Informing Design for Environment (DfE) in Semiconductor Manufacturing

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Content

- 1. LCA Context, Overview and Challenges
- 2. Overall, first-order semiconductor LCA results using Economic Input Output Methods
- 3. The Environmental Value Systems (EnV-S) Analysis
- 4. Connecting the EnV-S to LCA analyses: preliminary results
1. Context and Overview

from raw materials extraction to manufacture, use and end of life

Raw materials ➔ Manufacturing ➔ Use ➔ End of life

Design: Ability to effect environmental improvements/changes - Greatest leverage is during product design and development

Environmental and health issues concerns arise at each stage

Human health impacts ➔ Environmental impacts
Contextual background

• LCA as a support tool
• Strategies - inventory, impact, score
• Strategies - cradle to grave
Typical Methodologies for Implementation

- ‘Typical’ LCA Approach/SETAC
- Streamlined Approaches
- Economic Input Output
- Hybrid?

Pre-Analysis
- Why LCA?
- Kinds of results
- Scope
- Functional unit
- Fair comparison

Inventory Analysis
- Data sources and supplements
- Completeness - Cradle to grave?
- Scope and boundary

Impact Analysis
- Several Methods
- CML/SETAC

Classification
- Metrics scores
- Modeling intensive
- Damage functions?
- Weighting functions

Normalization
- Baseline effects
- Eco-indicator for Europe

Evaluation
- Weighting factors for one ‘score’
- Ecopoints?

An ‘accurate’ LCA approach
- Entire product life cycle
- Quantitative inventory
- Cost and time intensive
- Data gaps
- Uncertainties
Typical Methodologies for Implementation

- **Streamlined LCA (SLCA) - Gradel**
  - Simplified approach
  - Cost and time improvements
  - Similar results to full analysis?
  - Unexpected results unseen

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Life cycle stage</th>
<th>Raw materials</th>
<th>Manufacturing</th>
<th>Use</th>
<th>Disposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air pollution</td>
<td></td>
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<tr>
<td>Energy use</td>
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<tr>
<td>Water use</td>
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<td>Hazardous waste</td>
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<td>Toxic</td>
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<tr>
<td>EHS costs</td>
<td></td>
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</tr>
</tbody>
</table>

- **Economic Input Output - Green Design Initiative**
  - Sectoral approach
  - Circumvent data issues
  - Economic ripple effect
  - Cost and time improvements
  - Approximate nature
  - Temporally fixed on data
  - $1 million of asbestos related products

- **Hybrid Approaches**
  - Combine strengths of various approaches
  - Theoretically effective
  - Practical/implementation issues?
  - Case - specific application


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Commercial Software

- Product Based
  - Gabi (Stuttgart)
  - Simapro (Pré consultants)
  - Umberto (ifu Hamburg)
  - Others (LCAit, KCL, Sylvatica)

  • Tools use multiple databases/sources
  • Ease of use
  • Different valuation approaches
  • Databases are site/region specific
  • Databases are hidden - transparency issues
  • Valuation issues - site specific and hidden

Sankey diagram - Gabi
• Process focus
  – Idemat (TU Delft)

• Process focus - unusual
• Still, data driven

– Environmental Value Systems (EnV-S) Analysis (Berkeley)

• Process focus
• Model based
• More information on model-based approaches later
Challenges

1. Functional unit
   - Important for a fair comparison

2. Temporal scale
   - Analysis is static
   - Time lags cannot be understood

3. Spatial scale
   - Analysis of local Vs. global effects
   - Different at different stages of the inventory

Case Example (Semiconductors)

- Perfluorocarbon (PFC) Abatement
  - Comparison based on mass flow
  - Comparison based on wafer pass - 200, 300mm

- Copper in semiconductors
  - Idle flow, continuous flow (specification from the tool)
  - Copper discharge limits (bath dumps)
  - Need average analysis and peak analysis
  - Bay area - 2lb/day Cu discharge regulation, ~2ppm Cu concentration regulation

- Health factors Vs. Environmental factors

Health Hazard scoring

Challenges (contd.)

- **Boundary problem**
  - circumvented in Economic Input Output type analyses and streamlined analyses

- **Cost and time**
  - Variable and hard to judge
  - circumvented in Economic Input Output type analyses
  - Top down Vs. bottom up view of semiconductor manufacturing?

- **Data availability**
  - Gaps
  - Multiple, non-compatible sources
  - Obsolete
  - Monitoring energy consumption at tool
  - Estimating from recipes
  - Averaging from facilities

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Case Example *(Semiconductors)*

Manufacturing phase

- [Diagram of manufacturing process]

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Challenges (contd.)  Case Example (Semiconductors)

- **Product focus**
  - No process focus (ability to impact process)
  - No service focus (needs based analyses)

- **Uncertainty**
  - In methodology, data, impacts
  - Quantitative? Comparative?

- **Valuation**
  - Subjective decision making
  - No ‘correct’ approach
  - Site specific
  - Perhaps no standardization feasible - or sensible, given uncertainties

Inform design and decision making

Variation in Environmental Cost of Ownership

- Present multiple impacts
  - Health
  - Environmental
  - Manufacturing
  - Process
  - Cost
2. Environmental overview of the industry

Semiconductor Impacts relative to US National

Impacts

% of US National

- Liquid Waste
- Hazardous Waste
- GWP
- PFC's
- Water
- Electricity
- Chemicals

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Waste</td>
<td>75 gal/in^2 [1]</td>
</tr>
<tr>
<td>Hazardous Waste</td>
<td>0.1 kg/in^2 [1]</td>
</tr>
<tr>
<td>GWP</td>
<td>2.6 kgCE/in^2 [2, 3, 4]</td>
</tr>
<tr>
<td>PFC's</td>
<td>0.9 kgCE/in^2 [4]</td>
</tr>
<tr>
<td>Toxic Releases</td>
<td>0.01 kg/in^2 [5]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inputs to the Fab</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>30 gal/in^2 [3, 6, 2]</td>
</tr>
<tr>
<td>Electricity</td>
<td>10 KWhr/in^2 [2, 3]</td>
</tr>
<tr>
<td>Chemicals</td>
<td>0.2 kg/in^2 [5]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs from the Fab</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Waste</td>
<td>8.03E+04 billion gallons</td>
</tr>
<tr>
<td>Hazardous Waste</td>
<td>40.0 Million Tons</td>
</tr>
<tr>
<td>GWP</td>
<td>1600.0 MMTCE</td>
</tr>
<tr>
<td>PFC's</td>
<td>37.1 MMTCE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Toxic Releases</th>
<th>Million Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>123735 billion gallons</td>
</tr>
<tr>
<td>Electricity</td>
<td>3652.0 billion KWhr</td>
</tr>
<tr>
<td>Chemicals</td>
<td>8500.0 Million Tons</td>
</tr>
</tbody>
</table>

Impacts per square inch of Si
Life cycle environmental analysis for the semiconductor industry

- Using Economic Input-Output Analysis
1997 Summary of sector life cycle results

<table>
<thead>
<tr>
<th>Sector #570200: Semiconductors and related devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997 Data (Adjusted)</td>
</tr>
<tr>
<td><strong>Size of Industry Output</strong>: 52924 Millions of Dollars</td>
</tr>
<tr>
<td><strong>Output Semiconductors</strong>:</td>
</tr>
<tr>
<td>Liquid Waste: 2.543 Million Tons</td>
</tr>
<tr>
<td>Hazardous Waste: 23.231 MMTCE</td>
</tr>
<tr>
<td>GWP: 0.052 Million Tons</td>
</tr>
<tr>
<td>Toxic Releases: 0.203 Million Tons</td>
</tr>
<tr>
<td>Conventional Pollutants:</td>
</tr>
<tr>
<td>Water: 137.484 billion gallons</td>
</tr>
<tr>
<td>Electricity: 19.556 billion kW-hr</td>
</tr>
<tr>
<td>Chemicals:</td>
</tr>
</tbody>
</table>

1997 Economic Output Comparison of Selected US Industries

1997 Environmental Impact Comparison of Selected US Industries

1997 Environmental Impact Comparison of Selected US Industries (continued)

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1997 impacts normalized to sector output

- Semiconductor sector is high when normalized per $ of output
1997 and 1992 results comparison


3. The Environmental Value Systems (EnV-S) Analysis
Problem Statement & Baseline

• Equipment manufacturers need a tool for the quantitative evaluation and comparison of tool-centric environmental solutions

• EnV-S Model Blueprint
  – Focus the model on the process tool and the support equipment
  – Ensure the model output is in terms of important business metrics such as CoO
  – Factor in all controllable variables that significantly affect the key outputs
  – Provide sensitivity analysis for those controllable variables
  – Enable “what-if” comparisons between various solutions
  – Make the tool suitable for the casual user (i.e., user-friendly)
  – Use industry norms for cost/performance parameters (e.g., UPW costs)
  – Make the tool readily available and, if possible, an industry standard

EnV-S Summary

• The Environmental Value Systems (EnV-S) Analysis
  – Informing Design for Environment (DFE) in semiconductor manufacturing
  – Focus on bottom-up, tool-centric views - develop analysis for platforms
  – Inform design decisions for equipment suppliers

- Stepping stone to complete LCA - Spatial scale and boundary around the facility
- Bottom up as opposed to top down
  • Model as opposed to data based (temporal issues)
  • Data availability issues - better sensitivity analysis
- Valuation metrics
  • Discrete (uncombined)
  • Decisions are subjective and combinations of $ values, health and environmental and process issues
- Support equipment design, process design, new product development
Case study: PFC Abatement Option Space

Options space - Different combinations of abatement and downstream options

Analysis: (Environmental Cost of Ownership (COO))
1. Sensitivity analysis of costs and cost differences
2. Cost of downstream HF treatment as a function of flow and configuration parameters

Design graphs and trade off analysis

- 200mm flows are lower - there is region of operation (0-10c/wafer pass) With many chambers connected to a few absorption systems

Trade off analysis in examining different HF treatment systems
**PFC Abatement Cost Variability**

- Uncertain cost of individual options, but robust selections between options!

**Legend**
- Chamber
- Flow/chamber
- Flow/fab
- Absorption
- Plasma
- House scrubber
- Water Scrubbing
- Catalytic
- Combustion
- Pump

**Cost variation - 200**

**Cost difference 200mm**

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4. Connecting the EnV-S to LCA tools

• The EnV-S can be used as a DfE tool for
  – Semiconductor process and equipment design and selection

• Current work is expanding the analysis to new Semiconductor modules by developing platform-based modules (CMP, etch, deposition, etc.)

• One of the future directions
  – Expand the analysis to look at life cycle effect during the design stage. ie, DFE with a Life cycle focus.
    • This has potentially different users or audiences
    • Different applications within product design cycles

• Two approaches to this hybrid analysis
  – 1. EnV-S + SETAC LCA Methods
  – 2. EnV-S + Economic Input Output Method
  – Preliminary results with the second approach are outlined here
Case Study: the copper CMP process

Summary of parameters for a “typical” copper CMP process

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Primer</th>
<th>21 g/min</th>
<th>0.01 $/wafer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UPW</td>
<td>7514 g/min</td>
<td>0.07 $/wafer</td>
</tr>
<tr>
<td></td>
<td>Slurry</td>
<td>0.13 gal/wafer</td>
<td>3.99 $/wafer</td>
</tr>
<tr>
<td></td>
<td>Other additives</td>
<td>0.08 g/min</td>
<td>0.00 $/wafer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solid</th>
<th>Pad</th>
<th>293 wafers/item</th>
<th>0.75 $/wafer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pad conditioning</td>
<td>167 wafers/item</td>
<td>0.60 $/wafer</td>
</tr>
<tr>
<td></td>
<td>PVA brushes</td>
<td>2333 wafers/item</td>
<td>0.13 $/wafer</td>
</tr>
<tr>
<td></td>
<td>Other consumables</td>
<td>2933 wafers/item</td>
<td>0.26 $/wafer</td>
</tr>
</tbody>
</table>

| Electricity      | 3000 W   | 0.01 $/wafer   |
Preliminary results - life cycle CMP effects

- **Metric tons (MTCE for GWP)**:
  - Hazardous Waste
  - GWP

- **Million gallons**
  - Water

- **Tons**
  - Toxic Releases
  - Conventional Pollutants

- **MKW-hr**
  - Electricity
Summary and future work

- Preliminary life cycle effects using EIOLCA
  - high growth rates
  - high impacts/$
  - Explore applicability of data further
- Develop combination of EnV-S and EIOLCA and other life-cycle approaches
  - Compare results with SETAC-type methods for a few case studies
  - This could offer a quick and easy way
    - to inform DFE for certain environmental issues during early product development phases
    - Or to draft/examine broad policy decisions
Appendix
1992 summary of sector life cycle results

<table>
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<td><strong>1992 Data</strong></td>
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<td><strong>Output Semiconductors</strong></td>
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<tr>
<td>Liquid Waste</td>
</tr>
<tr>
<td>Hazardous Waste</td>
</tr>
<tr>
<td>GWP</td>
</tr>
<tr>
<td>Toxic Releases</td>
</tr>
<tr>
<td>Conventional Pollutants</td>
</tr>
<tr>
<td><strong>Input Semiconductors</strong></td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Electricity</td>
</tr>
</tbody>
</table>

1992 Economic Output Comparison of Selected US Industries

1992 Environmental Impact Comparison of Selected US Industries

1992 Environmental Impact Comparison of Selected US Industries (continued)

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Environmental Trends

- Determining the right solution can be tedious
- Equipment makers need decision-enabling tools
- To be effective, tools must allow trade-off analysis

Typical Design Trade-Offs

- Operation costs?
- ROI?
- Point Of Use or Centralized?
- Capital costs?
- Types of Technology?
- Maintenance costs?
- Byproduct treatments?
- Energy Efficiency?
- Make or buy?
- Modular?
### Summary of System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>200mm</th>
<th>300mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF4 (sccm) flow from process chamber</td>
<td>50</td>
<td>250</td>
</tr>
<tr>
<td>Throughput (wafers/chamber)</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Utilization (%)</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Annual hours of processing</td>
<td>6115</td>
<td>6115</td>
</tr>
<tr>
<td>Pump dilution ratio (nitrogen to gas flow)</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>C equivalent (g/min)</td>
<td>332</td>
<td>1662</td>
</tr>
<tr>
<td>Cequivalent (g / wafer pass)</td>
<td>1330</td>
<td>6648</td>
</tr>
<tr>
<td>C/year for a 5 layer etch (tons). 5000 wpsps</td>
<td>1728</td>
<td>8642</td>
</tr>
<tr>
<td>C from energy use (10KWhr/in^2, SIA Roadmap)</td>
<td>24937</td>
<td>56109</td>
</tr>
<tr>
<td>If unabated and unscrubbed, HF (g/wafer pass)</td>
<td>0.7</td>
<td>3.4</td>
</tr>
<tr>
<td>A difference of 1 c/wafer pass =</td>
<td>2751 $/Etch tool/year</td>
<td></td>
</tr>
</tbody>
</table>
Cost of HF treatment

2 choices were explored
- absorption
- water scrubbing

Absorption system details:
Could configure by
(i) cascading multiple chambers to an absorption system
(ii) Chaining multiple absorption systems together (essentially adjusting absorption capacity)

Plasma PFC Abatement
Modeled based on CF₄ flow rate

Absorption
Catalytic Combustion
Pump

(simplified equations)

\[ CoO_{abs} = \frac{a.(FC + UC)}{c.w} + \frac{CC + DC}{a.w} \]

Where,
\[ CoO_{abs} = \text{Absorption System Cost} \]
\[ a = \text{Number of absorption systems cascaded together} \]
\[ c = \text{Number of chambers connected to the systems} \]
\[ FC = \text{Fixed costs/system/year} \]
\[ UC = \text{Utility costs/system/year} \]
\[ w = \text{Number of wafers processed/year} \]
\[ CC = \text{Consumable costs} \]
\[ DC = \text{Disposal costs} \]
Determining Important Variables

- For the individual units (plasma and catalytic), HF treatment costs are the most important!
- But these disappear in the plasma-catalytic CoO difference. Now catalytic capital cost is the biggest cost factor!