalPages.com, a London-based metals database often cited by the *New York Times,* provides historical pricing charts for individual metals. It shows rising prices from

November, 2010 to May, 2011 for all eleven REE that it lists.[21] Rare earth stocks and indices follow the same trend. Three large rare earth-producing companies have seen increases in their stock prices over the past year. Great Western Minerals Group (CVE:GWG) had a 52-week range of $0.15-1.23; Lynas Corporation Limited (ASX:LYC) spanned $0.38-2.70; and Molycorp, Inc. (NYSE:MCP) had the greatest upward movement from $12.10-79.16. Finally, the Rare Earth Strategic Metals ETF (REMX) which attempts to track the Market Vectors Rare Earth/Strategic Metals Index of smaller companies involved in mining and refining rare earths, had a range of $19.25 – 28.91. (Financial data retrieved from Google Finance, May 5, 2011.)

In the wake of the embargo, capital investment in rare earth mineral resources has also surged. Before the embargo, Molycorp had been looking to fund a $500 million expansion at its Mountain Pass, CA site. It is pursuing that plan aggressively, but has also bought and made offers for other mines and refining companies in order to boost overall capacity (Hoium, Apr. 19, 2011). Japan is working with Lynas Corporation to raise $325 million for an expansion of the Mount Weld mine near Laverton, Western Australia, and to finish building a refining plant in Malaysia. In return for $250 million of investment, the Japanese market would be promised 8500 tons of rare earths per year for ten years (FitzGerald, March 31, 2011). The *Sydney Morning Herald* reported on several other Australian REE mining firms which had experienced stock price increases

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[21] For example, neodymium: http://www.metal-pages.com/metals/neodymium/metal-prices-news-information/

after the last published export quota from China (Australian Associated Press, Dec. 29, 2010).

However, plans for expanded mining are not without obstacles. The *New York Times* recently reported that every week politicians and residents in Kuantan, Malaysia have protested the proposed permitting of the Lynas refinery. They are concerned about the “thousands of tons of radioactive waste” that the mine would produce, so they are demanding reviews of the disposal plan and resisting the construction of the refinery (Bradsher, May 2, 2011). As market pressure mounts to develop new REE resources, the Kuantan protests could be a preview of battles to come. Will the barriers to establishing new mining resources be high enough to make recycling a competitive choice?

## 2.5 The Role, And Limitations, Of Recycling

The monopolized rare earth market invites comparisons to other critical resources and the pressure to develop domestic sources. Oil and natural gas provide obvious parallels, but there is a key difference. While fossil fuels are strictly consumable, metals are highly recyclable. Thus, a question arises from the lessons of the 2010 embargo: What is the role of recycling in ameliorating the environmental and social impacts of rare earth mining and stabilizing the price and availability of these materials?

Most of the recent media coverage focuses on mining rather than recycling (and rare earth substitutes to a lesser extent, see Biello, Oct 13, 2010), for reasons that echo the barriers to recycling across all electronics. The data gaps, the mechanical and chemical difficulties of separation, the absence of managed recycling stockpiles, and the resulting economic barriers prevent recycling from being the first choice for corporations in the current financial structure.

However, subject matter experts like members of the United Nations Environment Programme's Panel for Sustainable Resource Management (The Resource Panel) stress that recycling in general “is expected to be an important source for metal supply in the future” (Graedel et al, 2010). The National Research Council's critical minerals report states that “minerals for which there is not significant recovery of material from old scrap may be more prone to supply risk than otherwise.” (p. 9) Lisa Margonelli, the director of the New America Foundation's Energy Policy Initiative, sees recycling as a critical part of a rare earths strategy. Specifically, she advocates for a system in which the manufacturer “owns the minerals forever” as a way to conserve REEs, implement a type of manufacturer take-back, and create jobs that are difficult to outsource (Margonelli, Mar. 8, 2010).

Japanese recycling efforts, especially since the embargo, are particularly informative because in that economy, externalizing the costs of mining temporarily ceased to be an option at any price. Even if imports had not been interrupted, it would still be in Japan's best interest to seek diverse sources, since the small nation has few mineral resources of its own.

Researchers estimate that there are about 300,000 tons of rare earths in Japanese “urban mines”, or stockpiles of used electronics. According to the *New York Times*, at the Kosaka Smelting and Refining facility located in the old mining town of Kosaka, Japan, workers had successfully extracted indium and antimony from waste electronics, and were working on reclaiming rare earths. Kohmei Harada, of the National Institute of Materials Science in Japan, claims that the equivalent of 16% of the world's gold reserves may be lying dormant in old electronics. He stressed the idea that collecting waste is a viable method of aggregating mineral resources: “Japan’s economy has grown by gathering resources from around the world, and those resources are still with us, in one form or another.” (Tabuchi, Oct. 4, 2010)

The *Times* also reported that Japan's New Energy and Industrial Technology Development Organization, or N.E.D.O. had developed a rare earth-free hybrid vehicle motor. Other researchers inside and outside of Japan are working to find substitutes for rare earths or find ways to get comparable performance out of less material. Recently the *Times* reported that the Japanese recycling firm Dowa was experiencing unanticipated difficulty in producing usable rare earths from electronic scrap (Bradsher, May 2, 2011). But considering all the barriers to mining, from mineral discovery to permitting to litigation to environmental protection, there may be a strong value proposition in recycling research. From a chemical standpoint, isolating rare earths from electronics versus ore should entail almost identical processing, meaning that the biggest research barrier could be mechanical pre-processing (Prof. Eric Schelter, Apr. 18, 2011, personal communication).

Other Japanese companies and institutes are also working on the problem. In late 2010, Hitachi announced that it was developing machinery to recycle rare earths from hard drives and air conditioner compressors (*Recycling Today*, 2010). By 2013 the company expects the system to be up and running, potentially providing ten percent of its rare earth demand (*Electronics Recycling Info*, Dec 7, 2010).

Japan is not alone in recognizing the potential mineral wealth in scrap. In November, 2010, Rhea wrote in the New America Foundation's Open Technology Initiative blog that China was considering legalizing more e-waste imports following tremendous success of a buy-back program that started in June, 2010. The subsidized program gives a voucher for 10% of the price of a new device for each old one turned in. Wang Gongmin, a recycling industry leader told a conference that e-waste contains “valuable renewable resources” and that recycling technology “has matured, and the processing shall not result in secondary pollution.” (Nov. 23, 2010) The fact that this program is running in a country rich in rare earth resources, which has tolerated environmentally harmful e-waste processing for a long time, sends a powerful message about the potential of recycling.

## 2.6 Research Needs And Recommendations

Further research is needed on the following topics:

- DOD: Complete the report on REEs in the defense supply chain

  Defense funding reauthorization required a study of the role of rare earths in products for defense. Other agencies have filed reports addressing criticality of REEs but DOD has failed to file this report.

- Perform waste assessments to determine what resources lie dormant in waste electronics and best measurement methodologies going forward

  Large data gaps exist for waste production and collection. Develop best practices for measuring electronic waste in the long term. Use best available information to estimate the quantity of mineral resources currently in US landfills, recycling facilities, and in storage.

- Assess new costs in building mines and recycling plants

  One recommendation from the first section of this paper was to perform a comprehensive cost-benefit analysis comparing new mines to new recycling facilities. This could be extended to estimate any new costs that should be addressed. Do local politics or geopolitics make it likely that permitting or litigation will become more expensive? Does the global business environment introduce new costs in terms of patents, labor, local expertise or compliance with local regulations?

- Follow progress in Japan and China

Both nations have made compelling advances in recycling policy, infrastructure, and research. Stay apprised of their successes and challenges, and apply lessons learned to the US context.

Main recommendations:

- Make electronics recycling a serious part of the US's critical mineral portfolio

The US should hedge against market volatility and plan for long term domestic supply of critical minerals by making recycling a serious part of its strategy.

- Develop plan for “mining” landfills

Disposal of electronics, appliances, construction waste and more in the US mean that landfills could be a source of “anthropogenic ore”. Assess the best opportunities for extracting critical minerals from landfills, and sites most likely to leach toxins. Large gaps in e-waste disposal data may necessitate heuristic or iterative methods such as analysis to identify municipalities most likely to have high rates of electronics disposal and easily accessible landfill contents. Target those sites for early adoption of “urban mining”.

- Fund recycling research

By failing to make recycling part of its critical mineral strategy, the US is already at a disadvantage in terms of market robustness and readiness for renewable energy, compared to Japan and the EU. Partner with nations that have invested in recycling research and infrastructure to share research findings.

- If federal funds go to exploration, commit the same amount to recycling

Molycorp requested government loan guarantees and research and development funding when it made an initial public offering (Kidela Capital Group, 2010). If the US government commits funds to geologic mineral exploration, it should commit at least the same level of funding to recycling research and infrastructure. Otherwise, federal funding will favor mining and further discourage the recycling market.

- Where possible, reduce mining footprint by reusing existing mines

Focus mining development on brownfields. Existing mines should be studied to find out if existing stocks or tailings can be refined. This avoids significant economic overhead, shortens the time to production, and reduces the environmental footprint.

- Invest in education

There is an increasing gap between the need for technical expertise in and the incoming students available to supply it. Provide support and incentives to encourage more people to study materials science, chemistry, mechanical engineering, industrial engineering, patent law, and geology. Fully support educational feeder systems at all levels.

# 3 CONCLUSIONS: RARE EARTHS AS A MICROCOSM OF THE E-WASTE CYCLE

In the first section of this paper, we explored the vicious cycle that brought the electronic waste problem into being, and discussed how to turn it into a virtuous cycle with recycling at the core. In the second section, we saw that a rare earth shortage triggered widespread concern about availability, and reminded market analysts, governments, and technology manufacturers of the dangers of a volatile, monopolized market.

Rare earth mining speculation continues, but as demand rises and exploitable ores are drawn down, recycling will become an economic necessity. One clear lesson from the Chinese rare earth embargo in late 2010 is that a lack of preparation for market swings can lead to raw material shortages, violent price spikes, speculative buying, and market bubbles, none of which are conducive to a healthy business environment. Recycling remains the better choice for the long-term good of people and the environment, but increasingly, it should also be viewed as important economic insurance.

In section one, we found that electronic waste is loosely regulated and weakly enforced in the US. We also saw that much of the 18% of electronics that are destined for recycling are actually exported to countries where disassembly is inexpensive but harmful. We looked at the best available data for understanding how much electronic equipment falls out of use in different parts of the world, and where it ends up.

In section two, we saw that various stakeholders are concerned about the domestic availability of REEs, up to and including the US Armed Forces. We saw that Japan is responding to similar pressures by both acquiring mineral holdings and by following the advice of UNEP researchers to extract resources from its “urban mines” of used electronics.

In view of the high infrastructure costs, high environmental and human impact of mining, and the finite nature of ore deposits, the author urges US industry and government to pursue recycling, or urban mining, as an alternative or supplement to traditional mining. Extant electronics are rich in the materials required to support a post-industrial economy, in concentrations many times greater than those found in nature. With strategic regulatory inputs, the US can halt the vicious cycle in which recycling is not economically viable, because electronics are difficult to disassemble, because they are not designed for recycling. Instead, it could set in motion a virtuous cycle in which design for the environment encourages recycling, discourages mining, and draws potentially toxic waste out of disposal sites and back into productive use.

Currently, the US is not properly equipped to handle the growing stream of electronic waste. Audited recyclers certainly provide a valuable service. But until the US undergoes systemic change and builds more robust electronics recycling infrastructure, the author finds it difficult to endorse e-waste “recycling” as it stands today. The average consumer faces daunting uncertainty about whether their old electronics will end up being mined for valuable data, burned to expose valuable copper, dissolved in acid to extract gold, or funneled into a competitor's mineral market.

Strong regulations requiring design for the environment could help drive the necessary systemic change. The success of European WEEE legislation, even if incremental and occasionally controversial, shows that regulation and enforcement provide critical recycling incentives that the market does not provide on its own.

The need for regulation has gone beyond an interest in consumer protection and environmental justice. In January of 2011, a *Time* magazine feature about the US job market reiterated a fact that financial analysts and underemployed blue collar workers have known for a long time. In the US's post-industrial economy, in which growth is centered around health care and high tech, engineering positions remain unfilled even amid high unemployment rates. Technology is a major driver in the global economy. Domestic recycling infrastructure, as well as investment in the people and skills to perform high-tech work like developing methods to extract resources from used electronics, must be part of a long-term technology strategy.

High tech is more than just information. Information exists in a physical infrastructure, one whose components were built for replacement, not for longevity or reuse. In the short term, that infrastructure demands new inputs of servers, fiber optic cables, battery backup, and hard drives every day. Electronics recycling can provide the raw materials needed for those infrastructure inputs. In the medium to long term, a virtuous cycle with recycling as its touchstone could shift that infrastructure to one that is less resource intensive, more robust, and more efficient.

Further study is needed to determine what resources lie dormant in waste electronics and how much investment is required to start extracting those resources from various anthropogenic sources. Research is needed to find the best electronics designs for a true cradle-to-cradle life cycle. These data gaps are significant.

However, as UNEP's Resource Panel suggests, some of those data will have value beyond their use for facilitating urban mining. Understanding historical resource usage can help predict future demand and the cost of urban mining (Graedel et al, p. 25). As those data are gathered, we can compare them to known factors. For example, we know that without regulation, current market forces drive electronic waste overseas. However, we also know that the only company that extracted rare earths in the US for many years recently considered it worthwhile to invest $500M to resume operations at a retired facility (Biello, 2010). Furthermore, we have historical data about the environmental impact and risks of mining, and we have some tools to evaluate the externalized costs that we bear in the form of pollution, public health costs, and economic cost of damaged ecosystems, both in terms of cleanup costs and lost natural resources and ecosystem services. Last, we have economic growth predictions that inform how we plan to source the materials that will drive the information economy.

Electronics recycling can play a critical role in ensuring the health of people, the environment, and the long-term financial sustainability of the US technology market. It should be a touchstone of US technology and critical mineral strategy. Currently, the US lacks the infrastructure and market conditions to support a healthy recycling market. However, effective regulatory instruments can foster new markets, create new inputs into established markets, and nurture the research and intellectual resources needed for the US's long-term viability in the global information economy.

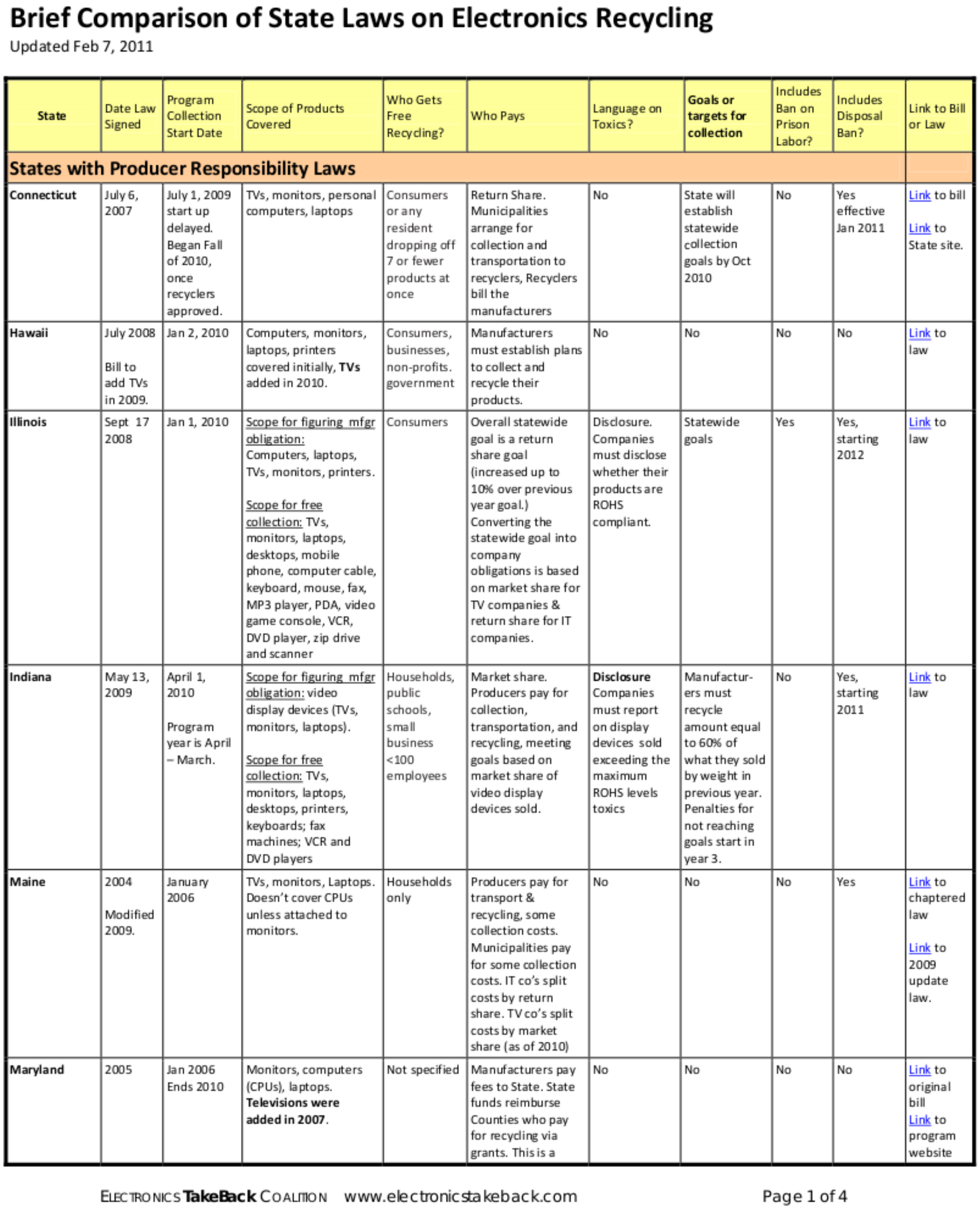
# APPENDIX A: GLOBAL GOLD DEMAND, 2001-2010

**Global Gold Demand from 2001-2010, in tons**

| Year | Jewelry | % of total | Investment | % of total | Technology | % of total | Total |
|---|---|---|---|---|---|---|---|
| 2001 | 3009 | 80.69 | 357 | 9.57 | 363 | 9.73 | 3729 |
| 2002 | 2662 | 79.16 | 343 | 10.2 | 358 | 10.65 | 3363 |
| 2003 | 2484 | 77.46 | 340 | 10.6 | 382 | 11.91 | 3207 |
| 2004 | 2616 | 74.42 | 485 | 13.8 | 414 | 11.78 | 3515 |
| 2005 | 2718 | 72.42 | 601 | 16.01 | 433 | 11.54 | 3753 |
| 2006 | 2298 | 66.9 | 676 | 19.68 | 462 | 13.45 | 3435 |
| 2007 | 2417 | 67.68 | 689 | 19.29 | 465 | 13.02 | 3571 |
| 2008 | 2192 | 57.5 | 1181 | 30.98 | 439 | 11.52 | 3812 |
| 2009 | 1760 | 50.39 | 1360 | 38.94 | 373 | 10.68 | 3493 |
| 2010 | 2060 | 54.04 | 1333 | 34.97 | 420 | 11.02 | 3812 |

***Table 3: Global Gold Demand, 2001-2010. Source: World Gold Council***

# APPENDIX B: COMPARISON OF STATE EPR LAWS BY ETBC

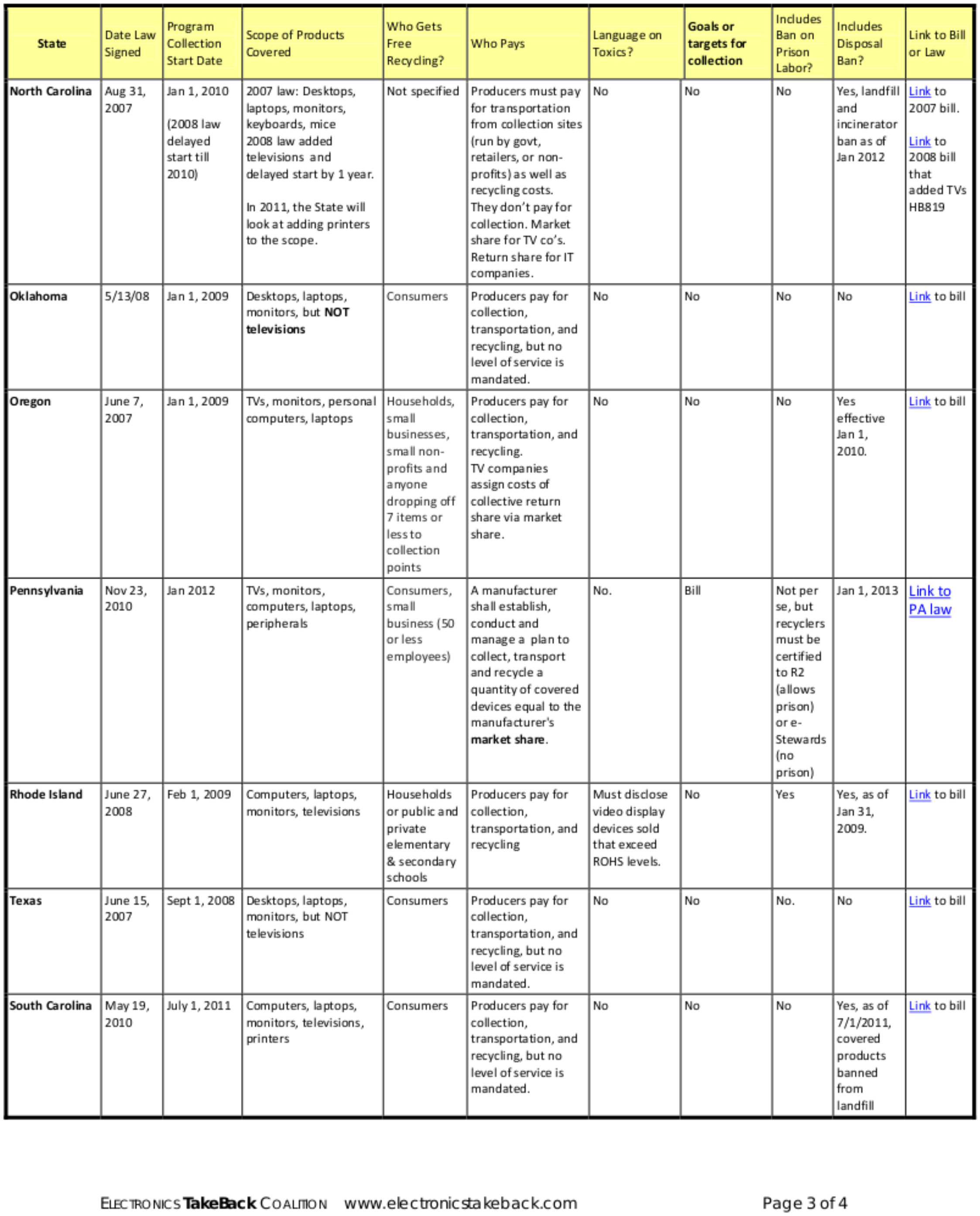


## Brief Comparison of State Laws on Electronics Recycling

Updated Feb 7, 2011

| State | Date Law Signed | Program Collection Start Date | Scope of Products Covered | Who Gets Free Recycling? | Who Pays | Language on Toxics? | **Goals or targets for collection** | Includes Ban on Prison Labor? | Includes Disposal Ban? | Link to Bill or Law |
|---|---|---|---|---|---|---|---|---|---|---|
| **States with Producer Responsibility Laws** | | | | | | | | | | |
| **Connecticut** | July 6, 2007 | July 1, 2009 start up delayed. Began Fall of 2010, once recyclers approved. | TVs, monitors, personal computers, laptops | Consumers or any resident dropping off 7 or fewer products at once | Return Share. Municipalities arrange for collection and transportation to recyclers, Recyclers bill the manufacturers | No | State will establish statewide collection goals by Oct 2010 | No | Yes effective Jan 2011 | Link to bill<br>Link to State site. |
| **Hawaii** | July 2008<br>Bill to add TVs in 2009. | Jan 2, 2010 | Computers, monitors, laptops, printers covered initially, **TVs** added in 2010. | Consumers, businesses, non-profits. government | Manufacturers must establish plans to collect and recycle their products. | No | No | No | No | Link to law |
| **Illinois** | Sept 17 2008 | Jan 1, 2010 | Scope for figuring mfgr obligation: Computers, laptops, TVs, monitors, printers.<br>Scope for free collection: TVs, monitors, laptops, desktops, mobile phone, computer cable, keyboard, mouse, fax, MP3 player, PDA, video game console, VCR, DVD player, zip drive and scanner | Consumers | Overall statewide goal is a return share goal (increased up to 10% over previous year goal.) Converting the statewide goal into company obligations is based on market share for TV companies & return share for IT companies. | Disclosure. Companies must disclose whether their products are ROHS compliant. | Statewide goals | Yes | Yes, starting 2012 | Link to law |
| **Indiana** | May 13, 2009 | April 1, 2010<br>Program year is April – March. | Scope for figuring mfgr obligation: video display devices (TVs, monitors, laptops).<br>Scope for free collection: TVs, monitors, laptops, desktops, printers, keyboards; fax machines; VCR and DVD players | Households, public schools, small business <100 employees | Market share. Producers pay for collection, transportation, and recycling, meeting goals based on market share of video display devices sold. | **Disclosure** Companies must report on display devices sold exceeding the maximum ROHS levels toxics | Manufacturers must recycle amount equal to 60% of what they sold by weight in previous year. Penalties for not reaching goals start in year 3. | No | Yes, starting 2011 | Link to law |
| **Maine** | 2004<br>Modified 2009. | January 2006 | TVs, monitors, Laptops. Doesn't cover CPUs unless attached to monitors. | Households only | Producers pay for transport & recycling, some collection costs. Municipalities pay for some collection costs. IT co's split costs by return share. TV co's split costs by market share (as of 2010) | No | No | No | Yes | Link to chaptered law<br>Link to 2009 update law. |
| **Maryland** | 2005 | Jan 2006 Ends 2010 | Monitors, computers (CPUs), laptops. **Televisions were added in 2007**. | Not specified | Manufacturers pay fees to State. State funds reimburse Counties who pay for recycling via grants. This is a | No | No | No | No | Link to original bill<br>Link to program website |

| **State** | Date Law Signed | Program Collection Start Date | Scope of Products Covered | Who Gets Free Recycling? | Who Pays | Language on Toxics? | **Goals or targets for collection** | Includes Ban on Prison Labor? | Includes Disposal Ban? | Link to Bill or Law |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | modest 5 year pilot program. | | | | | |
| **Michigan** | Dec 26, 2008 | April 1, 2010 | Computers, monitors, TVs, laptops | Consumers, small business dropping off 7 or fewer units per day | Producers pay for collection, transportation, and recycling, but no level of service is mandated. | None | TV companies have non - binding goal of 60% by weight of what company sold in prev year | Yes (in SB 898) | No – will be studied | Link to bill<br>Link to 898 |
| **Minnesota** | May 8, 2007<br>Revised in 2009. | August 2007 | Scope for figuring mfgr obligation: video display devices (TVs, monitors, laptops).<br>Scope for free collection: TVs, monitors, laptops, desktops, printers, keyboards; fax machines; and DVD players | Consumers | Market share. Producers pay for collection, transportation, and recycling. | **Disclosure** Companies must report on display devices sold to households if they exceed the maximum ROHS levels for lead, mercury, cadmium, hexavalent chromium, (PBBs),(PBDEs) | Year 1: Manufacturers must recycle amount equal to 60% of what they sold by weight in previous year<br>Year 2+: 80% of previous year sales | Yes, except for non-profit refurbish-ment and reuse activities | Was already in place | Link to bill<br>Link to 2009 update |
| **Missouri** | Jun 16, 2008 | Plans due July 1, 2010. Collection starts after that. | Desktops, laptops, monitors, but **NOT televisions** | Consumers | Producers pay for collection, transportation, and recycling, but no level of service is mandated. | No | No | No | No | Link to bill |
| **New Jersey** | Jan 15, 2008<br>Revision signed Jan 2009. | Jan 1, 2011<br>New legislation delayed start date from 2010 to 2011 | TVs, monitors, personal computers, laptops | Consumers and small business (50 or less employees) | Return share. Producers pay for collection, transportation, and recycling. TV companies assign costs of collective return share via market share. | Must be ROHS compliant on heavy metals. | Law directs state agency to set goals by Jan 2011. | Yes | Yes as of Jan 1, 2011. | Link to bill |
| **New York City** | 4/1/08 | 7/1/2009 Pre-empted by state law | Computers, TVs, monitors, laptops, **printers,** keyboards, mice | Everyone – consumers, business, etc. | Market Share. Producers must collect and recycle products. | No | Yes. Collection goals based on market share:<br>2012: 25%<br>2015: 45%<br>2018: 65% | No | Yes, as of July 1, 2010 | Link to bills:<br>Int728<br>Int 729 |
| **New York State**<br>Note: New York has a separate law requiring cell phone recycling by the providers. | 5/29/10 | 4/1/2011 | Computers, Televisions, Small Scale Servers Computer Peripherals[1] (Monitors, Electronic Keyboards, Electronic Mice, Faxes, Scanners Printers), Small Electronic Equipment (VCRs, DVRs, Portable Digital Music Players, DVD Players, Digital Converter Boxes, Cable or Satellite Receivers, Electronic or Video Game Consoles) | All except large businesses (50 or more employees) and large non profits (75 or more employees) | Producers pay for collection, transportation, and recycling according to their market share. Law establishes a statewide goal, then producers are assigned their portion according to market share.<br>Producers also must take back one unit for every unit sold. | Yes, must disclose any products for sale that don't comply with ROHS. | Combines goals plus convenience. Statewide collection goals per person:<br>2011: 3 lbs<br>2012: 4 lbs<br>2013: 5lbs<br>After 2013, goal is recalculated based on experience. | No | Yes as of April 1, 2011 for manufacturers, retailers and waste handlers, and eff Jan 1, 2012 for consumers | Link to bill |



| State | Date Law Signed | Program Collection Start Date | Scope of Products Covered | Who Gets Free Recycling? | Who Pays | Language on Toxics? | **Goals or targets for collection** | Includes Ban on Prison Labor? | Includes Disposal Ban? | Link to Bill or Law |
|---|---|---|---|---|---|---|---|---|---|---|
| **North Carolina** | Aug 31, 2007 | Jan 1, 2010<br>(2008 law delayed start till 2010) | 2007 law: Desktops, laptops, monitors, keyboards, mice 2008 law added televisions and delayed start by 1 year.<br>In 2011, the State will look at adding printers to the scope. | Not specified | Producers must pay for transportation from collection sites (run by govt, retailers, or non-profits) as well as recycling costs. They don't pay for collection. Market share for TV co's. Return share for IT companies. | No | No | No | Yes, landfill and incinerator ban as of Jan 2012 | Link to 2007 bill.<br>Link to 2008 bill that added TVs HB819 |
| **Oklahoma** | 5/13/08 | Jan 1, 2009 | Desktops, laptops, monitors, but **NOT televisions** | Consumers | Producers pay for collection, transportation, and recycling, but no level of service is mandated. | No | No | No | No | Link to bill |
| **Oregon** | June 7, 2007 | Jan 1, 2009 | TVs, monitors, personal computers, laptops | Households, small businesses, small non-profits and anyone dropping off 7 items or less to collection points | Producers pay for collection, transportation, and recycling. TV companies assign costs of collective return share via market share. | No | No | No | Yes effective Jan 1, 2010. | Link to bill |
| **Pennsylvania** | Nov 23, 2010 | Jan 2012 | TVs, monitors, computers, laptops, peripherals | Consumers, small business (50 or less employees) | A manufacturer shall establish, conduct and manage a plan to collect, transport and recycle a quantity of covered devices equal to the manufacturer's **market share**. | No. | Bill | Not per se, but recyclers must be certified to R2 (allows prison) or e-Stewards (no prison) | Jan 1, 2013 | Link to PA law |
| **Rhode Island** | June 27, 2008 | Feb 1, 2009 | Computers, laptops, monitors, televisions | Households or public and private elementary & secondary schools | Producers pay for collection, transportation, and recycling | Must disclose video display devices sold that exceed ROHS levels. | No | Yes | Yes, as of Jan 31, 2009. | Link to bill |
| **Texas** | June 15, 2007 | Sept 1, 2008 | Desktops, laptops, monitors, but NOT televisions | Consumers | Producers pay for collection, transportation, and recycling, but no level of service is mandated. | No | No | No. | No | Link to bill |
| **South Carolina** | May 19, 2010 | July 1, 2011 | Computers, laptops, monitors, televisions, printers | Consumers | Producers pay for collection, transportation, and recycling, but no level of service is mandated. | No | No | No | Yes, as of 7/1/2011, covered products banned from landfill | Link to bill |

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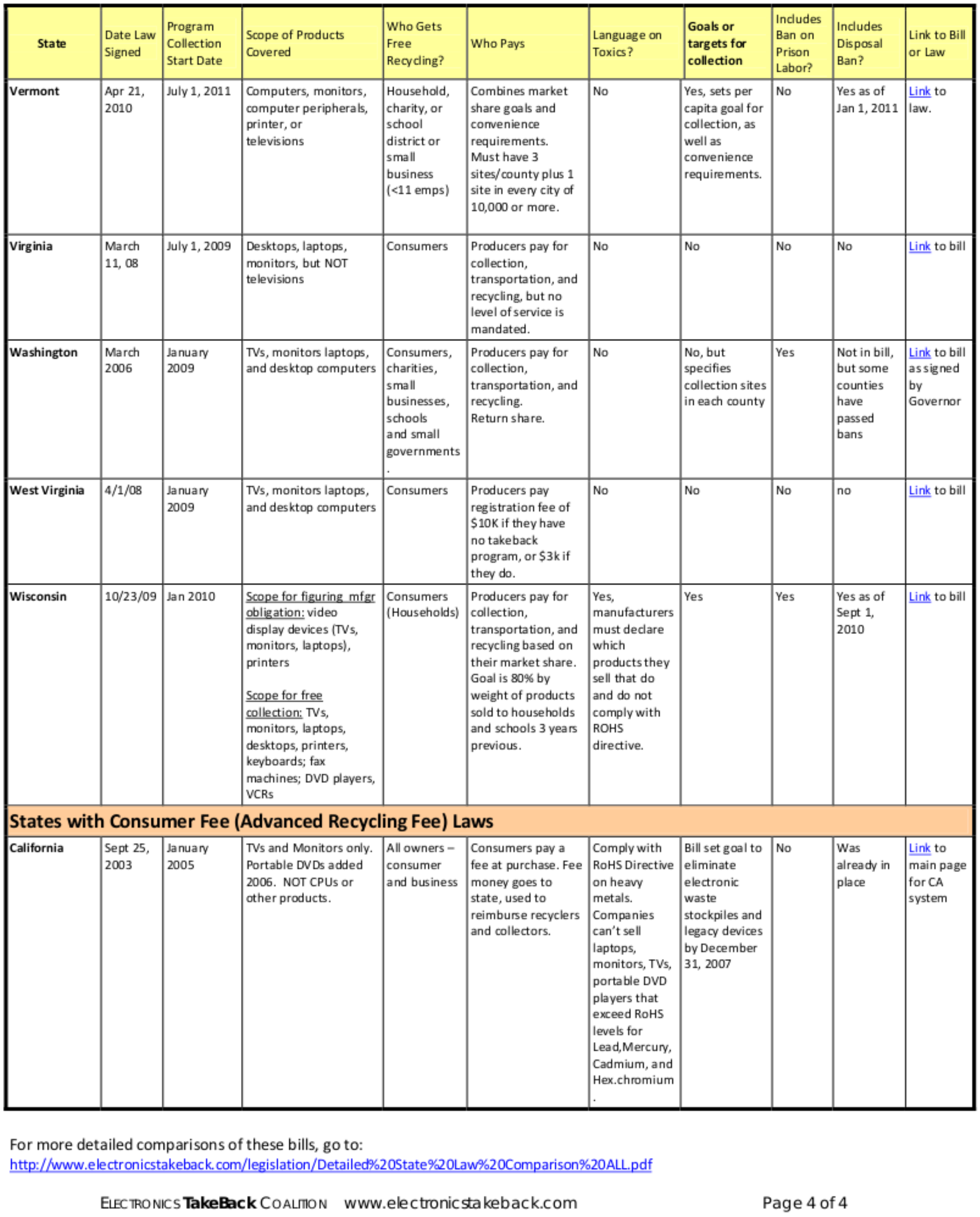

| State | Date Law Signed | Program Collection Start Date | Scope of Products Covered | Who Gets Free Recycling? | Who Pays | Language on Toxics? | **Goals or targets for collection** | Includes Ban on Prison Labor? | Includes Disposal Ban? | Link to Bill or Law |
|---|---|---|---|---|---|---|---|---|---|---|
| **Vermont** | Apr 21, 2010 | July 1, 2011 | Computers, monitors, computer peripherals, printer, or televisions | Household, charity, or school district or small business (<11 emps) | Combines market share goals and convenience requirements. Must have 3 sites/county plus 1 site in every city of 10,000 or more. | No | Yes, sets per capita goal for collection, as well as convenience requirements. | No | Yes as of Jan 1, 2011 | Link to law. |
| **Virginia** | March 11, 08 | July 1, 2009 | Desktops, laptops, monitors, but NOT televisions | Consumers | Producers pay for collection, transportation, and recycling, but no level of service is mandated. | No | No | No | No | Link to bill |
| **Washington** | March 2006 | January 2009 | TVs, monitors laptops, and desktop computers | Consumers, charities, small businesses, schools and small governments . | Producers pay for collection, transportation, and recycling.<br>Return share. | No | No, but specifies collection sites in each county | Yes | Not in bill, but some counties have passed bans | Link to bill as signed by Governor |
| **West Virginia** | 4/1/08 | January 2009 | TVs, monitors laptops, and desktop computers | Consumers | Producers pay registration fee of $10K if they have no takeback program, or $3k if they do. | No | No | No | no | Link to bill |
| **Wisconsin** | 10/23/09 | Jan 2010 | Scope for figuring mfgr obligation: video display devices (TVs, monitors, laptops), printers<br>Scope for free collection: TVs, monitors, laptops, desktops, printers, keyboards; fax machines; DVD players, VCRs | Consumers (Households) | Producers pay for collection, transportation, and recycling based on their market share. Goal is 80% by weight of products sold to households and schools 3 years previous. | Yes, manufacturers must declare which products they sell that do and do not comply with ROHS directive. | Yes | Yes | Yes as of Sept 1, 2010 | Link to bill |
| **States with Consumer Fee (Advanced Recycling Fee) Laws** | | | | | | | | | | |
| **California** | Sept 25, 2003 | January 2005 | TVs and Monitors only. Portable DVDs added 2006. NOT CPUs or other products. | All owners – consumer and business | Consumers pay a fee at purchase. Fee money goes to state, used to reimburse recyclers and collectors. | Comply with RoHS Directive on heavy metals. Companies can't sell laptops, monitors, TVs, portable DVD players that exceed RoHS levels for Lead,Mercury, Cadmium, and Hex.chromium . | Bill set goal to eliminate electronic waste stockpiles and legacy devices by December 31, 2007 | No | Was already in place | Link to main page for CA system |

For more detailed comparisons of these bills, go to:
http://www.electronicstakeback.com/legislation/Detailed%20State%20Law%20Comparison%20ALL.pdf

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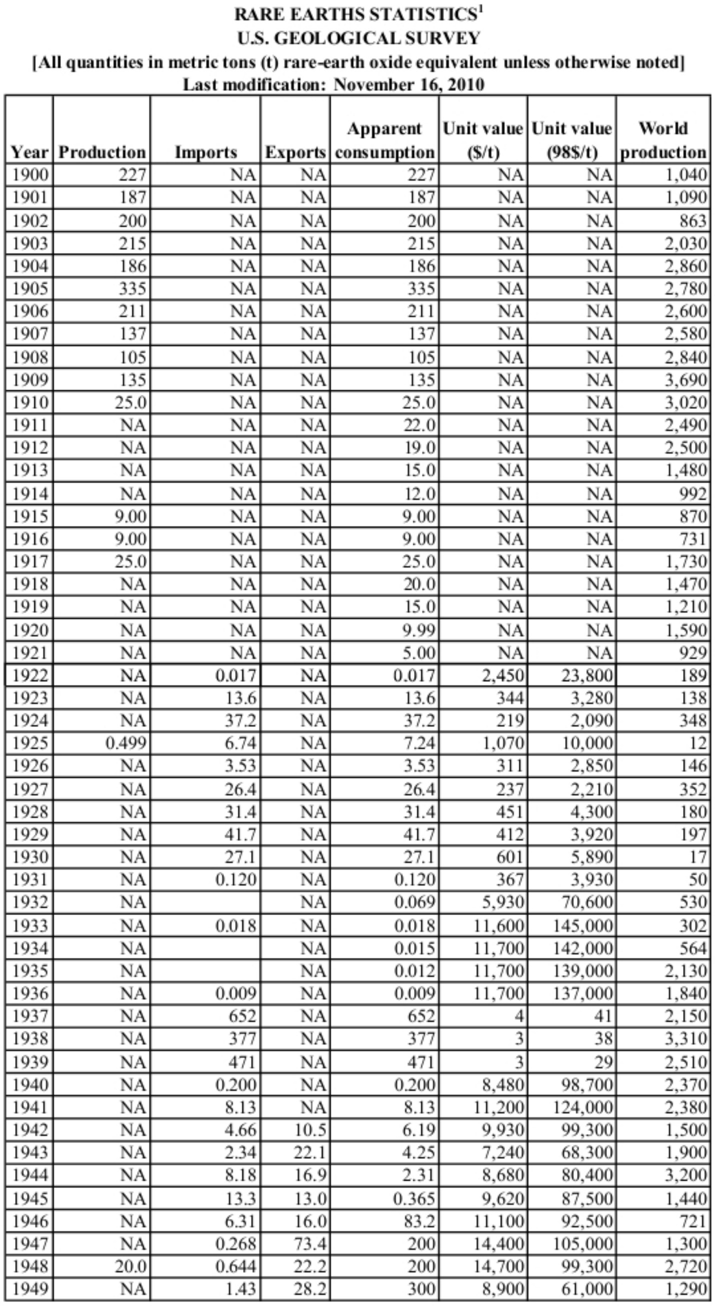
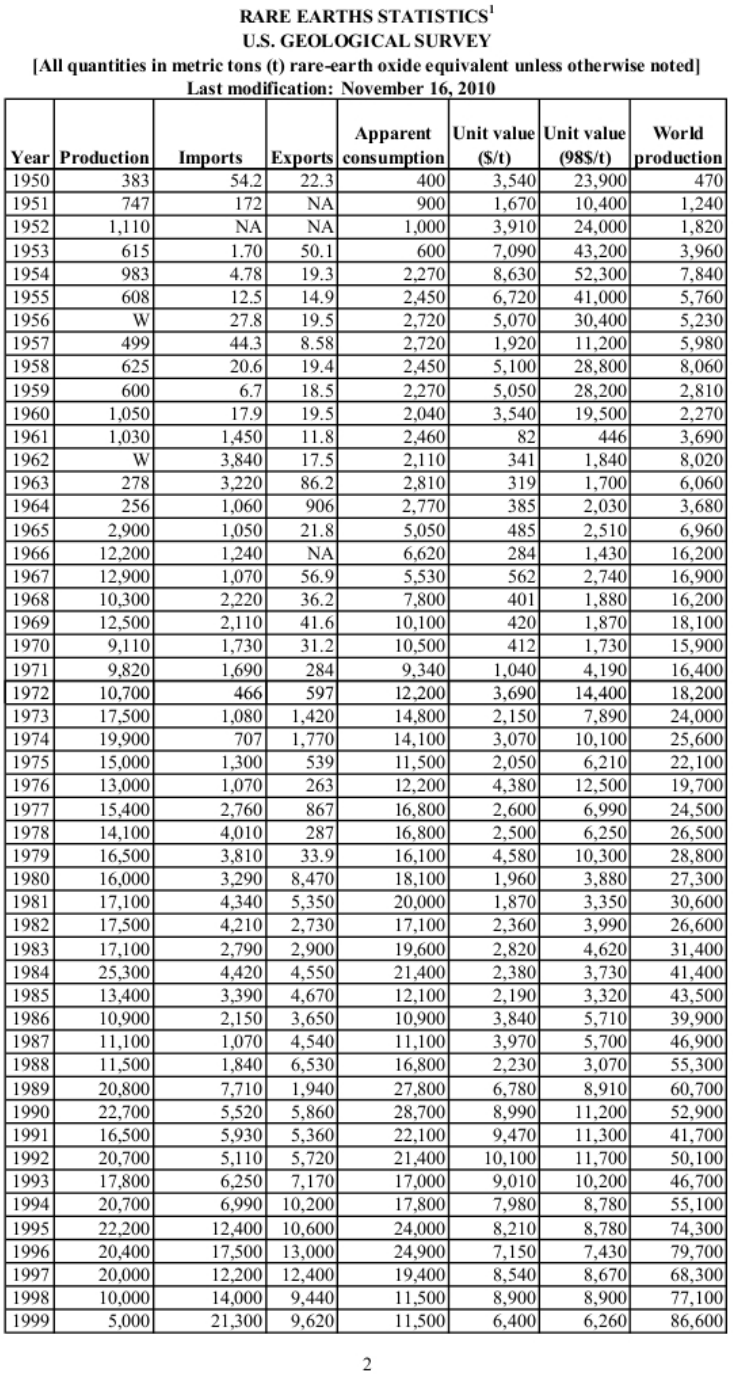
# APPENDIX C: RARE EARTH STATISTICS 1900-2009



**RARE EARTHS STATISTICS[1]**
**U.S. GEOLOGICAL SURVEY**
**[All quantities in metric tons (t) rare-earth oxide equivalent unless otherwise noted]**
**Last modification: November 16, 2010**

| Year | Production | Imports | Exports | Apparent consumption | Unit value ($/t) | Unit value (98$/t) | World production |
|---|---|---|---|---|---|---|---|
| 1900 | 227 | NA | NA | 227 | NA | NA | 1,040 |
| 1901 | 187 | NA | NA | 187 | NA | NA | 1,090 |
| 1902 | 200 | NA | NA | 200 | NA | NA | 863 |
| 1903 | 215 | NA | NA | 215 | NA | NA | 2,030 |
| 1904 | 186 | NA | NA | 186 | NA | NA | 2,860 |
| 1905 | 335 | NA | NA | 335 | NA | NA | 2,780 |
| 1906 | 211 | NA | NA | 211 | NA | NA | 2,600 |
| 1907 | 137 | NA | NA | 137 | NA | NA | 2,580 |
| 1908 | 105 | NA | NA | 105 | NA | NA | 2,840 |
| 1909 | 135 | NA | NA | 135 | NA | NA | 3,690 |
| 1910 | 25.0 | NA | NA | 25.0 | NA | NA | 3,020 |
| 1911 | NA | NA | NA | 22.0 | NA | NA | 2,490 |
| 1912 | NA | NA | NA | 19.0 | NA | NA | 2,500 |
| 1913 | NA | NA | NA | 15.0 | NA | NA | 1,480 |
| 1914 | NA | NA | NA | 12.0 | NA | NA | 992 |
| 1915 | 9.00 | NA | NA | 9.00 | NA | NA | 870 |
| 1916 | 9.00 | NA | NA | 9.00 | NA | NA | 731 |
| 1917 | 25.0 | NA | NA | 25.0 | NA | NA | 1,730 |
| 1918 | NA | NA | NA | 20.0 | NA | NA | 1,470 |
| 1919 | NA | NA | NA | 15.0 | NA | NA | 1,210 |
| 1920 | NA | NA | NA | 9.99 | NA | NA | 1,590 |
| 1921 | NA | NA | NA | 5.00 | NA | NA | 929 |
| 1922 | NA | 0.017 | NA | 0.017 | 2,450 | 23,800 | 189 |
| 1923 | NA | 13.6 | NA | 13.6 | 344 | 3,280 | 138 |
| 1924 | NA | 37.2 | NA | 37.2 | 219 | 2,090 | 348 |
| 1925 | 0.499 | 6.74 | NA | 7.24 | 1,070 | 10,000 | 12 |
| 1926 | NA | 3.53 | NA | 3.53 | 311 | 2,850 | 146 |
| 1927 | NA | 26.4 | NA | 26.4 | 237 | 2,210 | 352 |
| 1928 | NA | 31.4 | NA | 31.4 | 451 | 4,300 | 180 |
| 1929 | NA | 41.7 | NA | 41.7 | 412 | 3,920 | 197 |
| 1930 | NA | 27.1 | NA | 27.1 | 601 | 5,890 | 17 |
| 1931 | NA | 0.120 | NA | 0.120 | 367 | 3,930 | 50 |
| 1932 | NA |  | NA | 0.069 | 5,930 | 70,600 | 530 |
| 1933 | NA | 0.018 | NA | 0.018 | 11,600 | 145,000 | 302 |
| 1934 | NA |  | NA | 0.015 | 11,700 | 142,000 | 564 |
| 1935 | NA |  | NA | 0.012 | 11,700 | 139,000 | 2,130 |
| 1936 | NA | 0.009 | NA | 0.009 | 11,700 | 137,000 | 1,840 |
| 1937 | NA | 652 | NA | 652 | 4 | 41 | 2,150 |
| 1938 | NA | 377 | NA | 377 | 3 | 38 | 3,310 |
| 1939 | NA | 471 | NA | 471 | 3 | 29 | 2,510 |
| 1940 | NA | 0.200 | NA | 0.200 | 8,480 | 98,700 | 2,370 |
| 1941 | NA | 8.13 | NA | 8.13 | 11,200 | 124,000 | 2,380 |
| 1942 | NA | 4.66 | 10.5 | 6.19 | 9,930 | 99,300 | 1,500 |
| 1943 | NA | 2.34 | 22.1 | 4.25 | 7,240 | 68,300 | 1,900 |
| 1944 | NA | 8.18 | 16.9 | 2.31 | 8,680 | 80,400 | 3,200 |
| 1945 | NA | 13.3 | 13.0 | 0.365 | 9,620 | 87,500 | 1,440 |
| 1946 | NA | 6.31 | 16.0 | 83.2 | 11,100 | 92,500 | 721 |
| 1947 | NA | 0.268 | 73.4 | 200 | 14,400 | 105,000 | 1,300 |
| 1948 | 20.0 | 0.644 | 22.2 | 200 | 14,700 | 99,300 | 2,720 |
| 1949 | NA | 1.43 | 28.2 | 300 | 8,900 | 61,000 | 1,290 |



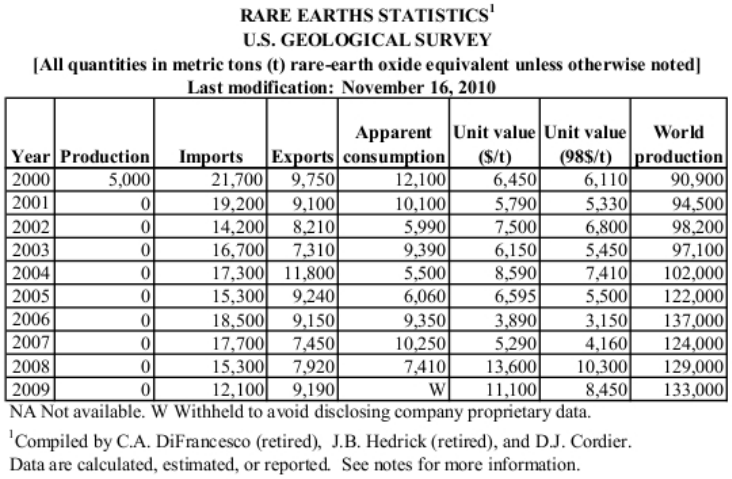
**RARE EARTHS STATISTICS[1]**

**U.S. GEOLOGICAL SURVEY**

**[All quantities in metric tons (t) rare-earth oxide equivalent unless otherwise noted]**

**Last modification: November 16, 2010**

| Year | Production | Imports | Exports | Apparent consumption | Unit value ($/t) | Unit value (98$/t) | World production |
|---|---|---|---|---|---|---|---|
| 1950 | 383 | 54.2 | 22.3 | 400 | 3,540 | 23,900 | 470 |
| 1951 | 747 | 172 | NA | 900 | 1,670 | 10,400 | 1,240 |
| 1952 | 1,110 | NA | NA | 1,000 | 3,910 | 24,000 | 1,820 |
| 1953 | 615 | 1.70 | 50.1 | 600 | 7,090 | 43,200 | 3,960 |
| 1954 | 983 | 4.78 | 19.3 | 2,270 | 8,630 | 52,300 | 7,840 |
| 1955 | 608 | 12.5 | 14.9 | 2,450 | 6,720 | 41,000 | 5,760 |
| 1956 | W | 27.8 | 19.5 | 2,720 | 5,070 | 30,400 | 5,230 |
| 1957 | 499 | 44.3 | 8.58 | 2,720 | 1,920 | 11,200 | 5,980 |
| 1958 | 625 | 20.6 | 19.4 | 2,450 | 5,100 | 28,800 | 8,060 |
| 1959 | 600 | 6.7 | 18.5 | 2,270 | 5,050 | 28,200 | 2,810 |
| 1960 | 1,050 | 17.9 | 19.5 | 2,040 | 3,540 | 19,500 | 2,270 |
| 1961 | 1,030 | 1,450 | 11.8 | 2,460 | 82 | 446 | 3,690 |
| 1962 | W | 3,840 | 17.5 | 2,110 | 341 | 1,840 | 8,020 |
| 1963 | 278 | 3,220 | 86.2 | 2,810 | 319 | 1,700 | 6,060 |
| 1964 | 256 | 1,060 | 906 | 2,770 | 385 | 2,030 | 3,680 |
| 1965 | 2,900 | 1,050 | 21.8 | 5,050 | 485 | 2,510 | 6,960 |
| 1966 | 12,200 | 1,240 | NA | 6,620 | 284 | 1,430 | 16,200 |
| 1967 | 12,900 | 1,070 | 56.9 | 5,530 | 562 | 2,740 | 16,900 |
| 1968 | 10,300 | 2,220 | 36.2 | 7,800 | 401 | 1,880 | 16,200 |
| 1969 | 12,500 | 2,110 | 41.6 | 10,100 | 420 | 1,870 | 18,100 |
| 1970 | 9,110 | 1,730 | 31.2 | 10,500 | 412 | 1,730 | 15,900 |
| 1971 | 9,820 | 1,690 | 284 | 9,340 | 1,040 | 4,190 | 16,400 |
| 1972 | 10,700 | 466 | 597 | 12,200 | 3,690 | 14,400 | 18,200 |
| 1973 | 17,500 | 1,080 | 1,420 | 14,800 | 2,150 | 7,890 | 24,000 |
| 1974 | 19,900 | 707 | 1,770 | 14,100 | 3,070 | 10,100 | 25,600 |
| 1975 | 15,000 | 1,300 | 539 | 11,500 | 2,050 | 6,210 | 22,100 |
| 1976 | 13,000 | 1,070 | 263 | 12,200 | 4,380 | 12,500 | 19,700 |
| 1977 | 15,400 | 2,760 | 867 | 16,800 | 2,600 | 6,990 | 24,500 |
| 1978 | 14,100 | 4,010 | 287 | 16,800 | 2,500 | 6,250 | 26,500 |
| 1979 | 16,500 | 3,810 | 33.9 | 16,100 | 4,580 | 10,300 | 28,800 |
| 1980 | 16,000 | 3,290 | 8,470 | 18,100 | 1,960 | 3,880 | 27,300 |
| 1981 | 17,100 | 4,340 | 5,350 | 20,000 | 1,870 | 3,350 | 30,600 |
| 1982 | 17,500 | 4,210 | 2,730 | 17,100 | 2,360 | 3,990 | 26,600 |
| 1983 | 17,100 | 2,790 | 2,900 | 19,600 | 2,820 | 4,620 | 31,400 |
| 1984 | 25,300 | 4,420 | 4,550 | 21,400 | 2,380 | 3,730 | 41,400 |
| 1985 | 13,400 | 3,390 | 4,670 | 12,100 | 2,190 | 3,320 | 43,500 |
| 1986 | 10,900 | 2,150 | 3,650 | 10,900 | 3,840 | 5,710 | 39,900 |
| 1987 | 11,100 | 1,070 | 4,540 | 11,100 | 3,970 | 5,700 | 46,900 |
| 1988 | 11,500 | 1,840 | 6,530 | 16,800 | 2,230 | 3,070 | 55,300 |
| 1989 | 20,800 | 7,710 | 1,940 | 27,800 | 6,780 | 8,910 | 60,700 |
| 1990 | 22,700 | 5,520 | 5,860 | 28,700 | 8,990 | 11,200 | 52,900 |
| 1991 | 16,500 | 5,930 | 5,360 | 22,100 | 9,470 | 11,300 | 41,700 |
| 1992 | 20,700 | 5,110 | 5,720 | 21,400 | 10,100 | 11,700 | 50,100 |
| 1993 | 17,800 | 6,250 | 7,170 | 17,000 | 9,010 | 10,200 | 46,700 |
| 1994 | 20,700 | 6,990 | 10,200 | 17,800 | 7,980 | 8,780 | 55,100 |
| 1995 | 22,200 | 12,400 | 10,600 | 24,000 | 8,210 | 8,780 | 74,300 |
| 1996 | 20,400 | 17,500 | 13,000 | 24,900 | 7,150 | 7,430 | 79,700 |
| 1997 | 20,000 | 12,200 | 12,400 | 19,400 | 8,540 | 8,670 | 68,300 |
| 1998 | 10,000 | 14,000 | 9,440 | 11,500 | 8,900 | 8,900 | 77,100 |
| 1999 | 5,000 | 21,300 | 9,620 | 11,500 | 6,400 | 6,260 | 86,600 |

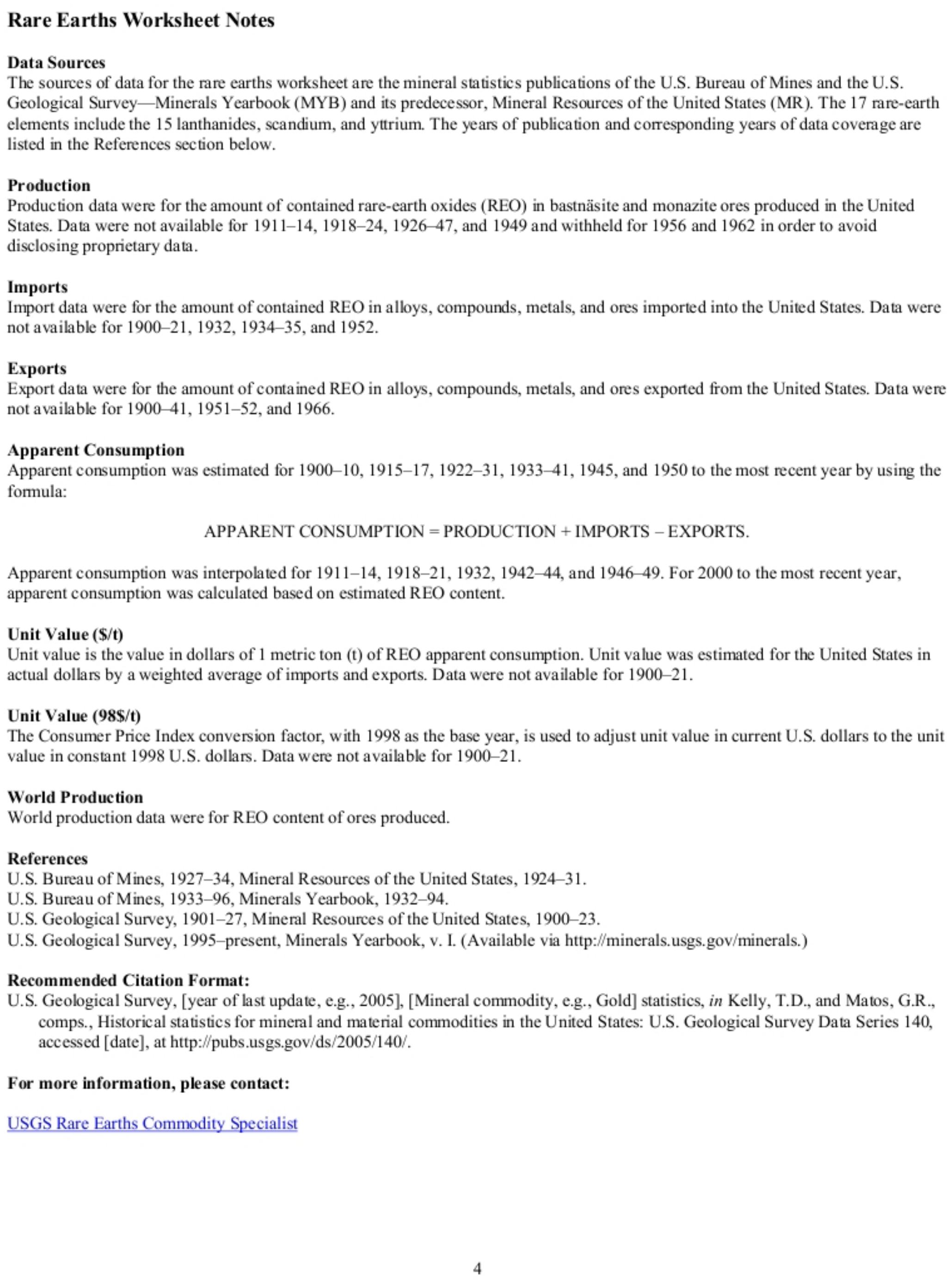


**RARE EARTHS STATISTICS[1]**
**U.S. GEOLOGICAL SURVEY**
**[All quantities in metric tons (t) rare-earth oxide equivalent unless otherwise noted]**
**Last modification: November 16, 2010**

| Year | Production | Imports | Exports | Apparent consumption | Unit value ($/t) | Unit value (98$/t) | World production |
|---|---|---|---|---|---|---|---|
| 2000 | 5,000 | 21,700 | 9,750 | 12,100 | 6,450 | 6,110 | 90,900 |
| 2001 | 0 | 19,200 | 9,100 | 10,100 | 5,790 | 5,330 | 94,500 |
| 2002 | 0 | 14,200 | 8,210 | 5,990 | 7,500 | 6,800 | 98,200 |
| 2003 | 0 | 16,700 | 7,310 | 9,390 | 6,150 | 5,450 | 97,100 |
| 2004 | 0 | 17,300 | 11,800 | 5,500 | 8,590 | 7,410 | 102,000 |
| 2005 | 0 | 15,300 | 9,240 | 6,060 | 6,595 | 5,500 | 122,000 |
| 2006 | 0 | 18,500 | 9,150 | 9,350 | 3,890 | 3,150 | 137,000 |
| 2007 | 0 | 17,700 | 7,450 | 10,250 | 5,290 | 4,160 | 124,000 |
| 2008 | 0 | 15,300 | 7,920 | 7,410 | 13,600 | 10,300 | 129,000 |
| 2009 | 0 | 12,100 | 9,190 | W | 11,100 | 8,450 | 133,000 |

NA Not available. W Withheld to avoid disclosing company proprietary data.

[1] Compiled by C.A. DiFrancesco (retired), J.B. Hedrick (retired), and D.J. Cordier.
Data are calculated, estimated, or reported. See notes for more information.



## Rare Earths Worksheet Notes

### Data Sources

The sources of data for the rare earths worksheet are the mineral statistics publications of the U.S. Bureau of Mines and the U.S. Geological Survey—Minerals Yearbook (MYB) and its predecessor, Mineral Resources of the United States (MR). The 17 rare-earth elements include the 15 lanthanides, scandium, and yttrium. The years of publication and corresponding years of data coverage are listed in the References section below.

### Production

Production data were for the amount of contained rare-earth oxides (REO) in bastnäsite and monazite ores produced in the United States. Data were not available for 1911–14, 1918–24, 1926–47, and 1949 and withheld for 1956 and 1962 in order to avoid disclosing proprietary data.

### Imports

Import data were for the amount of contained REO in alloys, compounds, metals, and ores imported into the United States. Data were not available for 1900–21, 1932, 1934–35, and 1952.

### Exports

Export data were for the amount of contained REO in alloys, compounds, metals, and ores exported from the United States. Data were not available for 1900–41, 1951–52, and 1966.

### Apparent Consumption

Apparent consumption was estimated for 1900–10, 1915–17, 1922–31, 1933–41, 1945, and 1950 to the most recent year by using the formula:

APPARENT CONSUMPTION = PRODUCTION + IMPORTS – EXPORTS.

Apparent consumption was interpolated for 1911–14, 1918–21, 1932, 1942–44, and 1946–49. For 2000 to the most recent year, apparent consumption was calculated based on estimated REO content.

### Unit Value ($/t)

Unit value is the value in dollars of 1 metric ton (t) of REO apparent consumption. Unit value was estimated for the United States in actual dollars by a weighted average of imports and exports. Data were not available for 1900–21.

### Unit Value (98$/t)

The Consumer Price Index conversion factor, with 1998 as the base year, is used to adjust unit value in current U.S. dollars to the unit value in constant 1998 U.S. dollars. Data were not available for 1900–21.

### World Production

World production data were for REO content of ores produced.

### References

U.S. Bureau of Mines, 1927–34, Mineral Resources of the United States, 1924–31.
U.S. Bureau of Mines, 1933–96, Minerals Yearbook, 1932–94.
U.S. Geological Survey, 1901–27, Mineral Resources of the United States, 1900–23.
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**For more information, please contact:**

USGS Rare Earths Commodity Specialist

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