

# Economics of PC Recycling

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## ABSTRACT

As the use of personal computers (PCs) increases, their short life cycle and the fact that they contain many hazardous materials means that their retirement and disposal represents a significant environmental concern. Many communities are mandating the recycling of these PCs, to recover parts and materials, and to minimize the amount of waste landfilled or incinerated. An industry to recycle these PCs is evolving to take advantage of this stream of materials. At present, PC recycling is not profitable. This paper investigates the factors that most influence the net cost to recycle PCs so that PC manufacturers, recyclers and legislators may better develop products and policies to insure that it is cost effective to recycle PCs.

**Keywords:** Computer recycling, electronics, economics, environment, disassembly.

## 1. INTRODUCTION

The use of personal computers continues to increase yearly, and sales of PCs have increased by more than 23% per year since 1985 in the US. Furthermore, the typical life of a PC in the workplace is approximately two to three years, while in the home, the typical life is three to five years. As these PCs become obsolete, they are replaced and the old PCs are disposed. It is estimated that between 14 and 20 million PCs are retired annually in the US. While 20 to 30% of the units may be resold, the other units are thrown away if they are not recycled. These discards represent a significant potential source of lead for the waste stream<sup>1, 2</sup>.

To address this problem, many communities are prohibiting the dumping of electronic equipment in landfills or incinerators. Although still not formally adopted in Europe, the Directive on Waste from Electrical and Electronic Equipment was approved by the European Commission. This legislation would require the producer take-back of used electrical and electronic equipment<sup>3</sup>. The state of Massachusetts is approaching these end-of-life (EOL) issues in a different way. The final owners of computer monitors or any other devices containing a cathode ray tube (CRT) are responsible for their disposal because garbage trucks are no longer permitted to collect these electronic devices. The state is subsidizing the recycling costs for municipalities and for several charitable institutions that accept working electronic devices, with a goal of fostering a system to reuse and recycle the electronics<sup>4</sup>.

The large volume of waste PCs has created an industry devoted to recycling computers and electronics. However, changes in the materials comprising circuit boards have made it difficult to garner significant profits. For instance, the precious metals content of a standard PC printed circuit board (PCB) was once quite significant. Platinum, palladium, gold and silver could be extracted from the PCBs in concentrations similar to those found in mine tailings. One precious metals refiner has found that more gold may be recovered from electronic scrap than may be found in the ground<sup>5</sup>.

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While the recycling of PCs is not profitable at present, legislation controlling the disposal of PCs will necessitate recycling. This paper investigates the factors that most influence the net cost of recycling PCs. By ascertaining the costs and parameters that most effect the recycling economics, PC manufacturers, recyclers and legislators may better develop products and policies to facilitate the cost effective recycling of PCs.

## 2. ELECTRONICS RECYCLING OVERVIEW

When a PC is shipped to a recycler it is first evaluated from a security and reshipping standpoint. Safety is a primary issue whether the materials have been obtained from corporate clients or from government contracts because the PCs arriving at the recycler are in highly variable condition. One of the most significant difficulties in remanufacturing and product recovery pertains to the uncertainty regarding the condition of the item to be recycled and its constituent components<sup>6</sup>. In the case of used PCs, there may be breakage or hazardous materials may be present. Only after the safety of the employees and the equipment has been ascertained, can the recycler assess whether the unit may be refurbished and sold. If no market exists for a refurbished unit, due to the condition of the unit or market forces, the unit is then evaluated for the sale of parts and materials<sup>7</sup>. Often, when there are salable components like monitors, hard drives or chips, profits derived from the sale are split with the customer on a prearranged basis<sup>5</sup>.

If there are components that may be sold, the PCs may be disassembled to the fragment level. This process, however, is very labor intensive, and often quite complicated since some PCs are not designed for EOL disassembly. The use of different types of screws and fasteners may further slow down the disassembly process. When this level of disassembly occurs, the residual fragments are sorted by hand to identify their dominant materials and sold to the secondary materials industry. Otherwise, the PCs are shredded and then sorted and separated into streams of copper, aluminum, steel, brass and plastics. Precious metals are also collected. One fully automated system used for electronic scrap can shred approximately 3 tons of materials per hour. These shredders are marketed as a means of avoiding the cost of dismantling, which is perceived as labor intensive and very expensive.

Another significant challenge in recycling computer and electronic equipment is in handling and disposing of hazardous materials. The presence of components that would be hazardous if they are degraded in landfills adds another level of complexity. By reclaiming these components, the ultimate effect on the environment may be mitigated. The hazardous materials that recyclers confront are typically: mineral oil capacitors containing polychlorinated biphenyls, batteries, printed circuit boards containing lead, mercury relays, cathode ray tubes containing lead and cadmium, photoreceptor drums containing selenium and arsenic, and gas springs containing oil. If these components are not resellable, they must be disposed of as hazardous waste. Typically, these hazardous components can be disposed of in a blast furnace<sup>1</sup>.

Monitors, and the presence of the leaded glass found in cathode ray tubes (CRTs), present a specific challenge to recyclers because the glass is considered hazardous waste. The lead content of the leaded glass varies by manufacturer and by component, and this influences the future applications of the recycled glass. Leaded glass is currently reused in a variety of ways: as a fluxing agent for lead smelting, as a sandblasting medium, and in the manufacture of CRT glass. The most promising future markets for this glass may include the production of decorative tile and the manufacture of x-ray shielding products<sup>8</sup>.

## 3. FORMULATION

The net costs incurred by the PC recycler are the difference between the costs of acquiring the PCs and sorting, dismantling, processing and disposing of the various components and the revenues derived from the sale of parts and materials. A cost model is developed using known recycling costs and revenues, to assess the effect of changes in different variables on recycler profits.

The model is based on the transfer of various masses of materials,  $X_i$ , where  $X_i$  ( $i = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10$ ) represent: 1) the mass of monitors, 2) other parts and equipment identified for resale, 3) high grade breakage, 4)

circuit boards, 5) mixed metals, 6) wire, 7) steel, 8) plastic, 9) non-hazardous waste and 10) hazardous waste sorted by the recycler respectively.

The revenues,  $R_i$ , generated by the recycler are a function of the fraction of monitors that are serviceable and resellable ( $R_1 a_1 X_1$ ) and the market price and mass of the other parts and materials present in a given lot of scrap PCs

$\sum_{i=2}^8 (R_i X_i)$ . The costs incurred by the recycler are a function of the cost to transport the scrap PCs to the recycler

$C_1 \sum_{i=1}^{10} X_i$ , the cost to sort the scrap  $C_2 \sum_{i=1}^{10} X_i$ , the cost to dismantle the PCs  $C_3 \sum_{i=3}^{10} X_i$ , the cost to recycle and

process any monitors not sold ( $C_4(1-a_1)X_1$ ), the cost to dispose of non-hazardous wastes ( $C_5 X_9$ ) and the cost to dispose of hazardous wastes ( $C_6 X_{10}$ ).

The net cost function for the recycler ( $C_{recycler}$ ) can be written as follows:

$$C_{recycler} = C_1 \sum_{i=1}^{10} X_i + C_2 \sum_{i=1}^{10} X_i + C_3 \sum_{i=3}^{10} X_i + C_4(1-a_1)X_1 \\ + C_5 X_9 + C_6 X_{10} - R_1 a_1 X_1 - \sum_{i=2}^8 R_i X_i$$

#### 4. INPUT PARAMETERS

Most of the cost and revenue values used in the cost model were obtained from a pilot study conducted in San Jose, CA in 1997 where used computer equipment was dropped off by local consumers at three participating electronics stores. Once a week, the equipment was picked up by a recycler and transported to a processing facility where it was sorted for resale or material recovery. The recoverable equipment was sold by auction, and the other equipment was dismantled and the materials were sorted. The scrapped materials such as the circuit boards, wire and metals were sold to the appropriate secondary markets, and materials like plastic and steel were given to recyclers for further processing. The monitors in the San Jose study were processed in China, resulting in a low cost solution<sup>9</sup>.

The cost to dismantle the PCs was derived from the University of Massachusetts Amherst Scrap Electronics Processing study.<sup>10</sup> The direct labor cost for the dismantling in this study was \$119 per ton. The workers in the University of Massachusetts study were paid \$6.25/hour<sup>10</sup>. This dismantling cost was normalized to the \$15/hour wage level employed in San Jose, CA. Table 1 shows the costs and revenue assumptions employed in the cost model.

Table 1. Assumptions for cost and revenue input parameters <sup>9</sup>

Costs		(\$/kg)	Revenues		(\$/kg)
$C_1$	Cost to transport to recycler	0.0172	$R_1$	Monitor sales	0.761
$C_2$	Cost to sort	0.140	$R_2$	Sales of other equipment	0.616
$C_3$	Cost to dismantle	0.315	$R_3$	High-grade breakage	0.554
$C_4$	Cost to recycle monitors	0.110	$R_4$	Scrap printed circuit boards	1.784
$C_5$	Cost to dispose non-hazardous wastes	0.0330	$R_5$	Mixed metals	0.237
$C_6$	Cost to dispose hazardous wastes	0.200	$R_6$	Wire	0.311
			$R_7$	Steel	0.00
			$R_8$	Plastic	0.00

The San Jose study was also used to model the composition of the scrap computer equipment received and processed by the recycler. Table 2 shows the masses of monitors and other electronic goods collected and the fractions of the various parts and materials found in the equipment collected, and also shows the derivation of the specific masses ( $X_i$ ) employed in the model.

Table 2. Assumptions for the composition of the electronics scrap collected

		San Jose Results <sup>9</sup>	Model Parameters
$m_1$	Mass of monitors collected	15288 kg	$X_1 = m_1$
$m_2$	Mass of other electronic goods collected	12678 kg	
$a_1$	Fraction of monitors resold	0.101	
$a_2$	Fraction of other equipment in $m_2$	0.0983	$X_2 = a_2 m_2$
$a_3$	Fraction of high grade breakage in $m_2$	0.216	$X_3 = a_3 m_2$
$a_4$	Fraction of printed circuit boards in $m_2$	0.0596	$X_4 = a_4 m_2$
$a_5$	Fraction of mixed metals in $m_2$	0.0684	$X_5 = a_5 m_2$
$a_6$	Fraction of wire in $m_2$	0.0265	$X_6 = a_6 m_2$
$a_7$	Fraction of steel in $m_2$	0.443	$X_7 = a_7 m_2$
$a_8$	Fraction of scrap plastic in $m_2$	0.0662	$X_8 = a_8 m_2$
$a_9$	Fraction of waste in $m_2$	0.0214	$X_9 = a_9 a_{10} m_2$
$a_{10}$	Fraction of waste that was nonhazardous	1.00	$X_{10} = a_9 (1 - a_{10}) m_2$

## 5. RESULTS AND DISCUSSION

To assess the sensitivity of the recycler's net costs to the revenues derived from the sale of the various parts and materials, the profits were calculated with each individual revenue at -50%, -25%, +25% and +50% of the level found in San Jose, where the net cost to the recycler was \$0.157/kg. Figure 1 shows the independent sensitivities of the net costs to variations in revenues for six different revenue streams.

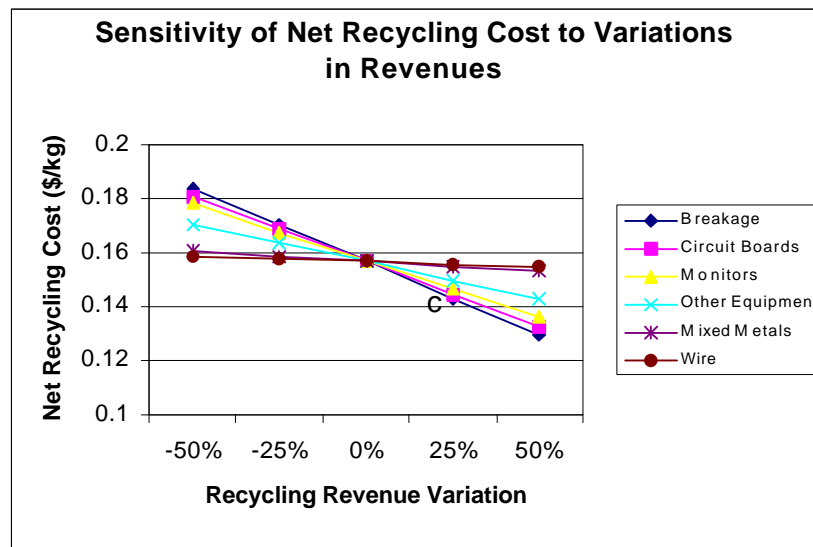


Figure 1. Sensitivity of net recycling costs to specific recycler revenues

The factor that most influences the net recycling costs is the revenue derived from high-grade breakage ( $R_3$ ). When the value of high-grade breakage is 50% less than that found in San Jose ( $R_3 = \$0.277/\text{kg}$ ), the net cost to the

recycler is \$0.184/kg. When that value is 50% more than found in San Jose ( $R_3 = \$0.831/\text{kg}$ ), the net cost to the recycler is \$0.130/kg. This broad range is due to the high percentage of high-grade breakage present in the electronic goods collected (21.6%). After steel, which comprised 44.3% of the mass of electronic goods collected and for which the recycler received no revenues, high-grade breakage comprised the greatest proportion of the electronic goods collected. The factor that least influences the net recycling costs is the revenue derived from the sale of wire ( $R_6$ ). When the value of the wire is 50% less than that found in San Jose ( $R_6 = \$0.155/\text{kg}$ ), the net cost to the recycler is \$0.159/kg. When that value is 50% more than found in San Jose ( $R_6 = \$0.466/\text{kg}$ ), the net cost to the recycler is \$0.155/kg. The amount of wire recovered from the electronic goods was very small, only 2.65%, correspondingly, the effect on the total net costs of variations in the wire revenues has little effect on the total net cost.

Figure 2 shows the independent sensitivities of the recycler to variations in five process costs to recycle the collected electronics. The cost to sort ( $C_2$ ) and the cost to disassemble ( $C_3$ ) show the greatest influence on the net recycling costs. When the cost to sort is 50% less than that found in San Jose, the net cost to the recycler is \$0.0869/kg and when the cost is 50% greater than found in San Jose, the net cost to the recycler is \$0.227/kg. When the cost to disassemble is 50% less than that found in San Jose, the net cost to the recycler is \$0.0926/kg, and when the cost is 50% greater, the net cost to the recycler is \$0.221/kg. Sorting and disassembling had the most influence on the net recycling cost because each involved a significant proportion of the collected monitors and equipment. Though transportation costs were incurred for the entire mass of items collected, compared to the cost per kilogram incurred to sort ( $C_2 = \$0.140/\text{kg}$ ) and dismantle ( $C_2 = \$0.315/\text{kg}$ ), transportation costs were relatively small ( $C_1 = \$0.0172/\text{kg}$ ). As a result, transportation costs had little effect on the net recycling costs. The factor that least influenced the net recycling costs is the cost to dispose of nonhazardous wastes. The small amount of nonhazardous waste disposed of in San Jose, means that when the cost to dispose of nonhazardous wastes varies, the net cost to the recycler is virtually unchanged at \$0.157/kg.

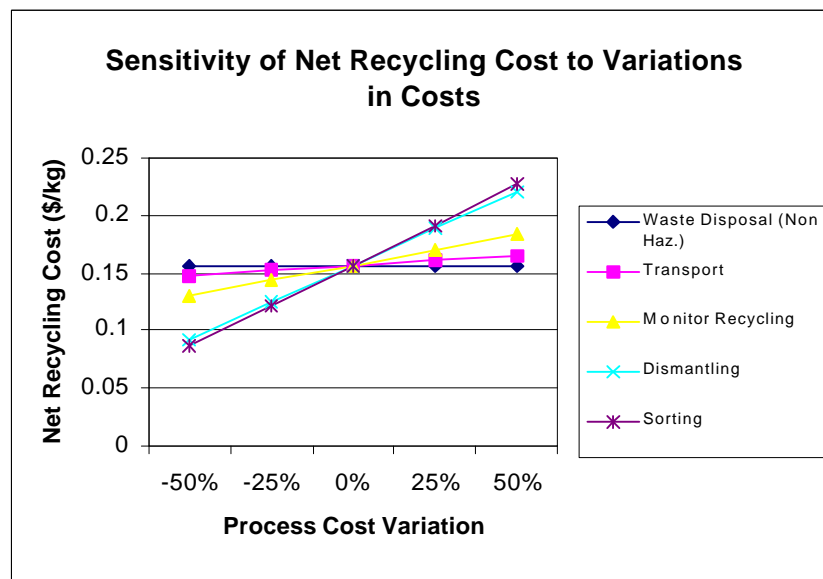


Figure 2. Sensitivity of net recycling costs to specific recycler costs

The effect of the composition of equipment collected on the net recycling costs is shown in Figure 3. Using the masses of monitors ( $m_1$ ) and other electronic goods ( $m_2$ ) collected in the San Jose study as the baseline, each mass was varied individually from 50% less than was found in San Jose, to 50% more than was found in San Jose. When the mass of monitors collected was 50% less ( $m_1 = 7644 \text{ kg}$ ,  $m_2 = 12678 \text{ kg}$ ), the net recycling cost was \$0.149/kg. When the mass of monitors collected was 50% more ( $m_1 = 22932 \text{ kg}$ ,  $m_2 = 12678 \text{ kg}$ ), the net recycling cost increased by 8.72% to \$0.162/kg. When the relative mass of monitors to process increased, the net recycling cost increased as the recycler was not able to capture the revenues derived from the other electronic goods. The recycler

derives significant funds from the sale of parts, high-grade breakage and scrap PCBs, and when the relative amount of these items declines, the total net recycling cost increases.

When the mass of other electronic goods collected was increased relative to the mass of monitors collected, the net recycling cost declined. When the mass of other electronic goods was 50% less than found in San Jose ( $m_1 = 15288$  kg,  $m_2 = 6339$  kg), the net recycling cost was \$0.165/kg. When the mass of other electronic goods was 50% more ( $m_1 = 15288$  kg,  $m_2 = 19018$  kg), the net recycling cost declined by 7.88% to \$0.152/kg. With relatively higher proportion of sellable parts, high grade breakage and scrap PCBs when the mass of electronic goods increases, the recycler is able to generate more revenues. With reductions in the mass of monitors among the PCs collected, which have high attendant disposal costs, the recycler can increase profits. The mix of monitors and other electronic equipment collected does effect the net recycling costs, however, when each was varied independently by 50%, the net cost varied over a small range of \$0.149/kg to \$0.165/kg. If producer or legislative measures encouraged the return of one type of equipment over the other (i.e., by prohibiting garbage truck pickup of monitors, but not other electronics) the net costs incurred by PC recyclers will not be significantly affected.

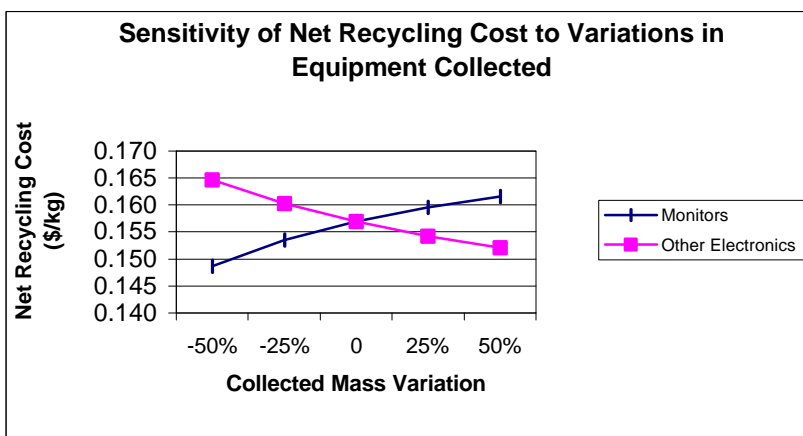


Figure 3. Sensitivity of net recycling costs to independent changes in the masses of monitors or of other electronics collected

When PCs are fully disassembled and sorted, the revenues associated from the sale of high-grade breakage and PCBs, and the costs associated with sorting and dismantling the electronics collected most influence the net recycling costs. However, revenues from wire and mixed metal sales and the costs associated with waste disposal, least influence the net recycling costs as these materials represent only a small portion of the total. By being sensitive to the factors which most affect the net cost to recycle, PC manufacturers may design new products that emphasize materials and components that generate the most revenues for the recycler, or that require fewer resources to dismantle.

At present, hazardous materials may be landfilled in the US for approximately \$0.20/kg. As seen in Figure 1, when the six revenues were varied independently, the net cost to recycle was lower than the cost to dispose of the scrap as hazardous waste in each of the cases examined in the model. Figure 2 shows that when the costs were varied independently, the net cost to recycle exceeded the cost to landfill only when the costs to sort and dismantle increased substantially. Variations in the type of electronics collected (Figure 3) did not result in net recycling costs that exceeded the cost to dispose of the electronics as hazardous waste. As a result, if recycling is to be encouraged on the basis of cost avoidance, particular attention must be paid to the labor costs associated with the sorting and dismantling of the EOL PCs. Modularization of the components in a PC may serve to control disassembly costs, likewise the easy identification and sorting of materials.

## 6. CONCLUSIONS

Recycling PCs is not profitable at present as demonstrated by the net recycling costs incurred in all scenarios. However, under most conditions, the net cost to recycle is less than the cost to dispose of the PCs if they are classified as hazardous wastes. The net costs incurred by the recycler are most sensitive to the revenues derived from high-grade breakage and to the costs associated with sorting the incoming electronics and dismantling the equipment not sold.

The mass of monitors also effects the recycler profitability as monitors are costly to dispose of, and these costs may come at the expense of the revenues derived from the parts and materials found in other electronic goods. The leaded glass present in the monitors makes the cost effective processing or disposal of monitors very difficult, despite the existence of useful means to reuse the materials.

The lack of profitability implies that there is no direct economic incentive to recycle. As a result, to insure that PCs are not disposed of improperly, either the state, the final owners or the PC manufacturers will have to play a significant role in the ultimate processing of PCs. Some states and communities are establishing guidelines governing the disposal and recycling of PCs. These initiatives will force the final owners to take greater responsibility and possibly incur costs to insure that these laws are met. It is hoped that the availability of old PCs, and the maturation of the recycling system that will process the used equipment, will create new markets for parts and materials to generate greater revenues. Furthermore, as these recycling systems mature, processing costs may decline, thereby rendering the recycling of PCs less burdensome. Until the recycling of PCs becomes profitable, however, the government will have to take an active role to insure that electronic equipment does not get disposed of improperly.

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