Photovoltaics
Life Cycle Analysis
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and

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www.clca.columbia.edu
www.pv.bnl.gov
The Life Cycle of PV

M, Q: material and energy inputs
E: effluents (air, water, solid)

- Raw Material Acquisition
- Material Processing
- Manufacture
- Use
- Decommissioning
- Treatment Disposal
- Recycling

Photovoltaic modules
Balance of System (BOS) (Inverters, Transformers, Frames, Metal and Concrete Supports)
Sample Metrics of Life-Cycle Performance

- Energy Payback Times (EPBT)
- Greenhouse Gas Emissions (GHG)
- Toxic Gases & Heavy Metal Emissions
- Risk Indicators
Energy Payback Times (EPBT)

2004-2005 Status: Crystal Clear & BNL Studies

![Bar chart showing EPBT for different solar cell types with insolation of 1700 kwh/m2-yr]

- Insolation: 1700 kwh/m2-yr
- Ribbon-Si: 11.5% (EPBT = 1.7 years)
- Multi-Si: 13.2% (EPBT = 2.2 years)
- Mono-Si: 14.0% (EPBT = 2.7 years)
- CdTe: 9% (EPBT = 1.1 years)

Sources:
- Alsema & de Wild, Material Research Society, Symposium vol. 895, 73, 2006
- Fthenakis & Kim, Material Research Society, Symposium vol. 895, 83, 2006
- Fthenakis & Alsema, Progress in Photovoltaics, 14, 275, 2006
Energy Payback Times
Effect of Si Slurry Recycling

Insolation: 1700 kwh/m²-yr

- Alsema, de Wild & Fthenakis, 21st EU-PV Conference, Aug., 2006
- Fthenakis & Alsema, Progress in Photovoltaics, 14, 275, 2006
Life Cycle GHG Emissions – Europe

Insolation: 1700 kWh/m²-yr

<table>
<thead>
<tr>
<th>Material</th>
<th>CO₂-eq (g/kWh)</th>
<th>BOS</th>
<th>Frame</th>
<th>Frameless Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ribbon</td>
<td>11.5%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Multi-Si</td>
<td>13.2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mono-Si</td>
<td>14%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdTe</td>
<td>9%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Alsema & de Wild, Material Research Society, Symposium vol. 895, 73, 2006
Fthenakis & Kim, Material Research Society, Symposium vol. 895, 83, 2006
Fthenakis & Alsema, Progress in Photovoltaics, Accelerated Publication, 14, 275, 2006
Life Cycle GHG Emissions – Comparison with Conventional Technologies

GHG (g CO2-eq./kWh)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Operation</th>
<th>Transportation</th>
<th>Fuel Production</th>
<th>Materials</th>
<th>Fuel Production</th>
<th>Fuel Production</th>
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<tbody>
<tr>
<td>Coal (Kim and Dale 2005)</td>
<td>24</td>
<td>18</td>
<td>37</td>
<td>1120</td>
<td>1120</td>
<td>1120</td>
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<tr>
<td>Natural Gas (Kim and Dale 2005)</td>
<td>18</td>
<td>24</td>
<td>37</td>
<td>1120</td>
<td>1120</td>
<td>1120</td>
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<tr>
<td>Petroleum (Kim and Dale 2005)</td>
<td>37</td>
<td>24</td>
<td>18</td>
<td>1120</td>
<td>1120</td>
<td>1120</td>
</tr>
<tr>
<td>Nuclear (Baseline - Fthenakis and Kim, in press)</td>
<td>18</td>
<td>24</td>
<td>37</td>
<td>1120</td>
<td>1120</td>
<td>1120</td>
</tr>
<tr>
<td>PV, CdTe (Fthenakis and Kim 2005)</td>
<td>37</td>
<td>24</td>
<td>18</td>
<td>1120</td>
<td>1120</td>
<td>1120</td>
</tr>
<tr>
<td>PV, mc-Si, (Fthenakis and Alsema, 2006)</td>
<td>37</td>
<td>24</td>
<td>18</td>
<td>1120</td>
<td>1120</td>
<td>1120</td>
</tr>
</tbody>
</table>
Emissions of Heavy Metals
-Focus on Cadmium from CdTe PV

1. Mining/Smelting/Refining
2. Purification of Cd & Production of CdTe
3. Manufacture of CdTe PV modules
4. Utilization of CdTe PV modules
5. Disposal of spent CdTe PV modules
Stage 1. Cd Flows in Zn Mining, Smelting & Refining

Mining → Ore → Crushing Grinding → Pb flotation → Sink → Zn flotation → Zn Concentrate

Pb Concentrate ← Float

Waste Rock ← Ore

Zn Concentrate → Roasting → Acid Leaching → Purification Stages → Electro-deposition → Zn

SO₂, ZnO, CdO fumes ← Roasting

ZnO → Cyclone Baghouse ESP → Cd dust

SO₂, ZnO, CdO fumes

Cyclone Baghouse ESP

Precipitates → Cd sludge

Ge, In, Ga

Fthenakis and Wang., Emission Factors in the Production of Materials Used in Photovoltaics, 20th EURPVSEC, 8BO.5.2, 2005
Stage 4. Operation of CdTe PV Modules

- Zero emissions under normal conditions
  (testing in thermal cycles of –80 C to +80 C)

- No leaching during rain from broken or degraded modules
  *Steinberger, Progress in Photovoltaics, 1997*

- Negligible emissions during fires
  *Fthenakis, Fuhrman, Heiser, Lanzilotti, Fitts and Wang, Progress in Photovoltaics, 2005*
CdTe PV sample for Fire-simulation Experiments

Front (Substrate) Glass
Soda Lime Glass – common window glass

Front Contact
TCO (transparent conducting oxide) – a thin layer of Tin Oxide is applied to the front glass. This is the same material used in low E-coating (insulator) for common insulating glass.

Semiconductor
CdS (Cadmium Sulfide) – window layer
CdTe (Cadmium Telluride) – absorber layer

Metal Conductor
Thin stack of metals that create the back contact

EVA
EVA (Ethyl Vinyl Acetate) – an adhesive, encapsulant material

Back (Cover) Glass
Soda Lime Glass – common window glass
CdTe PV Fire-Simulation Tests: XRF Analysis

XRF-micro-spectroscopy - Cd Mapping in PV Glass
1000 °C, Section taken from middle of sample

XRF-micro-probing - Cd Distribution in PV Glass
1000 °C, right end of sample

Fthenakis, Fuhrman, Heiser, Lanzirotti, Fitts and Wang, *Progress in Photovoltaics, 2005*
XRF-micro-probing -Cd & Zr Distribution in PV Glass
Unheated Sample -Vertical Cross Section
XRF-micro-probe -Cd Distribution in PV Glass
760 °C, Section taken from middle of sample
XRF-micro-probe -Cd Distribution in PV Glass

1000 °C, Section taken from middle of sample
XRF-micro-probing -Cd Distribution in PV Glass
1000 °C, Section taken from right side of sample
Stage 5. Recycling of Cd and Te from Spent CdTe PV Modules

PV Module Fragments

- H₂SO₄
- H₂O₂

Leach Device

Glass Slurry

- Filtration Facility

Leachate Solution (Te, Cd, Cu, Fe)

Elution Solution (Cu)

Cu Recovery (?)

CdSO₄

Cd Electrowinning Cell

Removal of Cu from Liquid Using Resin A

- Column I Cu
- Column II Cu

Removal of Cd and Fe from Liquid Using Resin B

- Column I Cd, Fe
- Column II Cd, Fe

Selective Precipitation

Effluent Solution (Te)

Tellurium

Clean Glass
CdTe Recycling: Separation of Te and Cd

Cd separation 99.99%

Cd effluent concentration <0.3 ppm

Fthenakis and Wang, Patent Application # 60/686,911, 2, 2005
Atmospheric Cd emissions from the Life-Cycle of CdTe PV Modules – **Direct Emissions**

<table>
<thead>
<tr>
<th>Process</th>
<th>Cd Emissions (g /GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mining/Smelting of Zn</td>
<td>$3.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>2. Purification/CdTe Production</td>
<td>$1.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>3. Module Manufacturing</td>
<td>$3.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>4. Operation (accidents)</td>
<td>$6.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>5. Recycling</td>
<td>-</td>
</tr>
<tr>
<td><strong>TOTAL Life-Cycle Emissions</strong></td>
<td><strong>0.02</strong></td>
</tr>
</tbody>
</table>
Total Life-Cycle Cd Air emissions in CdTe PV

Due to energy use
Life-Cycle Cd Emissions from Electricity Use
(European electricity grid)

<table>
<thead>
<tr>
<th>Source</th>
<th>Emissions (g/GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mono-Si</td>
<td>0.5</td>
</tr>
<tr>
<td>mc-Si</td>
<td>0.7</td>
</tr>
<tr>
<td>CdTe</td>
<td>0.6</td>
</tr>
<tr>
<td>Coal</td>
<td>0.3</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>3.7</td>
</tr>
<tr>
<td>Oil</td>
<td>44.3</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Cd is produced inevitably as a byproduct of Zn production and if not used, it may be discharged into the environment.

- Above statement is supported by:
  - US Bureau of Mines reports
  - Rhine Basin study (the largest application of Systems Analysis on Industrial Metabolism)
Cd Flow in the Rhine Basin

Source: Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The UN University, 1994
Rhine Basin: Cd Banning Scenario

Source: Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The UN University, 1994
Cd Use & Disposal in the Rhine Basin: The effect of banning Cd products

“So, the ultimate effect of banning Cd products and recycling 50% of disposed consumer batteries may be to shift the pollution load from the product disposal phase to the Zn/Cd production phase. … it indicates that if such a ban were to be implemented, special provisions would have to be made for the safe handling of surplus Cd wastes generated at the Zn refineries!

One possible option would be to allow the production and use of Cd-containing products with inherently low availability for leaching. The other option, depositing the Cd-containing wastes in safely contained landfills, has other risks”

Source: Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The United Nations University, 1994
Risk Analysis in a Life Cycle Context
## Hazardous Substances in PV Module Manufacturing

<table>
<thead>
<tr>
<th>Substance</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsine</td>
<td>GaAs MOCVD</td>
</tr>
<tr>
<td>Boron Trifluoride</td>
<td>Dopant</td>
</tr>
<tr>
<td>Diborane</td>
<td>a-Si dopant</td>
</tr>
<tr>
<td>Hydrochloric acid</td>
<td>Cleaning agent – c-Si</td>
</tr>
<tr>
<td>Hydrogen Fluoride</td>
<td>Etchant – c-Si</td>
</tr>
<tr>
<td>Hydrogen Selenide</td>
<td>CIGS selenization</td>
</tr>
<tr>
<td>Hydrogen Sulfide</td>
<td>CIS sputtering</td>
</tr>
<tr>
<td>Phosphine</td>
<td>a-Si dopant</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>a-Si deposition/GaAs</td>
</tr>
<tr>
<td>Silane</td>
<td>a-Si deposition</td>
</tr>
<tr>
<td>Trichlorosilane</td>
<td>Precursor - c-Si</td>
</tr>
</tbody>
</table>
Method for Estimating Accidental Risks

- We examined the risks related to the production, distribution and use of each substance in the whole U.S. industry based on the database of the EPA Risk Management Program (RMP)

Incident Injuries Death

Arsine
Boron Trifluoride
Diborane
Hydrochloric acid
Hydrogen Fluoride
Hydrogen Selenide
Hydrogen Sulfide
Phosphine
Dichlorosilane
Hydrogen Silane
Trichlorosilane
Estimated PV Risks by Chemical

Insolation = 1800 kWh/m2/yr; performance ratio = 0.8.
Comparison of Risk Estimates

Paul Scherrer Institute Report
(Hirschberg et al., 2004)
Comparisons of Estimated Maximum Consequences

Paul Scherrer Institute, German Case
(Hirschberg et al., 2004)
Conclusions

- A Life Cycle Framework is necessary for a complete description of the Sustainability of Energy Technologies
- Cadmium and other heavy metal emissions are negligible in comparison to the heavy metal emissions from the fossil power plants that PV will displace
- Modern PV Technologies have Low Energy Payback Times and low GHG emissions
- PV is also much safer than conventional electricity generation technologies

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