Life Cycle Analysis of PV

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LCA - a tool for Sustainability evaluation

- Sustainability is defined as patterns of economic, environmental, and social progress that meets the needs of the present generation without reducing the capacity to meet future needs.

- Sustainable energy refers to patterns of energy production that can support society’s present and future needs with the least life-cycle economic, environmental, and social costs.

- Life Cycle of a product starts from acquiring its raw materials, to manufacturing, transporting, and using it, to its final decommissioning and disposal.
The Life Cycle of PV

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

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

Photovoltaic modules

Balance of System (BOS)
(Inverters, Transformers, Frames, Metal and Concrete Supports)
Life Cycle Assessment

• Life Cycle Assessment is a standardized framework for quantifying the potential environmental impacts of material and energy inputs and outputs of a product or technology from cradle to grave.

• ISO 14040 “LCA Principles and Framework”, 1997
  ISO 14044 “LCA Requirements and Guidelines”, 2006

• IEA Task 12 “Guidelines for PV LCA”, 2009
Sample Metrics of Life-Cycle Performance

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

EPBT is defined as the period required for a renewable energy system to generate the same amount of primary energy that was used to produce the system itself.

\[ \text{EPBT} = \frac{(E_{\text{mat}} + E_{\text{manuf}} + E_{\text{trans}} + E_{\text{inst}} + E_{\text{EOL}})}{(E_{\text{agen.}} - E_{\text{am}})} \]

where,

- \(E_{\text{mat}}\): Primary energy demand to produce materials comprising PV system
- \(E_{\text{manuf}}\): Primary energy demand to manufacture PV system
- \(E_{\text{trans}}\): Primary energy demand to transport materials used during the life cycle
- \(E_{\text{inst.}}\): Primary energy demand to install the system
- \(E_{\text{EOL}}\): Primary energy demand for end-of-life management
- \(E_{\text{agen}}\): Annual electricity generation in primary energy
- \(E_{\text{am}}\): Annual energy demand for operation and maintenance in primary energy
Energy Payback Times

Insolation: 1700 kWh/m2-yr

LCI data from 12 EU and US companies

- 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
Progress in PV Technologies

Efficiency of CdTe

Thickness of Si PV

Sources: First Solar, de Wild-Scholten, ECN, 2009
Update of Energy Payback Times

Insolation: 1700 kWh/m2-yr

- Ribbon-Si: 1.3 years (13.2%)
- Multi-Si: 1.8 years (13.2%)
- Mono-Si: 1.9 years (14.0%)
- CdTe: 0.8 years (10.9%)

-deWild 2009, EUPV, 2009
-Fthenakis et al., EUPV, 2009
Energy Payback Times in the US-SW

Insolation: 2300 kWh/m2-yr

EPBT (Years)

- Ribbon-Si: 1.0 years (13.2% efficiency)
- Multi-Si: 1.3 years (13.2% efficiency)
- Mono-Si: 1.4 years (14.0% efficiency)
- CdTe: 0.6 years (10.9% efficiency)

deWild 2009, EUPV, 2009
Fthenakis et al., EUPV, 2009
Greenhouse Gas (GHG) Emissions
Crystal Clear & BNL LCAs
GHG Emissions – Europe

Insolation: 1700 kWh/m2-yr

CO2-eq (g/kWh)

<table>
<thead>
<tr>
<th>Technology</th>
<th>13.2%</th>
<th>13.2%</th>
<th>14%</th>
<th>10.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ribbon</td>
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<tr>
<td>Multi-Si</td>
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<tr>
<td>Mono-Si</td>
<td></td>
<td></td>
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<tr>
<td>CdTe</td>
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</tbody>
</table>

deWild 2009, EUPV, 2009
Fthenakis et al., EUPV, 2009
GHG Emissions from Life Cycle Energy of Electricity Production

GHG (g CO2-eq./kWh)

- Coal (Kim and Dale 2005)
- Natural Gas (Kim and Dale 2005)
- Petroleum (Kim and Dale 2005)
- Nuclear (Baseline - Fthenakis and Kim, 2007)
- PV, CdTe (Fthenakis et al, 2008)
- PV, mc-Si (Fthenakis et al, 2008)

Heavy Metal Emissions in the Life-Cycle of PV

Fthenakis, Kim, Alsema. ES&T, 2009
CdTe PV Life-Cycle Analysis (focus on Cd flows –air emissions)

Stages of the Life of CdTe PV:
1. Mining/Smelting/Refining –Cd & Te production
2. Purification of Cd & Production of CdTe
3. Manufacture of CdTe PV modules
4. Use of CdTe PV modules
5. End-of-life of CdTe PV modules

Fthenakis V. Life cycle impact analysis of Cd in CdTe PV,
Renewable and Sustainable Energy Reviews, 8, 303-334, 2004
1. Cd Flows in Zn Mining, Smelting & Refining

- **Mining:** Waste Rock → Ore
- **Crushing & Grinding:** Ore → Pb flotation → Sink → Zn flotation → Zn Concentrate
  - Dust emissions: 0.003-27 kg/ton
  - Float: Pb Concentrate

- **Roasting:** Zn Concentrate → SO₂, ZnO, CdO fumes → Cyclone Baghouse → Cd dust
  - Solids: ZnO, CdO

- **Acid Leaching:** Solids (ZnO, CdO) → ZnO → Precipitates (Ge, In, Ga) → Cd sludge

- **Purification Stages:** ZnO → Electro-deposition → Zn
2. Cd Flows from Cd Concentrates to CdTe

- Cd Dust & Sludge from Zn & Pb Refining (& Cd wastes from Iron & Steel Industries)
- Electrolytic Refinery
  - 1-2 % Cd loss (sludge)
  - Cd metallurgical grade
  - Cd 99.9%
- Production Milling
  - Recycling
  - Cd Powder 99.999%
- Melting & Atomization
  - Recycling
  - 2% Cd emissions (particulates)
- CdTe Powder
  - HEPA Filters
  - 0.03% gaseous emissions
  - 6 g /Mg Cd

Fthenakis V. Life cycle impact analysis of Cd in CdTe PV, Renewable and Sustainable Energy Reviews, 8, 303-334, 2004
3. Cd Emissions in CdTe PV Manufacturing - 2009

- 76% material utilization in the deposition process
- Residuals are recycled
- 99.97% filtration via pre filters and HEPA filters
- Total Cd emissions from all manufacturing and recycling operations (i.e., storage, deposition, lasers, annealing, edge delete, acid etch, recycling glass shredder, recycling hammer mill) are ~0.5 g Cd/ton Cd input
4. Use of CdTe PV Modules

- Zero emissions under normal conditions
  (testing in thermal cycles of –80 C to +80 C)
CdTe PV Use – Accidental Releases

- No leaching during rain from broken or degraded modules

“In a worst-case scenario for CdTe modules the leached Cd concentration in the collected water is estimated to be no higher than the German drinking water concentration. No critical increase of the natural element concentration is observed after leaching into the soil for 1 year“ (Steinberger, PiP, 1998)

- Negligible emissions during fires

(Fthenakis, Fuhrman, Heiser, Lanzirotti, Fitts and Wang, PiP, 2005)
Fire Simulation - Test Protocols

- UL 1256 30 min @760 C
- ASTM E119-98 Standard Temperature Curve

![Temperature vs Time Graph](image)
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
## Atmospheric Cd Emissions from the Life-Cycle of CdTe PV Modules – Reference Case

<table>
<thead>
<tr>
<th>Process</th>
<th>(g Cd/ton Cd*)</th>
<th>(%)</th>
<th>(mg Cd/GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mining of Zn ores</td>
<td>2.7</td>
<td>0.58</td>
<td>0.02</td>
</tr>
<tr>
<td>2. Zn Smelting/Refining</td>
<td>40</td>
<td>0.58</td>
<td>0.30</td>
</tr>
<tr>
<td>3. Cd purification</td>
<td>6</td>
<td>100</td>
<td>7.79</td>
</tr>
<tr>
<td>4. CdTe Production</td>
<td>6</td>
<td>100</td>
<td>7.79</td>
</tr>
<tr>
<td>5. CdTe PV Manufacturing</td>
<td>0.4*</td>
<td>100</td>
<td>0.52*</td>
</tr>
<tr>
<td>6. CdTe PV Operation</td>
<td>0.05</td>
<td>100</td>
<td>0.06</td>
</tr>
<tr>
<td>7. CdTe PV Recycling</td>
<td>0.1*</td>
<td>100</td>
<td>0.13*</td>
</tr>
<tr>
<td><strong>TOTAL EMISSIONS</strong></td>
<td><strong>16.55</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 2009 updates

**Plus** 200 mg Cd/GWh from fossil fuels in the electricity mix in the life-cycle of CdTe PV

*Fthenakis V. Renewable and Sustainable Energy Reviews, 8, 303-334, 2004*
Total Life-Cycle Cd Atmospheric Emissions

Fthenakis and Kim, Thin-Solid Films, 515(15), 5961, 2007
A Holistic View of Cd Use in PV

Cd is produced as a byproduct of Zn production and can either be put to beneficial uses or 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
“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. This … 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
A Holistic View: Notes

- Cd is produced as a byproduct of Zn production and can either be put to beneficial uses or discharged into the environment.

- CdTe PV is the safest current use of Cd; it is in a stable form that doesn’t leak into the environment during normal use or foreseeable accidents.

- Air emissions of Cd from the Life Cycle of CdTe PV are 230 times lower than Cd emitted into air from the best-controlled coal power plants that PV displaces.

5. End-of-life Issues of PV modules

- Rapid growth of PV market will result in an eventual waste disposal issue 25+ years after module installation
- Potential of environmental impacts from disposal of PV as municipal waste
- PV recycling will resolve environmental concerns and will create secondary sources of materials that benefit the environment
- CdTe PV recycling is technically and economically feasible
Recycling R&D at BNL: CdTe and CIGS PV Modules

PV Module Fragments → Leach Device → Leachate Solution (Te, Cd, Cu, Fe) → Filtration Facility → Clean Glass

Removal of Cu from Liquid Using Resin A → Column I → Column II → Elution of Column A

Removal of Cd and Fe from Liquid Using Resin B → Column I → Column II → Elution of Column B

Selective Precipitation → Tellurium → CdSO\(_4\) → Cd Electrowinning Cell → Cd Metal → Recycled Electrolyte

Cd-Te Separation Patent


First Solar Module Recycling Process

Collection → Shredder → Hammer mill → Film Removal

Metal Rich Filter Cake → Dewatering → Precipitation

Clean Glass → Glass Rinsing → Glass EVA Separation

Solid-Liquid Separation

Courtesy: First Solar
The PV CYCLE Voluntary Initiative

Current Members:
- Abound
- Aleo
- Arendi
- Avancis
- Bosch
- BP Solar
- Canadian Solar
- CEEG
- Chi Mei Energy
- Conergy
- DelSolar
- ET Solar
- First Solar
- GE Solar
- Gloria Solar
- Henot
- Isofoton
- Johanna Solar
- Kaneka
- Korax Solar
- Kyocera
- LDK Solar
- Martifer
- MoserBaer
- NexPower
- Photowatt
- Q-Cells
- REC
- Renergies
- Sanyo
- Scheuten Solar
- Schott Solar
- Schueco
- Sharp
- Siliken
- Solairedirect
- Solarfabrik
- Solarfun
- Solarworld
- Soleos
- Solon
- Solpower
- Sovello
- Sulfurcell
- Sunnoco
- Sunpower
- Solyndra
- Suntech
- Sunways
- T-Solar
- Tenesol
- Uni-Solar
- Vipiemme
- Würth Solar
- XGroup
- Yingli
- Yohkon

Associated:
- ASIF
- BSW
- DGS
- ECN
- EPIA
- Photon Tech
- Roth & Rau
- Subsun
- Syndicat

As of March 2010,
- 57 members and 9 associated members
- Full members cover more than 85% of European Market
PV - The Triangle of Success

- Low Cost
- Resource Availability
- Recycling
- Lowest Environmental Impact