Sustainability of Large Deployment of Photovoltaics: Environmental & Grid Integration Research

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www.clca.columbia.edu
www.pv.bnl.gov
Photovoltaic Global Sales and Projections

Doubling of added capacity every 2 years.

Source: PV Market Outlook European Photovoltaic Industry Association 2009
A Solar Grand Plan

By 2050 renewable energy to supply 69% of electricity, 35% of total energy needs of the U.S.
Zweibel, Mason, Fthenakis

The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US
Vasilis Fthenakis  James E. Mason  Ken Zweibel

PV Capacity Projections: United States 2030

DOE-EERE Solar Vision Study Report is in review, not to be cited
PV – Sustainability Criteria

Low Cost

Resource Availability

Lowest Environmental Impact

Te in CdTe
In in CIGS
Ge in a-SiGe & III/V
Ag in c-Si

Affordability in a competitive world

Lower than alternatives Life Cycle Impacts & Risks
Affordability - Cost Reductions

Prices and Production Costs of PV Modules

Module Price (2006$/Wp)

Cumulative Production (MWp)

Historical Prices

1980

Crystalline Si

Thin Films

a-Si (Unisolar)

2004

2006

2006

CdTe (First Solar)

2010

avg 2010 costs $0.7/W

avg 2010 costs $1.5-2/W

Courtesy R. Margolis, NREL
Update V. Fthenakis
Affordability: Projected PV Growth and Electricity Price Targets

Geographic Locations
- Phoenix, AZ
- Kansas City, MO
- New York, NY

Financing Conditions
- Low: 8.2%
- High: 9.9%

Tellurium for PV* from Copper Smelters

Tellurium for PV* from Copper Smelters

Tellurium Availability for PV* (MT/yr)

• Global Efficiency of Extracting Te from anode slimes increases to 80% by 2030 (low scenario); 90% by 2040 (high scenario)

* 322 MT/yr Te demand for other uses has been subtracted
   All the growth in Te production is allocated to PV
Te Availability for PV: Primary + Recycled

Tellurium Availability for PV (MT/yr)

Fthenakis V., Renewable & Sustainable Energy Reviews 13, 2746, 2009
CdTe PV Production Constraints

Annual (GW/yr)

Cumulative (TW)

Production can increase with direct mining starting at ~2015

Fthenakis V., Renewable & Sustainable Energy Reviews 13, 2746, 2009
Life Cycle Environmental Impacts

M, Q: material and energy inputs
E: effluents (air, water, solid)
Life Cycle Environmental Impacts

Experimental Research at BNL

M, Q: material and energy inputs

E: effluents (air, water, solid)
Comparative Life-Cycle Analysis

- Energy Payback Times (EPBT)
- Greenhouse Gas Emissions
- Resource Use (materials, water, land)
- EH&S Risks

Zero impact technology does not exist ➔
Compare with other energy producing technologies as benchmarks
Energy Payback Times (EPBT)

Insolation: 1700 kWh/m²-yr

Based on data from 13 US and European PV manufacturers

- Fthenakis et al., EUPV, 2009
- deWild 2009, EUPV, 2009
- Alsema & de Wild, Material Research Society, Symposium, 895, 73, 2006
- deWild & Alsema, Material Research Society, Symposium, 895, 59, 2006
- Fthenakis & Kim, Material Research Society, Symposium, 895, 83, 2006
- Fthenakis & Alsema, Progress in Photovoltaics, 14, 275, 2006
Greenhouse Gas (GHG) Emissions

Insolation: 1700 kWh/m²-yr

- Fthenakis & Kim, Encyclopedia of Energy, in press
- deWild 2009, EUPV, 2009
- Fthenakis et al., EUPV, 2009
- Fthenakis & Kim, ES&T, 42, 2168, 2008
- Alsema & de Wild, Material Research Society, Symposium, 895, 73, 2006
- deWild & Alsema, Material Research Society, Symposium, 895, 59, 2006
- Fthenakis & Kim, Material Research Society, Symposium, 895, 83, 2006
- Fthenakis & Alsema, Progress in Photovoltaics, 14, 275, 2006
GHG Emissions from Life Cycle of Electricity Production: Comparisons

- 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) 10.9%
- PV, mc-Si, (Fthenakis et al, 2008) 13.2%

California Energy Commission, Nuclear Issues Workshop, June 2007
Fthenakis & Kim, ES&T, 42, 2168, 2008
Dual and Ecological-friendly Use of Land

Does PV use a lot of land?

Sinzheim, Germany, with permission from Juwi, 2006
1.4MW
More Land is used by the Coal Life Cycle than PV

PV Plant, Tucson Electric Power, Springerville, Arizona

Mountain Top Coal Mining
Rawl, West Virginia

Land requirement for PV in the SW:
310 m²/GWh

Land requirement for US surface coal mining:
320 m²/GWh

Fthenakis V. and Kim H.C., Sustainable and Renewable Energy Reviews, 2009
CdTe PV Product Life – Accidental Releases

- Leaching from shuttered modules

  - 10 mm fragments - Rain-worst-case scenario - “leached Cd concentration in the collected water is no higher than the German drinking water concentration.”
    (Steinberger, Fraunhofer Institute Solid State Technology, Progress in Photovoltaics, 1998)

  - < 4 mm fragments “Leached Cd exceeds the limits for disposal in inert landfill but is lower than limits for ordinary landfills”
    (Okkenhaug, Norwegian Geotechnical Institute, Report, 2010)

  - < 2 mm fragments “CdTe PV sample failed California TTLC and STLC tests”
    (Sierra Analytical Labs for the “Non-Toxic Solar Alliance”, 2010)

All PV modules would fail the California tests

c-Si for Ag, Pb, and Cu (ribbon),
CIGS for Se; a-Si marginally for Ag

Eberspacher & Fthenakis, 26th IEEE PVSC, 1997;
Eberspacher 1998

We advocate for all PV modules to be recycled at the end of their life
CdTe PV Product Life – Accidental Releases

- PV Roof-top fires

Negligible emissions during fires

Fthenakis, *Renewable and Sustainable Energy Reviews*, 2004,
Fthenakis et al., *Progress in Photovoltaics*, 2005

*Based on standard protocols* by the ASTM and UL
*Expert Peer reviews by:*
- BNL, US-DOE, 2004
- EC-JRC, 2004
- German Ministry of the Environment, (BMU), 2005
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

XRF-micro-probing - Cd & Zr distribution in PV sample
Unheated Sample - Vertical Cross Section
XRF-micro-probe - Cd distribution in PV sample
760 °C, Section taken from middle of sample
XRF-micro-probe - Cd distribution in PV sample
1000 °C, Section taken from middle of sample
XRF-micro-probing - Cd distribution in PV sample

1000 °C, Section taken from right side of sample
XRF-micro-probing - Cd distribution in PV sample
1100 °C, Section taken from middle of sample
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>
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<tbody>
<tr>
<td>1. Mining of Zn ores</td>
<td>2.7</td>
<td>0.58</td>
<td>0.02</td>
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<td>2. Zn Smelting/Refining</td>
<td>40</td>
<td>0.58</td>
<td>0.30</td>
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<tr>
<td>3. Cd purification</td>
<td>6</td>
<td>100</td>
<td>7.79</td>
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<tr>
<td>4. CdTe Production</td>
<td>6</td>
<td>100</td>
<td>7.79</td>
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<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>TOTAL EMISSIONS</td>
<td></td>
<td></td>
<td>16.55</td>
</tr>
</tbody>
</table>

* 2009 updates

*Fthenakis V. Renewable and Sustainable Energy Reviews, 8, 303-334, 2004*
Indirect emissions, due to fossil fuels in the electricity mix in the life-cycle of CdTe PV, are more than 10x higher than direct emissions.

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 uncontrolled disposal of PV
Recycling of Spent Modules

- 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
The Triangle of Success

Low Cost

Resource Availability

Recycling

Lowest Environmental Impact
Major PV Sustainability metrics include cost, resource availability, and environmental impacts.

These three aspects are closely related; recycling spent modules will become increasingly important in resolving cost, resource, and environmental constraints to large scales of sustainable growth.

Environmental sustainability should be examined in a holistic, life cycle, comparative framework.

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