Environmental Issues in the Electronics Industry

A young and highly competitive industry for which technical performance rules, and environmental concerns have not yet been a priority.
Environmental Impacts of Computer Use

**DIRECT**

Environmental impacts in manufacturing
- energy consumption, many chemicals
- workers’ exposure
- upstream impacts of making chemicals

Energy consumption during use

Environmental impacts at disposal
- difficult disassembly, hazardous materials

**INDIRECT**

Health effects on users
- damage to wrists, eyes, spinal column
- lack of physical exercise – obesity
- addiction to computer games – poor tests scores

Impacts on industrial activities

Impact on consumer purchases
- manner of purchasing, not quantity

So-called “3rd-order effect”, rebound effect
- transportation of goods
- land use (“de-malling”), cell-phone towers
- consumption patterns, paper consumption

Chief issues concerning microchips, printed circuit boards and computers:

1. During manufacturing:
   - Use of many nasty chemicals
   - Human exposure

2. During use:
   - Energy consumption to power the devices

3. End of life:
   - Proliferation of electronics in waste stream
   - Complex disassembly
   - Dumping in poor countries
   - Toxics
National need (they said!) to be globally competitive in the face of a rapidly changing technology.

No wonder, we got this!

The highest concentration of superfund sites is in Silicon Valley.

[6] California’s Silicon Valley has more Federal Superfund sites than any other area of its size in the nation, plus many other toxic sites that are being monitored by state and regional agencies.

1. Impact during manufacturing

For its fabrication, a 2-gram microchip necessitates

1600 grams of petroleum,
72 grams of chemicals,
32,000 grams of water,
700 grams of elemental gases.
Preparation of the silicon wafer

- Ingot growth
to make crystal
doping, hi-temperature furnace

- Ingot blasting & cleaning
to remove oxides and surface contaminants
calcined alumina, silicon carbide, alcohol rinse

- Wafer slicing
to cut thin wafers
diamond saw, coolants

- Wafer washing
cleaning step
soap solution (NaOH), H₂O₂, H₂SO₄, alcohol

- Wafer lapping, etching & polishing
to provide a very smooth surface
acids (hydrofluoric, nitric, acetic)
sodium hydroxide (NaOH)
colloidal silica

- Silicon epitaxy
to make a protective film
chemical vapor deposition with intermediate rinses

FIGURE 1. Production chain for semiconductor devices.

The engraving of a microchip, layer by layer

1. Deposition of functional layer
2. Deposition of photosresist (polymer) (~0.6 μm thick) + baking
3. Exposure to UV light through optical mask, selective breaking of polymer
4. Removal of affected photosresist with a solvent (TCA, TMAH, other)
5. Etching of functional layer through holes in photosresist. Use of strong acids
6. Stripping of remaining photosresist (with acetone or stronger)

... and this is only one layer among very many!

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**TABLE 1.** Firm Data on Chemical Inputs to Semiconductor Fabrication per Square Centimeter of Input Wafer (g/cm²)

<table>
<thead>
<tr>
<th>category</th>
<th>substance</th>
<th>input per wafer area (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>elemental gas</td>
<td>H₂</td>
<td>1.3E-01</td>
</tr>
<tr>
<td></td>
<td>N₂</td>
<td>4.4E-02</td>
</tr>
<tr>
<td></td>
<td>O₂</td>
<td>3.0E-09</td>
</tr>
<tr>
<td></td>
<td>Ar</td>
<td>1.3E-09</td>
</tr>
<tr>
<td></td>
<td>H₂</td>
<td>4.6E-02</td>
</tr>
<tr>
<td>acidic gases</td>
<td>sulfuric acid (98%)</td>
<td>7.8E-03</td>
</tr>
<tr>
<td></td>
<td>phosphoric acid</td>
<td>1.3E-05</td>
</tr>
<tr>
<td></td>
<td>hydrochloric acid</td>
<td>4.3E-06</td>
</tr>
<tr>
<td></td>
<td>hydrobromic acid</td>
<td>4.3E-06</td>
</tr>
<tr>
<td></td>
<td>ruthenium</td>
<td>1.4E-03</td>
</tr>
<tr>
<td>resistants</td>
<td>dichlorosilane (DHSiCl₂)</td>
<td>9.3E-03</td>
</tr>
</tbody>
</table>

**category** | substance | input per wafer area (g/cm²) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>acids/alkalis</td>
<td>HF 1 vol % + NH₄OH 30 vol % mixture</td>
<td>2.85E-03</td>
</tr>
<tr>
<td></td>
<td>phosphoric acid</td>
<td>2.4E-03</td>
</tr>
<tr>
<td></td>
<td>hydrobromic acid</td>
<td>2.4E-03</td>
</tr>
<tr>
<td></td>
<td>hydrochloric acid</td>
<td>4.5E-04</td>
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<tr>
<td></td>
<td>sulfuric acid 98%</td>
<td>7.8E-03</td>
</tr>
<tr>
<td></td>
<td>hydrobromic acid 30%</td>
<td>2.5E-03</td>
</tr>
<tr>
<td></td>
<td>ammonia 28%</td>
<td>7.7E-04</td>
</tr>
<tr>
<td></td>
<td>silane</td>
<td>2.8E-04</td>
</tr>
<tr>
<td></td>
<td>HCℓ 30%</td>
<td>3.0E-04</td>
</tr>
<tr>
<td></td>
<td>NaOH 50%</td>
<td>8.5E-04</td>
</tr>
<tr>
<td></td>
<td>silicon dioxide</td>
<td>6.3E-04</td>
</tr>
</tbody>
</table>

**TABLE 2.** Aggregate Chemical Use/Emissions for Wafer Fabrication (10− 16)

After a very large number of layers, one gets something like this

![Intel Pentium processor](http://www.optics.rochester.edu/workgroups/cml/opt307/spr06/alex/index.htm)

By 2004, Intel processor chips had more than 100 million transistors per chip.

Several hundred microchips are engraved simultaneously on the same wafer, which is then snapped into little rectangular fragments, one chip on each.

![Wafer and chip](http://www.electronetwork.org/education/ico/)
![Wafer and chip](http://www.slicefsiliconvalley.com/story.html)
Terminals are then added, and each chip is packaged under a protective cover.

(Figure showing the process of chip packaging)


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**FIGURE 2. Summary input/output table for wafer fabrication**
Amounts of energy and chemicals used in the production of a memory chip

**ENERGY CONSUMPTION**

**in production and use of a 32MB DRAM chip**

Fabrication of the chip:
- 5.8 MJ in production of silicon wafer
- 2.3 MJ in production of etching chemicals
- 27.0 MJ in fabrication of chip
- 5.8 MJ in assembly process
- 0.17 MJ in production of assembly materials
TOTAL for fabrication: 41 MJ per chip manufactured

Use of the chip:
- 15 MJ electrical consumption during lifetime

TOTAL for both fabrication and use: 56 MJ per chip

Breakdown of energy consumption during manufacture per type of activity:
- 46% clean-room ventilation and air conditioning
- 35% wafer and chip actual fabrication
- 7% making liquid nitrogen
- 7% manufacturing assortment of chemicals
- 5% water purification
- 5% miscellaneous

100%
What can be done to clean the chip manufacturing process?

- **Avoidance**
- **Reduction**
- **Re-use**
- **Recycling**
- **Burning**
- **Treatment**
- **Disposal**

**Strategy for TCA and CFCs and for lead solder**

**Chemicals harder to eliminate, incl. TCA in certain applications**

**Capture of solvents**

- Clean-room ventilation
- Water purification

**Packaged chips now placed on circuit boards**

[Image: Packaged chips now placed on circuit boards](http://www.deskpicture.com/DPs/Technology/CircuitBoard_3.html)

[Image: Packaged chips now placed on circuit boards](http://www.electronetwork.org/education/iz/)
Besides a few additional components (resistors and capacitors), the circuit board includes a base, some wiring, gold plating on leads, and lead-tin solder.

By far, the dirtiest step is soldering, with a mix of lead and tin. This alloy is particularly advantageous because it melts in the range of 183°C (361°F).

Steps in applying solder:

1. Application of a “flux” (resin-based material) to provide adequate adhesion
2. Soldering proper
   use of lead-tin alloy; still no economically safer alternative
3. Removal of extra flux with solvent
   used to be TCE, then CFCs or TCA, now something less harmful
The European directives on Waste of Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances (RoHS) strongly suggest that lead-free electronic assemblies will be mandatory in Europe starting in the next few years.

An adequate substitute for lead solder must be:
- melting a low temperature
- electrically conductive
- safe for workers
- not toxic
- economically feasible
- hopefully recyclable, too.

There is no viable alternative at this time, but several potential candidates are:
- 95.5% tin, 3.9% silver, and 0.6% copper;
- 57.0% bismuth, 42.0% tin, and 1.0% silver;
- 96.0% tin, 2.5% silver, 1.0% bismuth, and 0.5% copper; and
- 99.2% tin and 0.8% copper;
- Electrically conductive adhesives (polymers containing tiny metallic flakes) are seen as another possibility.

Lead-free soldering – The search is on.
2. Impacts during use

![Bar chart showing energy consumption in production and use of a 32MB DRAM chip.]

**FIGURE 3.** Energy consumption in production and use of a 32MB DRAM chip.

In the United States, there are over 800 computers per 1000 people, and there are over 900 computers per 1000 employees in office buildings.

We are well on our way to one computer per person in the nation.

It could even go above one as people may own more than one computer.

It is estimated (2007) that electricity consumption for the internet alone amounts to 9.4% of the total electricity consumption in the USA or 868 billion kWh per year.

April 2011 estimate: 2% of global energy demand, growing about 12% a year.
EPA’s Energy Star program

Computers
An ENERGY STAR qualified computer uses 70% less electricity than computers without enabled power management features.

Earning the ENERGY STAR
- If left inactive, ENERGY STAR qualified computers enter a low-power mode and use 16 watts or less. New cup technologies make power management features more reliable, dependable, and user-friendly than ever just a few years ago.
- Spending a large portion of time in low-power mode not only saves energy, but helps equipment run cooler and last longer.
- Businesses that use ENERGY STAR enabled office equipment may realize additional savings on air conditioning and maintenance.
- Over its lifetime, ENERGY STAR qualified equipment in a single home office (e.g., computer, monitor, printer, and fax) can save enough electricity to light an entire home for more than 4 years.
- The ENERGY STAR specification for computers, game consoles, and other hardware was revised on October 20, 2006 and is effective starting July 20, 2007. More about the specification.

8 Ways to Easily Reduce the Energy Consumption of Your Computer – and Save Big Money
(http://www.thesimpledollar.com/2008/04/16/8-ways-to-easily-reduce-the-energy-consumption-of-your-computer-and-save-big-money/)

1. Plug all equipment into a SmartStrip.
2. Set up Windows so that it automatically shuts down every night.
3. Tinker with your computer’s energy settings.
4. Use an efficient uninterruptible power supply, especially for computers you don’t turn off.
5. Remove all unnecessary peripherals from home servers.
6. Put your laptop charger (and other chargers) on a timer.
7. “Green” your equipment when you replace it – go for EnergyStar 4.0 compliant.
8. Adjust your monitor’s brightness.
ENVIRONMENTAL IMPACTS OF COMPUTER USE:

Direct versus Indirect:

Direct:

- Energy consumption
- CDs, paper, etc.

Indirect:

- Health effects on user
  - Damage to wrists, eyes, spinal column
  - Lack of physical exercise
- Impact on industrial activities, business activities
- Impact on consumer purchases (manner, not quantity)

*3rd-order effect*, so-called rebound effects

- Shifts in consumption patterns, transportation, land use, etc.

Some indirect effects of computer usage are beneficial.

- Computer simulations → Forecasts (ex. hurricane, flooding) → prevention → saving lives and protecting the environment
- Quicker reactions and better organization following environmental accidents → reduced environmental damage
- Spreading news on web sites and blogs → increased environmental awareness
- Computer-aided design (CAD) → reduced need for prototypes → less material + possibility to add LCA and demanufacture design
- Digital photography → avoidance of photochemicals
- Computers in health care → computer-aided surgery → digital X-ray pictures (avoidance of chemicals)

It is very possible (but impossible to tell for sure) that more environmental gain can be achieved by using computers toward green activities than by improving computers themselves. This is because computers play such a major role in our lives.
3. Recycling of computer equipment

Where does this all go? What happens to it at its destination? What is the impact on people and the environment there?

And, it is getting increasingly more acute because:

- More people own computers (since invention of personal computers in the mid 1980s) and an increasing number of people now have more than one computer (since the advent of laptops).

- The lifetime of a computer is getting increasingly shorter:
  
  10 years in the 1960s
  4.3 years by 1998
  less than 2 years by 2000.

"Between 1997 and 2007, nearly 500 million personal computers became obsolete. Almost two computers for each person in the U.S. Some studies predict that a large number of televisions will be disposed when high definition television becomes widely available. (Source: National Recycling Coalition)."

"Nearly two million tons of used electronics, including computers and televisions, are discarded each year. In addition, an estimated 128 million cell phones are retired from use annually. " (Source: EPA)

The rate at which computers are being disposed of is skyrocketing.
Innovative approaches to computer recycling!
But mere cascading and very limited outlets…

Any forethought?

It is one thing to design a performing system and to make computers and personal electronics available to nearly all people.

But, how does it affect electronics recycling?

It does not seem that anyone plans for recycling at the time of acquiring computer equipment.

But, some early efforts are being made at the level of manufacturing.
In the early days of computing, the problem was virtually inexistent. Obsolete computers were simply stashed under the staircase. But, constant upgrading of computers did not make that last long…

Maine is first state to require computer and television manufacturers to pay for recycling and disposal.

Already more than 60 million computers in landfills!

Up to 80% is exported to places such as Nigeria and China.

Videos online (among many others)

Computer Recycling - Intercon Solutions

http://www.youtube.com/watch?v=4n0wOnLNXwc

Recycling of defective wafers at IBM, Burlington (Vermont, USA):

http://www.youtube.com/watch?v=ooMmwSqr9XY
Are we still operating with the slogan “out of sight out of mind”?

Shipment to and dumping in poor countries violates the 1989 Basel Convention on hazardous waste (which came into force in 1992).

Steps and issues in computer recycling

- Collection
  Some is still kept under staircases, in closets and attics.
  Some people still throw computers in the trash.
- Transportation to collection center, sorting
- Preliminary disassembly, destruction of hard-disk data
- Capture and recycling of precious metals (gold and silver)
- Shipment to another place (where labor is cheap) for further disassembly or shredding
- Recycling/resale or disposal of separated materials.
A case study

The intuitive answer is the correct one: Recycling is the best option. That is, from an environmental point of view. What about the economic point of view?
Situation in the European Union

Considerations range the gamut of environmental, social, economic & cultural dimensions.

ENVIRONMENTAL:
  Running out of landfill space.
  Pollution and “green issues” get press.

SOCIAL:
  People, or at least governments, want to be proactive.

ECONOMIC:
  High taxation enables more draconian action.

CULTURAL:
  Who pays for human health problems and environmental impacts?

Packaging
  1994 Directive (paper, plastics and metals)

Automotive
  End of Life Vehicles (ELV, 2000, 2003)
  Ban on lead, mercury, cadmium, and hexavalent chromium

Batteries

Electronics
  - Waste Electrical and Electronic Equipment (WEEE, 2003)
  Objectives: Prevention, reuse, recycling and recovery of WEEE
  At its core: WEEE directive sets a minimum recycling rate.
  - Restriction of Hazardous Substances in Electrical and
    Electronic Equipment (RoHS, 2003)
  Objective: Assist recycling efforts set forth by WEEE
  At its core: RoHS sets out maximum enforceable requirements
  (expressed as max % of substance per “homogeneous material”).

Same substance bans as for automobile industry, except that lead is still tolerated for electrical soldering.
Positive side effect of European legislation

American, Japanese and Chinese manufacturers cannot afford to overlook the European market. They therefore need to comply. This makes their products more benign and easier to recycle, not only in Europe but also across the world.

Situation in the United States

Among several other activities, there exists the National Center for Electronics Recycling (NCER)

The NCER has created an electronics recycling index, known as the Per-Capita Collection Index (PCCI) designed to measure changes in the amount of used electronic equipment, such as computers, televisions and monitors collected in representative programs across the United States.

$PCCI = \frac{P_1 + P_2 + P_3 + P_4 + P_5 + P_6}{6}$

$P_1$ through $P_6$ are the pounds per capita values of the six collection programs noted below. The index is stated in lbs collected per capita and is re-calculated every year.

<table>
<thead>
<tr>
<th>Program</th>
<th>Collection Total</th>
<th>Population Served</th>
<th>Lbs Per Capita 2009</th>
<th>Lbs Per Capita 2008</th>
<th>Lbs Per Capita 2007</th>
<th>Lbs Per Capita 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>182,064.676</td>
<td>36,901,964</td>
<td>4.6</td>
<td>4.4</td>
<td>5.2</td>
<td>3.5</td>
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<tr>
<td>Maine</td>
<td>7,912.232</td>
<td>1,318,000</td>
<td>6.0</td>
<td>4.0</td>
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<td>California</td>
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<td>Marianas</td>
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<td>Hartford, CT</td>
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<td>4.9</td>
<td>4.5</td>
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</table>

The CCPI collection index has increased 32% in 3 years
Company by company

Most major computer companies run their own national mailback programs. Usually for a fee, but sometimes free, these companies will send you a pre-paid mailing label, or let you print the label using their website. You then package your unwanted computer equipment and send them along, or arrange a pickup. Some companies, such as Sony, operate their own take-back programs and will take their own branded products back for free at certain pre-identified locations around the country.

Below is a list of consumer take-back programs:

HP: Mail-back program with home_office pickup for $13-34 depending on the type and quantity of hardware to be returned. Any HP or non-HP brands of personal/office computer equipment or peripherals are accepted. This program does not accept monitors with broken glass or other types of consumer electronic equipment such as VCRs, DVDs, televisions.

IBM: As part of its product end-of-life management (PELM) activities, IBM began offering product take-back programs in Europe in 1989 and has extended and enhanced them over the years. IBM’s Global Asset Recovery Services organization now offers Asset Recovery Solutions to commercial customers in 21 countries worldwide, and continues its efforts to extend them further.

Also, the IBM PC Recycling Service allows consumers and businesses to recycle any manufacturer’s PCs, including system units, monitors, printers and optional attachments for $30, shipping included.

Intel: Intel offers a mail-back program for any Intel branded product sold to individual consumers, such as Intel boxed processors, Intel boxed motherboards and Intel brand network cards. Historical items such as Intel brand PC cameras, Intel brand PC microscopes, Intel brand keyboards, etc. are also appropriate for recycling. Packaging and shipping are the responsibility of the individual.

Apple: US customers who buy a new Mac through the Apple Store or Apple’s retail stores receive free shipping and environmentally friendly disposal of their old computer.

Dell: Dell offers free PC recycling at any time for Dell-brand products. Dell also offers free recycling when purchasing a new Dell product. Packaging and shipping are the responsibility of the individual.

Canon: Canon offers a mail-back program that accepts CANON brand of consumer binoculars, camcorders, cameras (digital & film), fax machines, ImageCLASS products, PC copiers, printers, projectors or other video equipment, and scanners.

Epson: Epson offers a mail-back program that accepts EPSON printer, scanner, digital camera, laptop, computer or projector. The fee for this service is only $10 per item which includes shipping and recycling costs. Users of the service also receive a $5 coupon per item returned, for use at the Epson Store.

Sony: The Sony Take-Back Program gives Sony customers a free and convenient way to recycle up to five Sony products per day by dropping them off at designated Waste Management eCycling Drop-Off Centers throughout the country.

Gateway: Gateway offers a trade-in program and a recycling program available to customers who have made a recent Gateway purchase. In order to verify your eligibility, you need to provide a valid serial number and proof of purchase of your new Gateway or eMachines product. The cost of the recycling program is a function of weight.

Toshiba: Toshiba offers a trade-in program.

Lexmark: Lexmark offers a mail back program called the Lexmark Equipment Collection Program. Through this program, customers may return any end-of-life Lexmark branded products (inkjet and laser printers, all-in-one products and multifunction products), and Lexmark will recycle the equipment for free.

Creative Recycling Systems introduces revolutionary electronics recycling system

CRS has introduced a new state-of-the-art electronics recycling system at the company’s headquarters in Tampa, Fla. The revolutionary structure allows for the recycling of electronic components in a single computerized process. In addition to computer monitors and TV’s, the system will economically process CPU’s, consumer electronics, office equipment, telecommunications equipment and the whole range of E-Scrap without any need to pre-sort.

Acquired by Creative Recycling to meet the growing demands of the electronics recycling business, the innovative system dissects up to 24,000 pounds of recyclables per hour – the equivalent of 800 monitors – in an extremely worker-friendly and environmentally safe manner. It takes less than five minutes for a single item to complete the recycling process.

The system integrates components from leading manufacturers of shredding, pulverizing and separation equipment. Maximum output is achieved through video monitors, scales and computerized logic controllers. Pulverizing takes place in a controlled atmosphere enclosure with negative air pressure. A complete dust collection and control system attached to a high efficiency particulate air (HEPA) filter ensure a pristine atmosphere.

System outputs include glass, plastics, ferrous and non-ferrous metals. This equipment is part of a multi-million dollar investment the company has made in expanding its capacity. It further distinguishes CRS as an industry leader in electronics recycling with the most cost-effective and best environmental solution.