Environmental Issues in the Electronics Industry

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

### Direct versus Indirect

**DIRECT**
- Environmental impacts in manufacturing
  - energy consumption, many chemicals
  - workers' exposure
  - upstream impacts of making chemicals
- Electricity consumption during use
- Environmental impacts at disposal
  - difficult disassembly, hazardous materials, valuable rare materials

**INDIRECT**
- Health effects on users
  - damage to wrists, eyes, spinal column
  - lack of physical exercise → obesity
  - addiction to computer games → poor tests scores
- Paper consumption
  - Online banking and the like → less paper
  - Personal printers → more paper
- Impacts on industrial activities
  - just-on-time purchasing → less inventory → fewer, smaller warehouses
- Impact on consumer purchases
  - manner of purchasing, packaging & transportation
- So-called “3rd-order effects” or rebound effects
  - transportation of goods, land use (“de-malling”), cell-phone towers
- Consumption patterns

### 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
In the 1980s, national need (they said!) to be globally competitive in the face of a rapidly changing technology led the regulators to turn a blind eye to ground pollution.

No wonder, we got this! The highest concentration of superfund sites is in Silicon Valley.

[1] 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
The engraving of a microchip, layer by layer

1. Deposition of functional layer
2. Deposition of photoresist (polymer) (~0.6 µm thick) + baking
3. Exposure to UV light through optical mask, selective breaking of polymer
4. Removal of affected photoresist with a solvent (TCA, TMAH, other)
5. Etching of functional layer through holes in photoresist; Use of strong acids
6. Stripping of remaining photoresist (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 (106)**

<table>
<thead>
<tr>
<th>category</th>
<th>substance</th>
<th>input per wafer area (g/cm²)</th>
<th>category</th>
<th>substance</th>
<th>input per wafer area (g/cm²)</th>
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</thead>
<tbody>
<tr>
<td>elemental gas</td>
<td>H₂</td>
<td>1.36 x 10⁻¹</td>
<td>acid/bases</td>
<td>HF 1 M + NH₄OH 30% vol mixture</td>
<td>2.84 x 10⁻¹</td>
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<tr>
<td></td>
<td>O₂</td>
<td>1.36 x 10⁻²</td>
<td></td>
<td>phosphoric acid  H₃PO₄ 85%</td>
<td>2.14 x 10⁻³</td>
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<tr>
<td></td>
<td>Ar</td>
<td>1.36 x 10⁻⁹</td>
<td></td>
<td>hydrofluoric acid  HF 5%</td>
<td>3.42 x 10⁻³</td>
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<tr>
<td></td>
<td>N₂</td>
<td>4.46 x 10⁻²</td>
<td></td>
<td>hydrofluoric acid  HF 30%</td>
<td>4.56 x 10⁻³</td>
</tr>
<tr>
<td>solder gases</td>
<td>Sulfur</td>
<td>4.66 x 10⁻²</td>
<td></td>
<td>sulfuric acid 96%</td>
<td>2.52 x 10⁻³</td>
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<tr>
<td>deposition/etchants</td>
<td>Silane (SiH₄)</td>
<td>7.8 x 10⁻³</td>
<td></td>
<td>hydrofluoric acid  HF 28%</td>
<td>7.82 x 10⁻³</td>
</tr>
<tr>
<td></td>
<td>Arsenic (AsH₃)</td>
<td>4.3 x 10⁻³</td>
<td></td>
<td>fluoro</td>
<td>2.52 x 10⁻³</td>
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<tr>
<td></td>
<td>Boron (B₂H₆)</td>
<td>4.2 x 10⁻⁶</td>
<td></td>
<td>yttrium</td>
<td>7.82 x 10⁻³</td>
</tr>
<tr>
<td></td>
<td>Oxygen (O₂)</td>
<td>1.46 x 10⁻⁶</td>
<td></td>
<td>HCl 30%</td>
<td>2.06 x 10⁻¹</td>
</tr>
<tr>
<td></td>
<td>Hydrogen (H₂)</td>
<td>1.46 x 10⁻⁶</td>
<td></td>
<td>NaOH 50%</td>
<td>6.51 x 10⁻³</td>
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<tr>
<td></td>
<td>Hydrocarbon (CH₄)</td>
<td>4.3 x 10⁻⁶</td>
<td></td>
<td>silicon</td>
<td>6.51 x 10⁻³</td>
</tr>
<tr>
<td></td>
<td>Photolithographic chemicals</td>
<td>4.3 x 10⁻⁶</td>
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<td>aluminum</td>
<td>6.51 x 10⁻³</td>
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<tr>
<td></td>
<td>photolithographic chemicals</td>
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<td></td>
<td>iron</td>
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<td></td>
<td>Isopropyl alcohol</td>
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<td></td>
<td>silicon</td>
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<td>Methyl-2-methacyclonolate</td>
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<td></td>
<td>silicon</td>
<td>6.51 x 10⁻³</td>
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<tr>
<td></td>
<td>3-Mercaptopropanol</td>
<td>4.3 x 10⁻⁶</td>
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<td>silicon</td>
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<td>total chemical input:</td>
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<td>45.2 g/cm²</td>
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</table>

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**TABLE 2. Aggregate Chemical Use/Emissions for Wafer Fabrication (10⁻⁹)**

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

Intel Pentium processor

A dual-core mobile variant of the Intel Core i3/i5/i7 has around 1.75 billion transistors for a die size of 101.83 mm², according to WikiChip.

This works out at a density of 17.185 million transistors per mm².
Several hundred or even thousand microchips are engraved simultaneously on the same wafer, which is then snapped into little rectangular fragments, one chip on each.

Terminals are then added, and each chip is packaged under a protective cover.
FIGURE 2. Summary input/output table for wafer fabrication

Amounts of energy and chemicals used in the production of a memory chip

(www.ce.cmu.edu/~hsm/NATO-ARW/pres/EricWilliams.ppt)
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

(Williams et al., 2002, cited on Slide 6)

What can be done to clean the chip manufacturing process?

Strategy for TCA and CFCs and for lead solder
Chemicals harder to eliminate, incl. TCA in certain applications
Clean-room ventilation
Water purification
Capture of solvents

TCA = Tri-chloro-acetic acid
Packaged chips now placed on circuit boards

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) and has proven hard to beat.
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.
2. Impacts during use

In the United States in 2019, it was estimated (Statista source) that there were 740 desktops or laptops per 1000 people. In office buildings, the number approaches 1 computer per worker.

Counting cell phones, too, it is estimated that there are more than one personal electronic device per person in the United States (not counting small children).

The lion’s share of electricity consumption is not due to personal electronics or computers at the office but due to data centers providing internet and cloud services.

In the US in 2014, data centers consumed 70 billion kilowatt-hours of electricity, the same amount that 6.4 million American homes used that year.

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

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 your computer 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 all this e-waste go? What happens to it at its destination? What is the impact on people and the environment there?

Innovative approaches to computer recycling!

But mere cascading and very limited outlets…
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.

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 electronic device (since the advent of smart phones and laptops).

- The lifetime of a computer is getting increasingly shorter:
  10 years in the 1960s
  4.3 years by 1998
  less than 2 years now.
Videos online (among many others)

Electronics Recycling – Intercon Solutions
ABC Channel 7 report, 2009
https://www.youtube.com/watch?v=Zc5un5Mf4zs

Recycling of e-waste in the UK (2014):
Extraction of metals, including gold
https://www.youtube.com/watch?v=zU62hh3DBfg

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

FIGURE 6.11
Functional analysis of the three PVC monitor housing disposal options by IBM.
(Adapted from Roman and Clehane, 1996)
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?

(slide adapted from Prof. Ron Lasky, Dartmouth)
Situation in the European Union (cont’d)

**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.

Situation in the United States

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

Why Recycle Electronics?
To conserve natural resources.
Useable material can be recovered and reused.
To support the community.
Donating old electronics supports schools, low-income families, and non-profits by providing needed electronics.
To create local jobs.
As demand for electronics recycling increases, new businesses will form and existing companies will grow.
To protect public health and the environment.
Most electronics contain hazardous materials that should not be disposed of in landfills.

How Are Electronics Recycled?
- There are currently two dominant approaches to recycling used electronics: disassembly (or manual dismantling) and shredding.
- **Disassembly**
  Reassembling laptops manually dismantling the electronics in order to make the in exploitable materials products that are hard. To disassembling
Best of class, in Belgium

A MAJOR INVESTMENT TACKLES A GLOBAL CHALLENGE

Recycling metals
The world is seeing a strong demand for metals as many become scarce. Recycling and recovery will