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

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www.pv.bnl.gov

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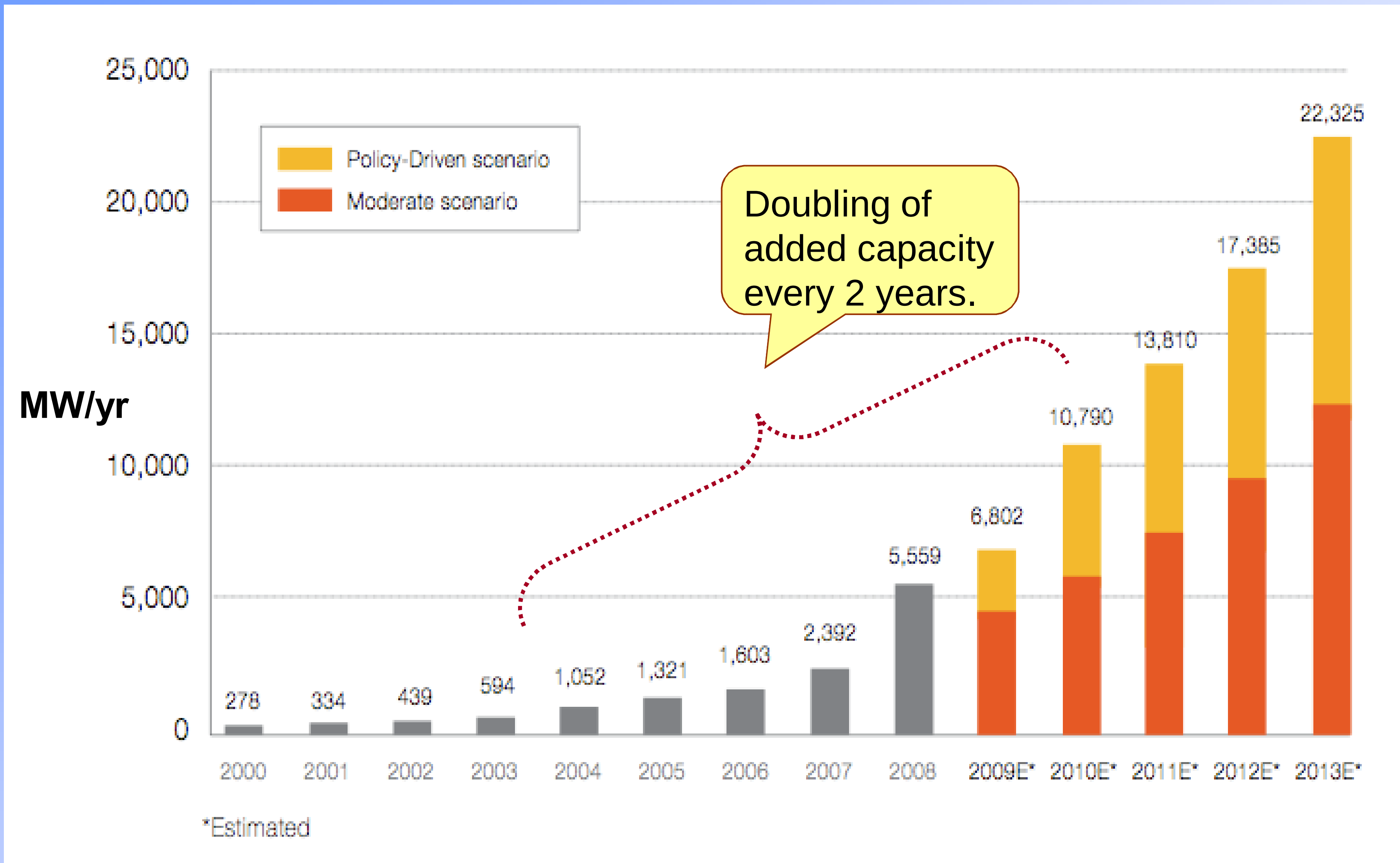
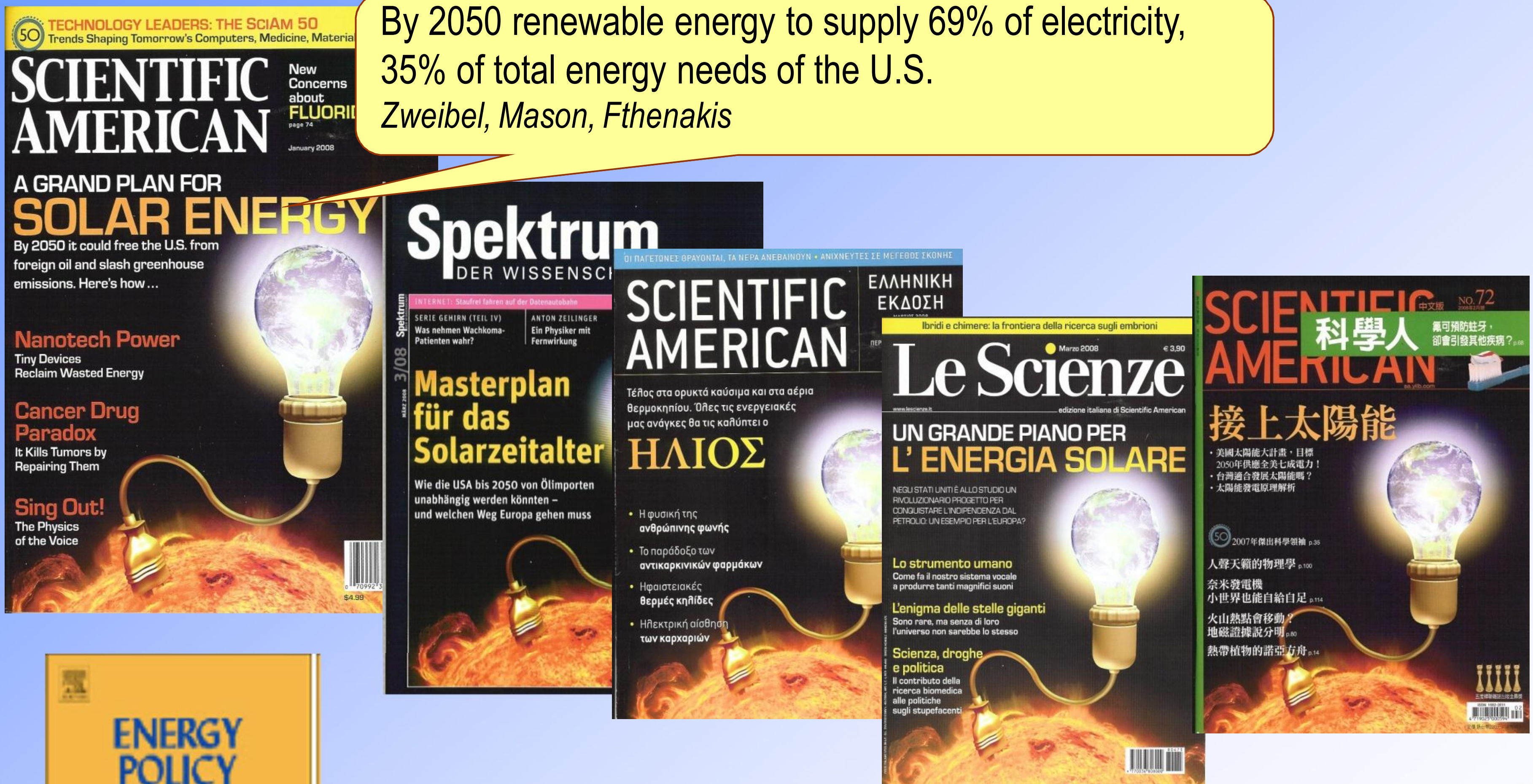
Photovoltaic Global Sales and Projections

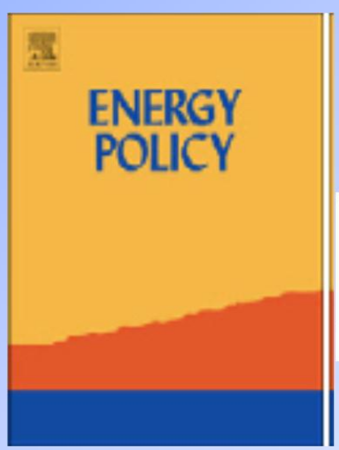


Source: PV Market Outlook European Photovoltaic Industry Association 2009

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

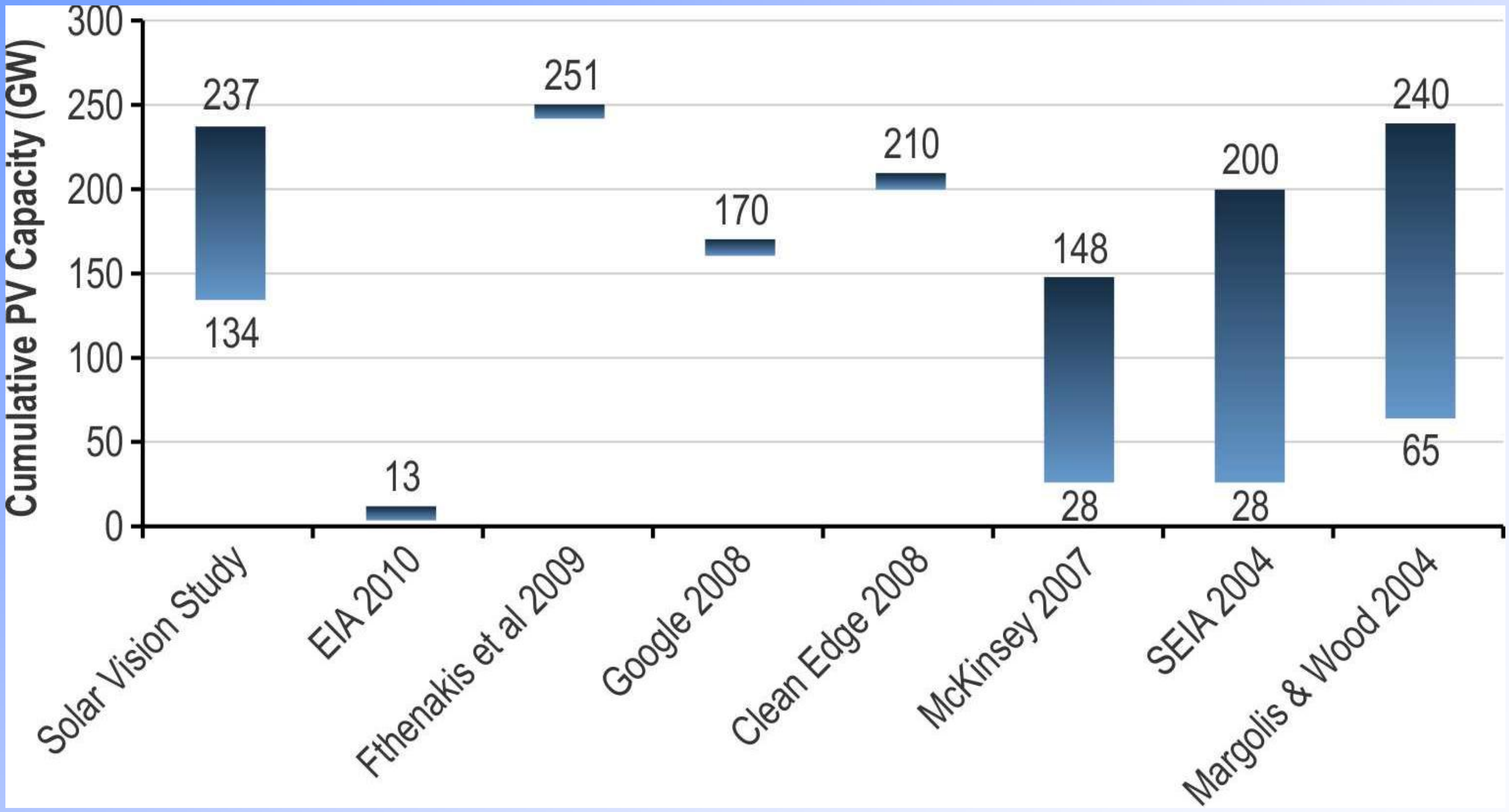




The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US

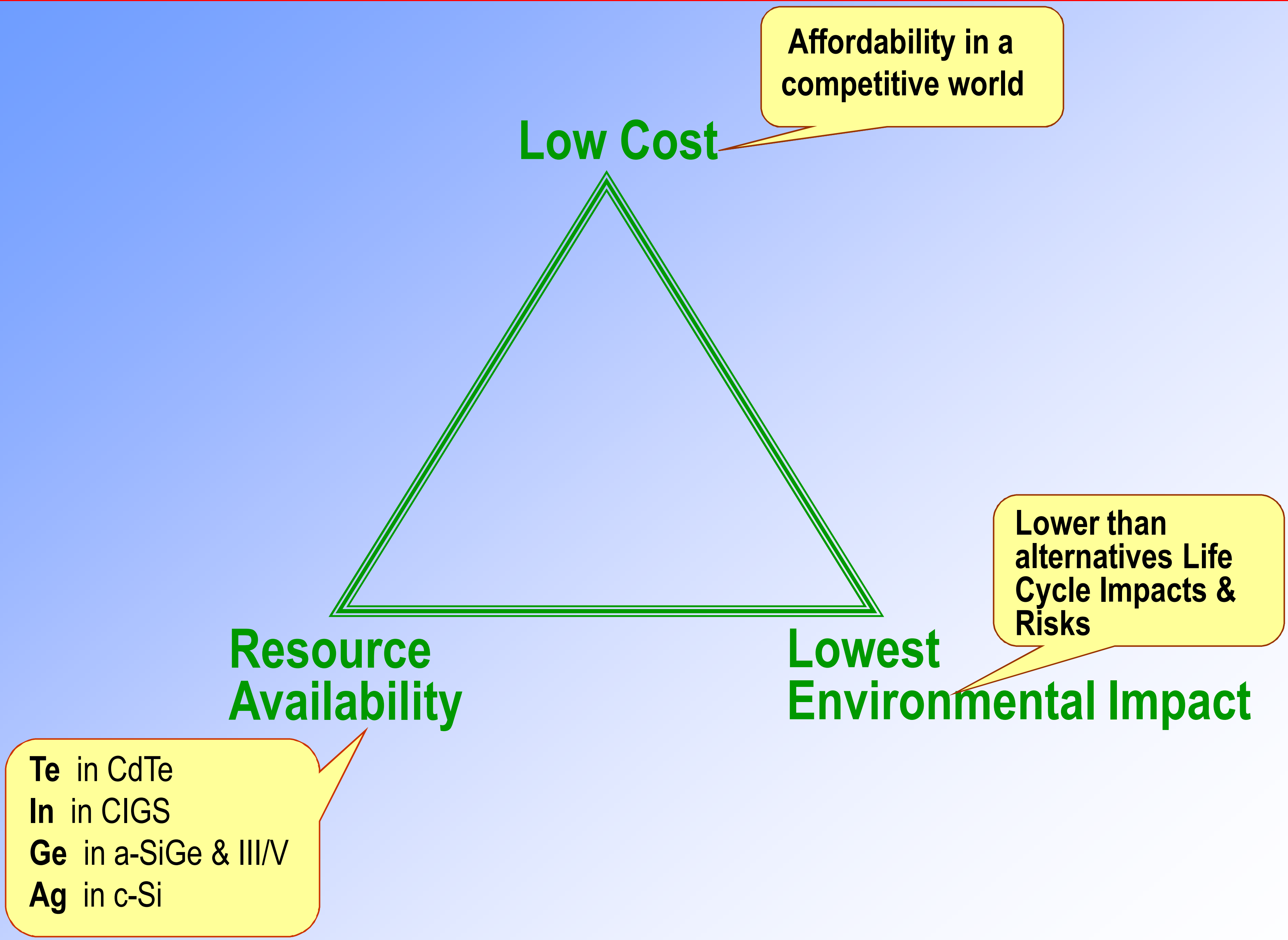
Vasilis Fthenakis James E. Mason Ken Zweibel *Energy Policy* 37 (2009)

PV Capacity Projections: United States 2030

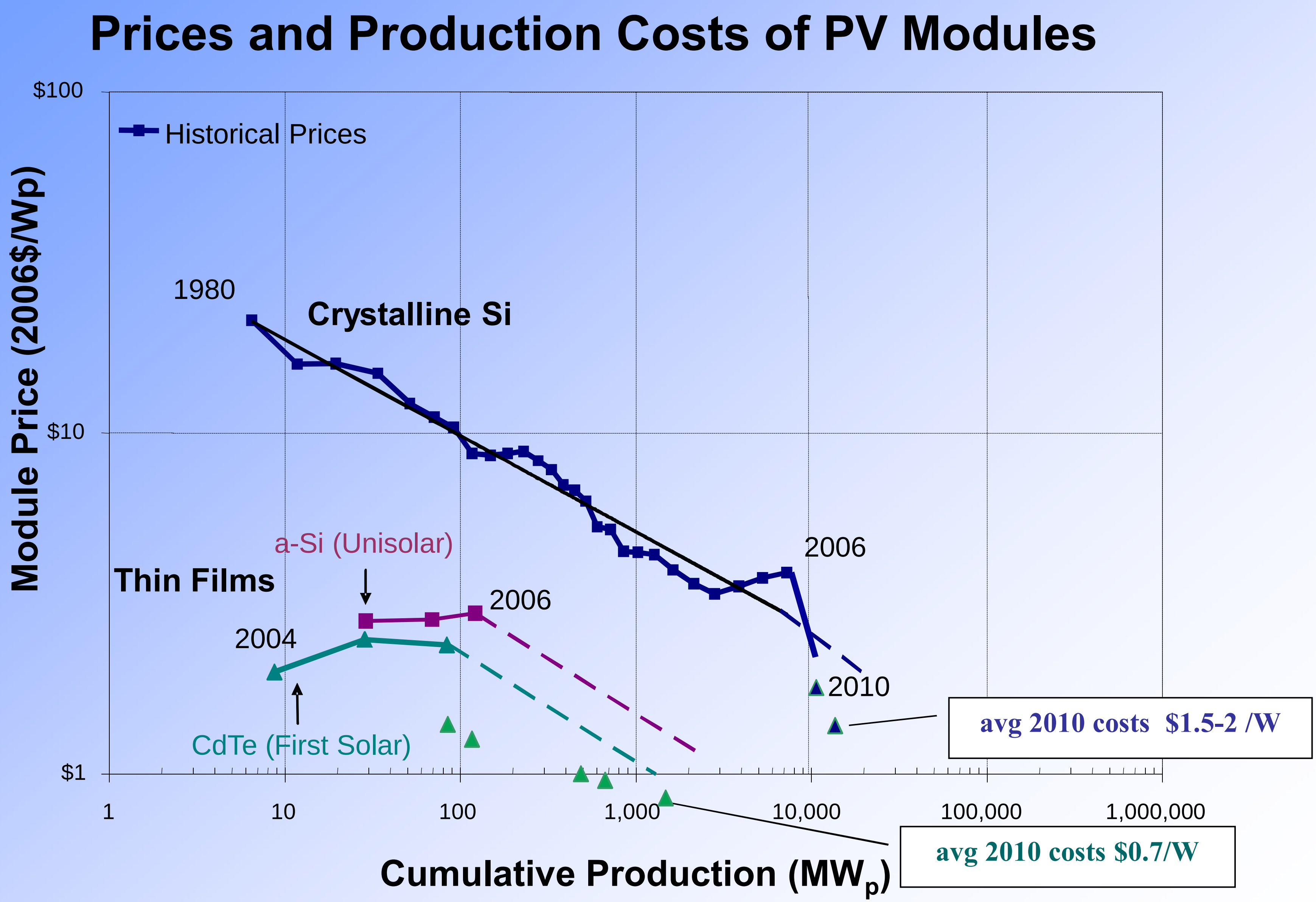


DOE-EERE Solar Vision Study Report is in review, not to be cited

PV –Sustainability Criteria



Affordability - Cost Reductions



Courtesy R. Margolis, NREL
Update V. Fthenakis

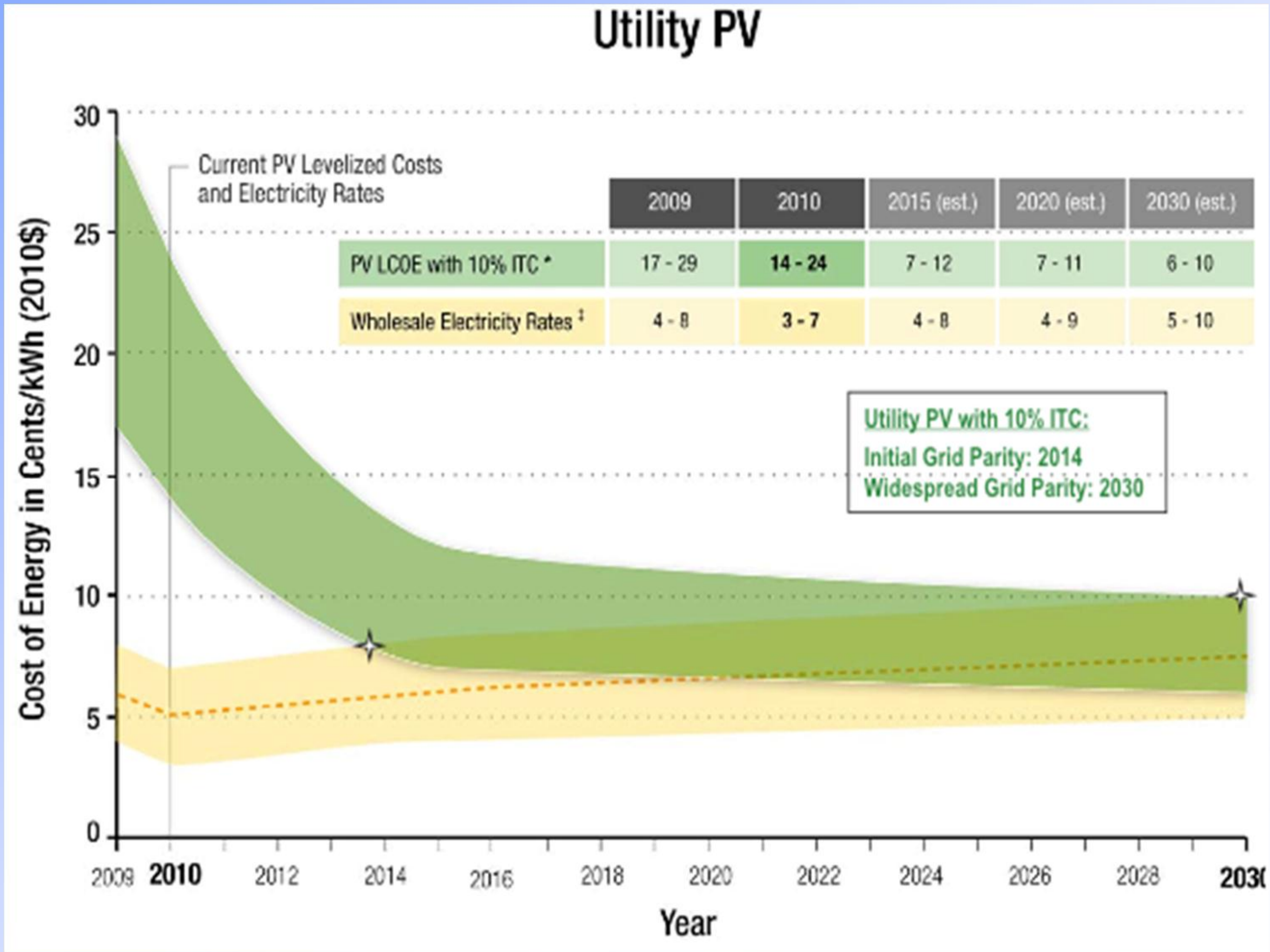
Affordability: Projected PV Growth and Electricity Price Targets

Geographic Locations

Phoenix, AZ
Kansas City, MO
New York, NY

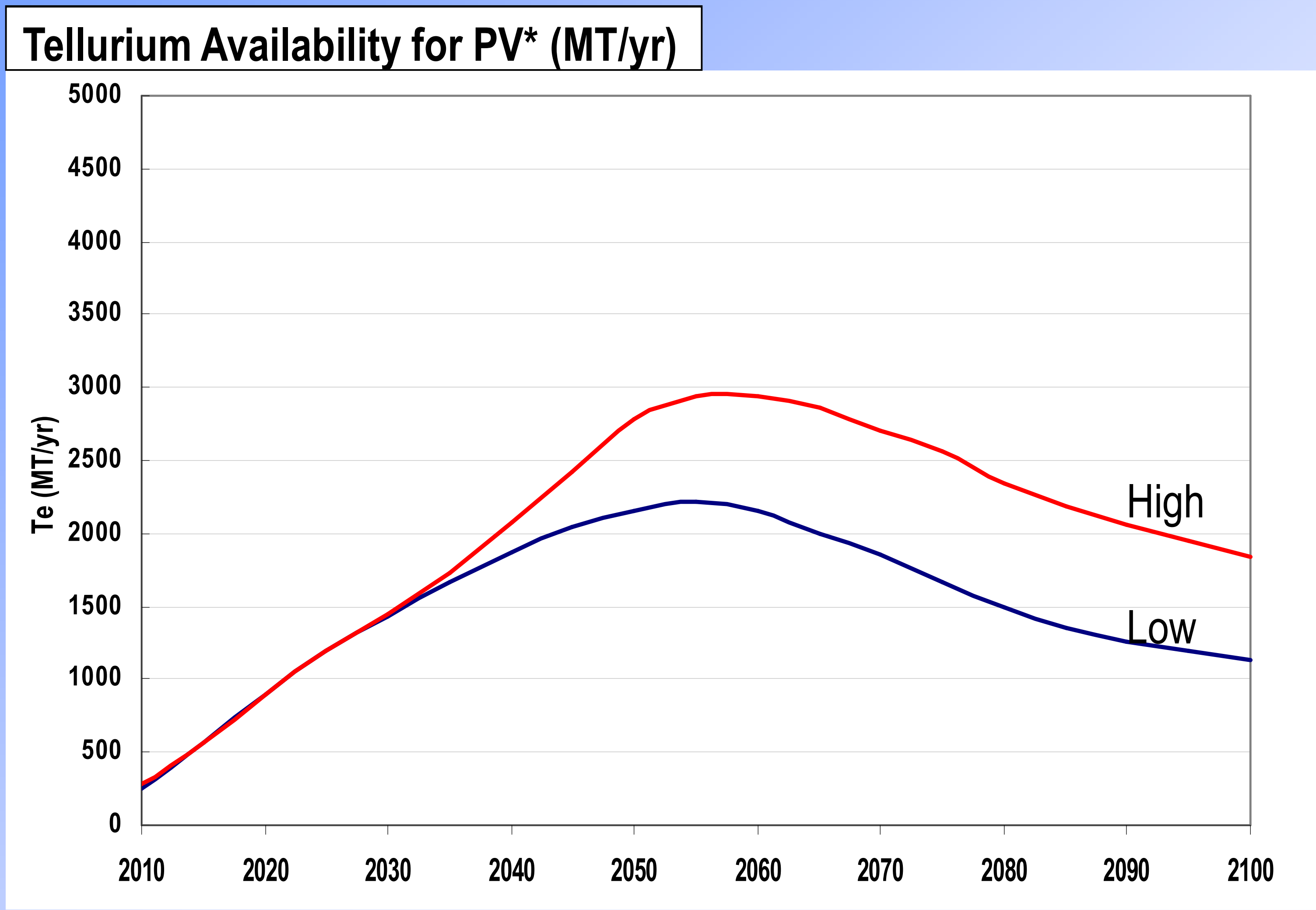
Financing Conditions

Low: 8.2%
High: 9.9%



Source: J. Lushetsky, Solar Technologies Program, US-DOE, 25th EUPV, Valencia, Spain, Sept. 2010

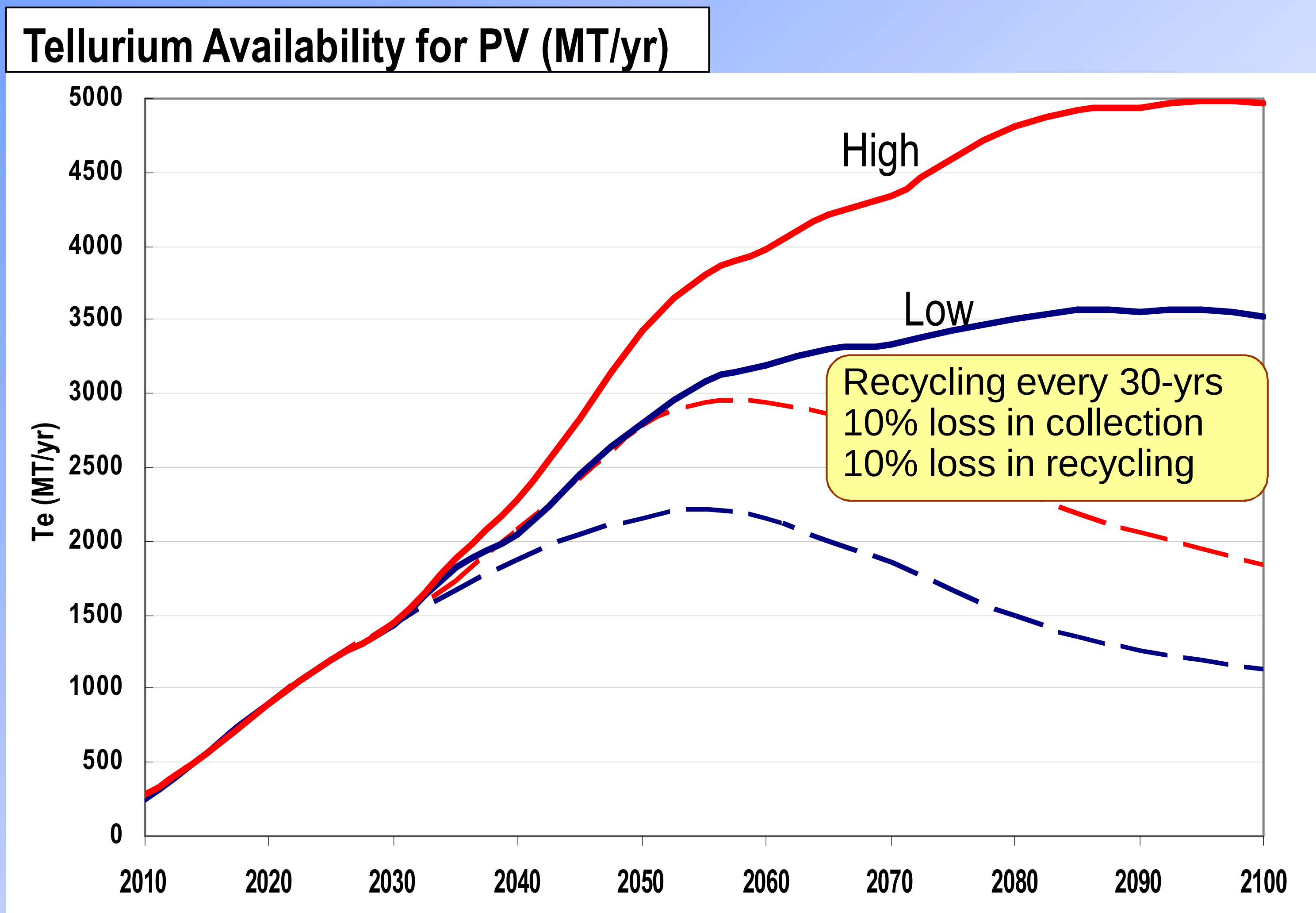
Tellurium for PV* from Copper Smelters



•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

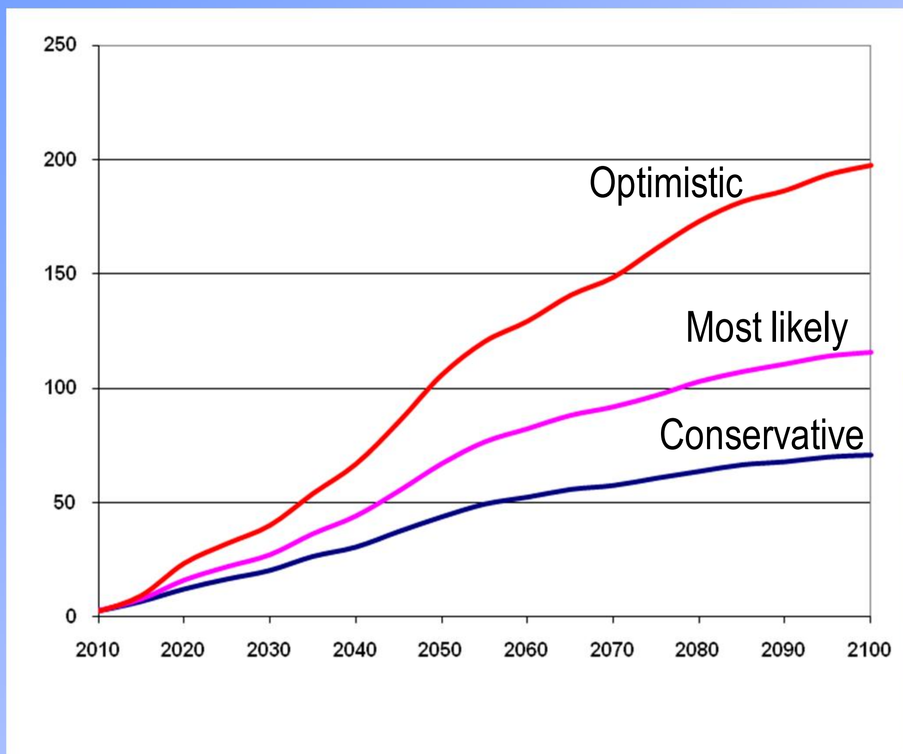
Te Availability for PV:
Primary + Recycled



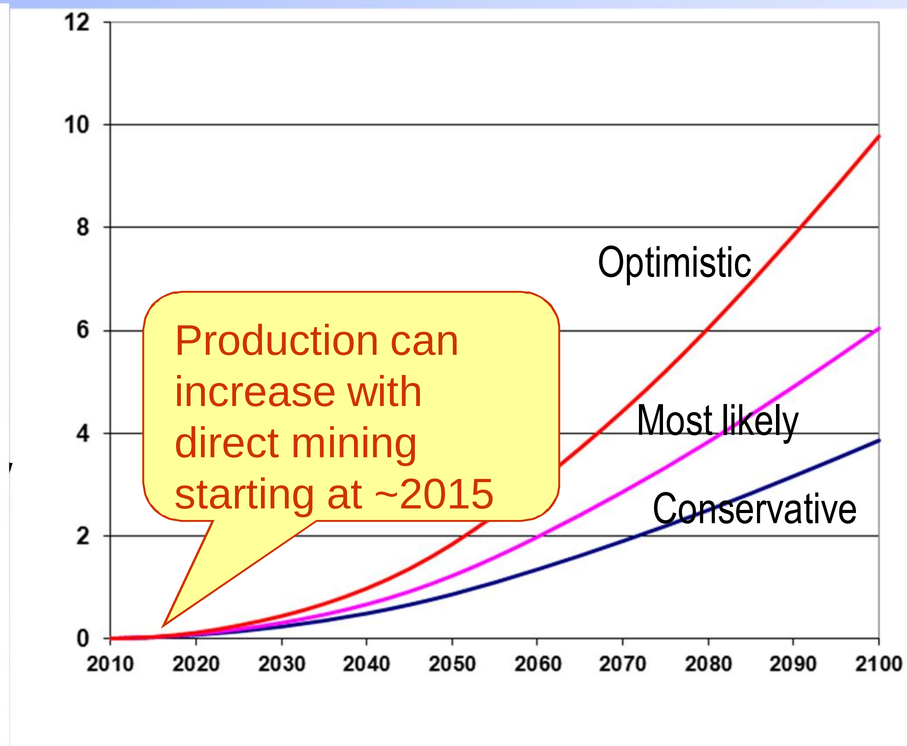
Fthenakis V., *Renewable & Sustainable Energy Reviews* 13, 2746, 2009

CdTe PV Production Constraints

Annual (GW/yr)

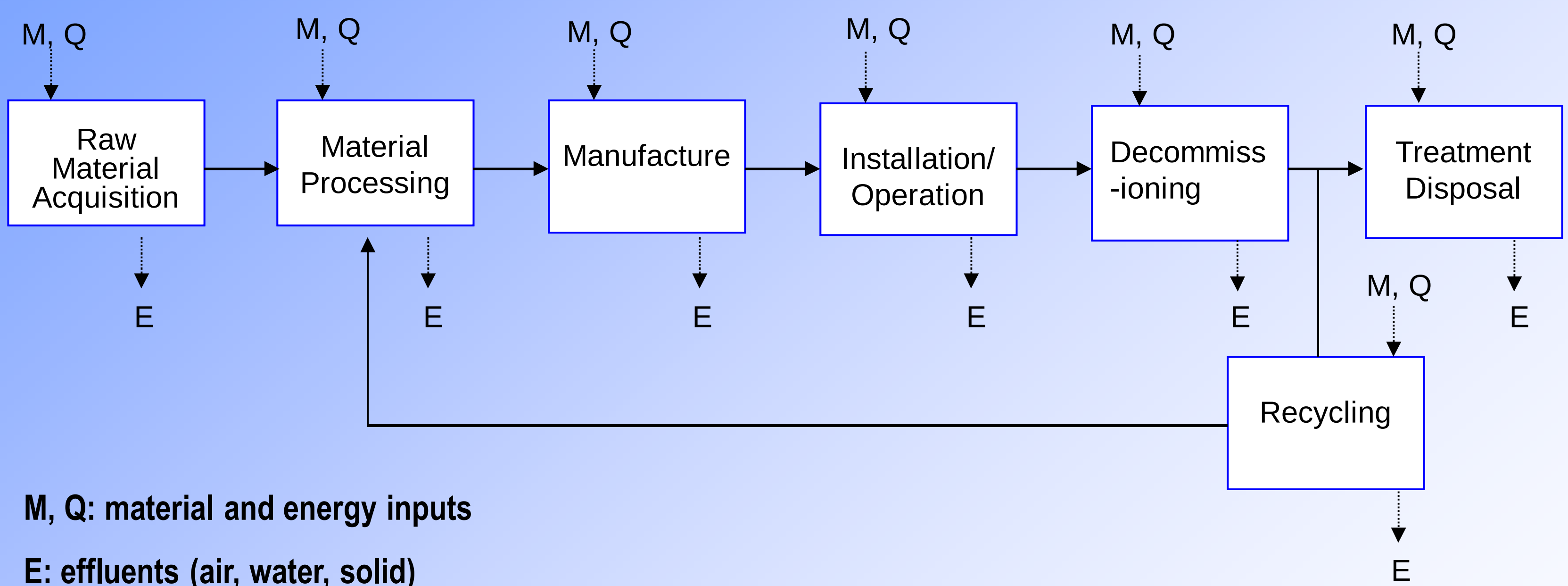


Cumulative (TW)



Fthenakis V., *Renewable & Sustainable Energy Reviews* 13, 2746, 2009

Life Cycle Environmental Impacts

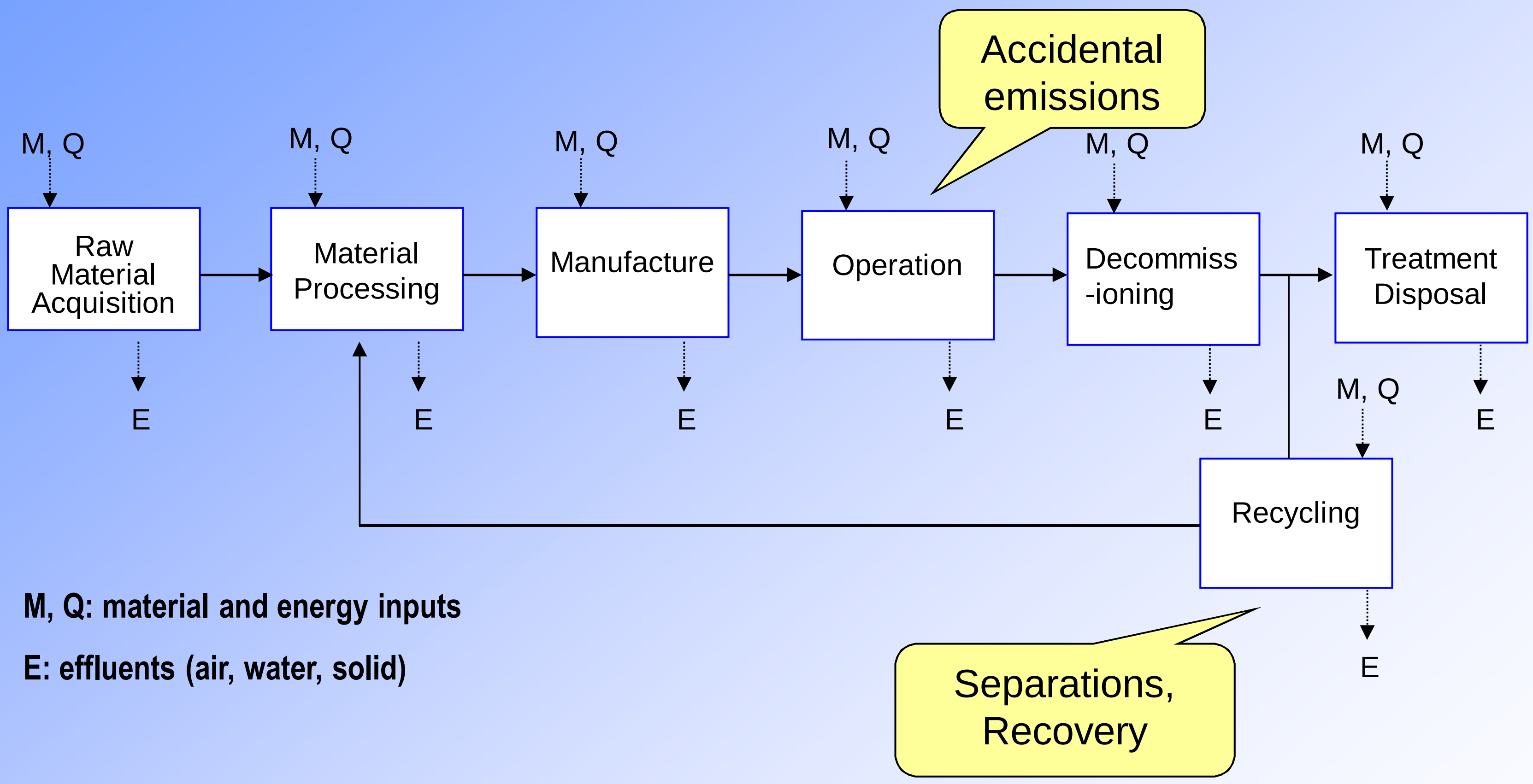


M, Q: material and energy inputs

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

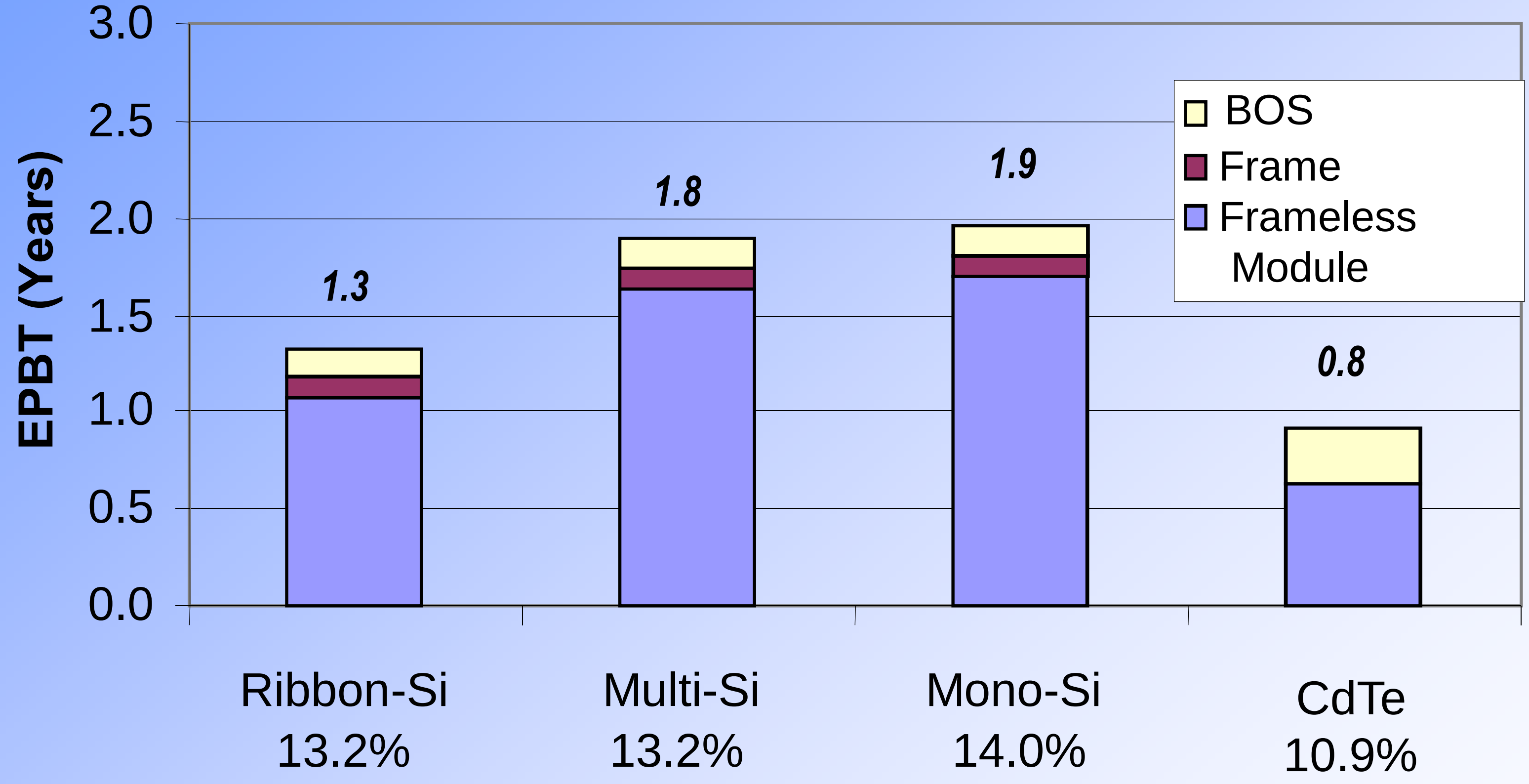
- Energy Payback Times (EPBT)
- Greenhouse Gas Emissions
- Resource Use (materials, water, land)
- EH&S Risks

Zero impact technology does not exist ➔

Compare with other energy producing technologies as benchmarks

Energy Payback Times (EPBT)

Insolation: 1700 kWh/m2-yr

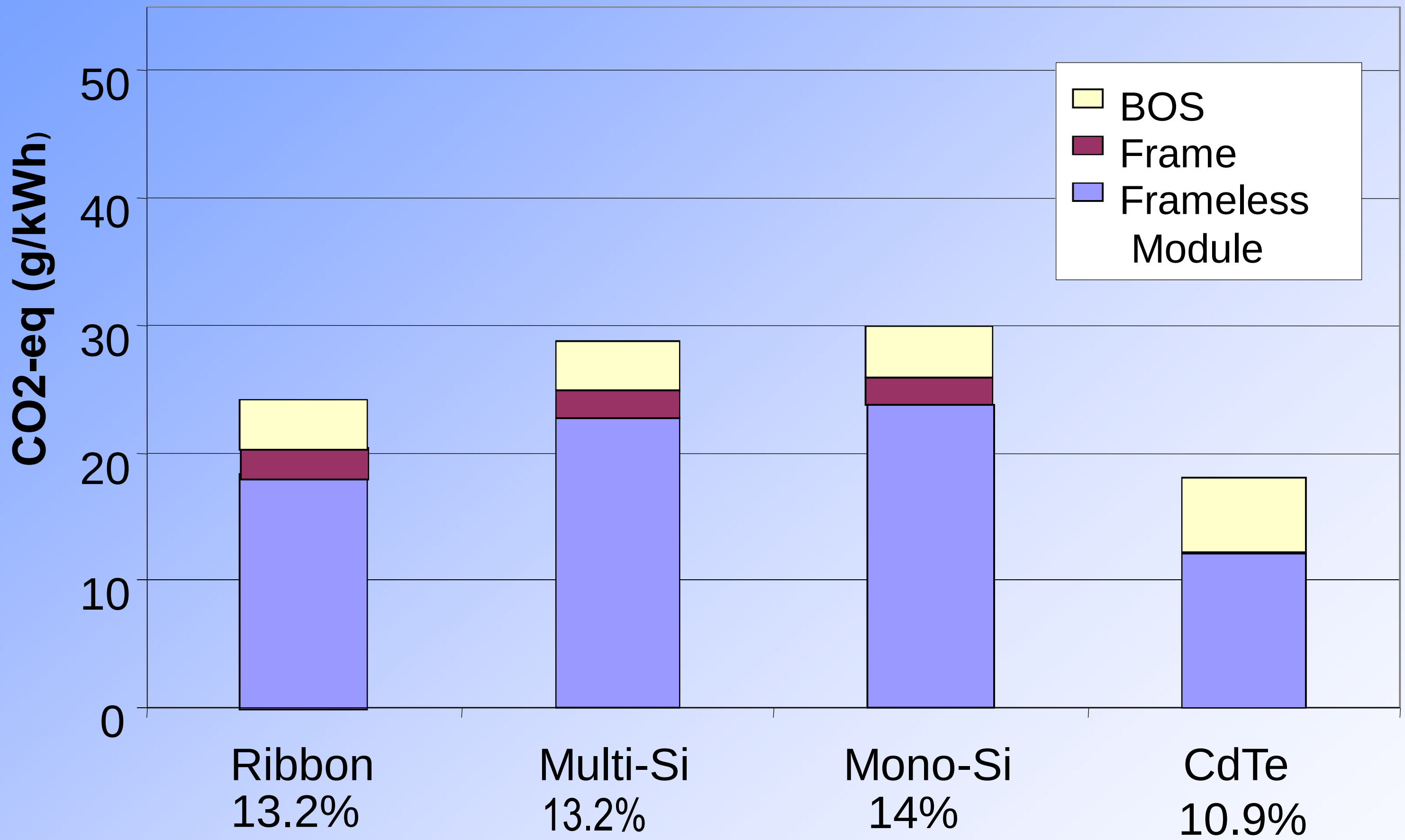


Based on data from 13 US and European PV manufacturers

- ***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*

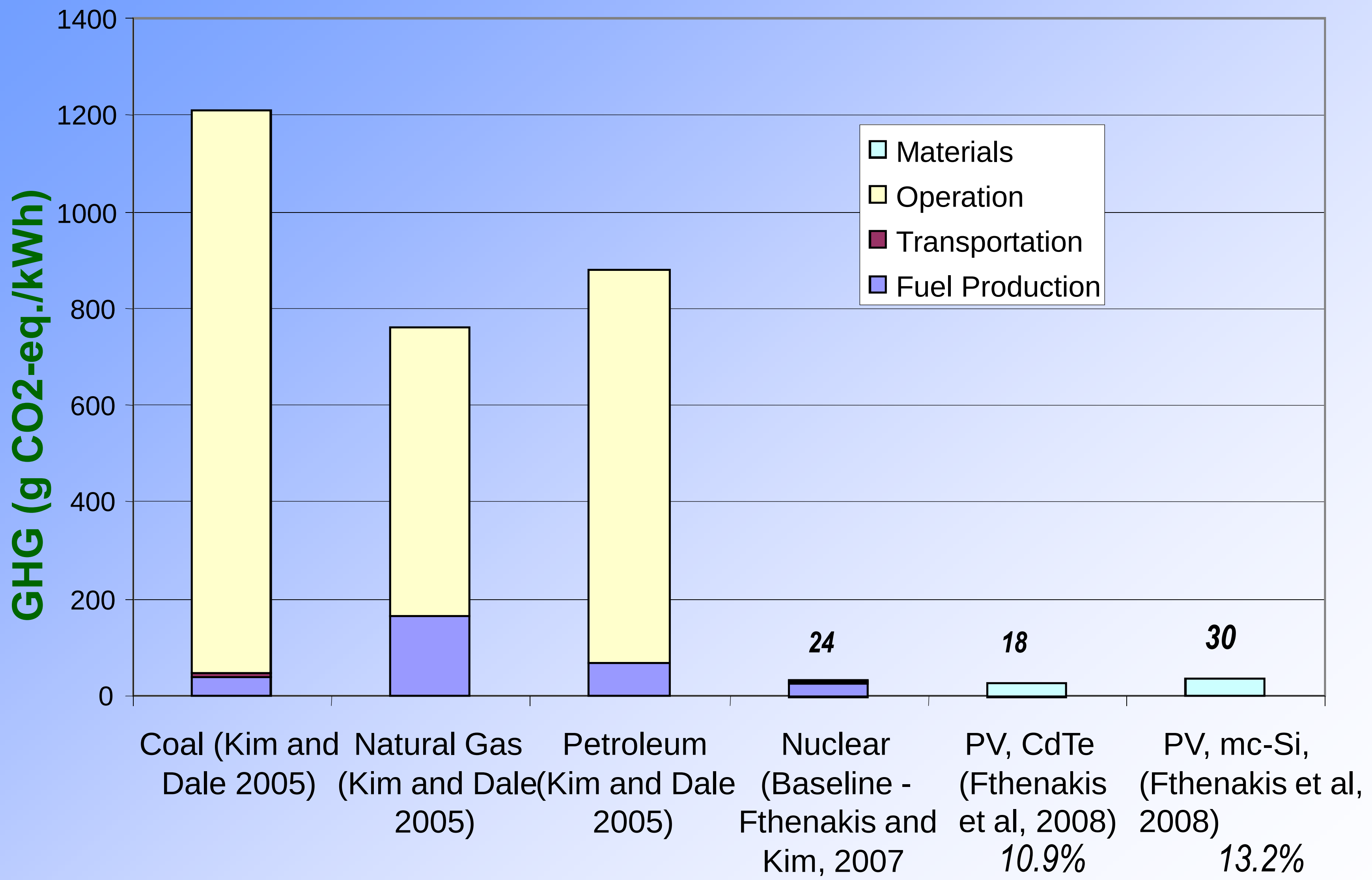
Greenhouse Gas (GHG) Emissions

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



California Energy Commission, *Nuclear Issues Workshop*, June 2007
Fthenakis & Kim, Life Cycle Emissions…, *Energy Policy, 35, 2549, 2007*
Fthenakis & Kim, *ES&T, 42, 2168, 2008*

Dual and Ecological-friendly Use 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 m^2 /GWh

Land requirement for US surface coal mining:
320 m^2 /GWh

Fthenakis V. and Kim H.C., *Sustainable and Renewable Energy Reviews*, 2009

CdTe PV Product Life –Accidental Releases

- **Leaching from shuttered modules**
  - Å *10 mm fragments -Rain-worst-case scenario- " leached Cd concentration in the collected water is no higher than the German drinking water concentration."*
    (Steinberger, Frauhoffer Institute Solid State Technology, Progress in Photovoltaics, 1998)
  - Å *< 4 mm fragments "Leached Cd exceeds the limits for disposal in inert landfill but is lower than limits for ordinary landfills"*
    (Okkenhaug, Norgegian Geotechnical Institute, Report, 2010)
  - Å *< 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 IEEEPVSC, 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**

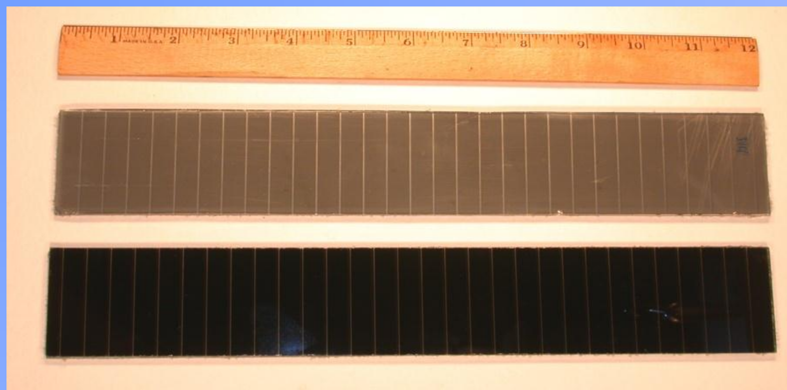
Negligible emissions during fires

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
French Ministry of Ecology, Energy, 2009

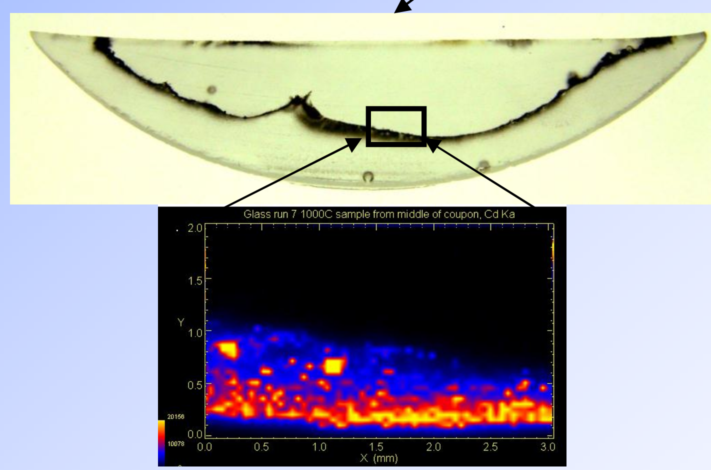
CdTe PV Fire-Simulation Tests: XRF Analysis

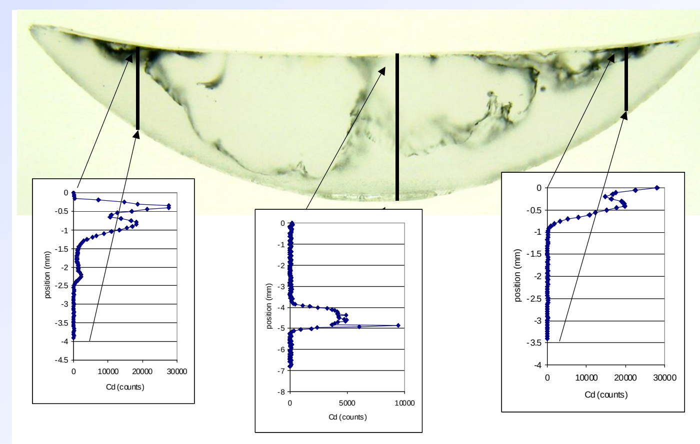


Heat

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

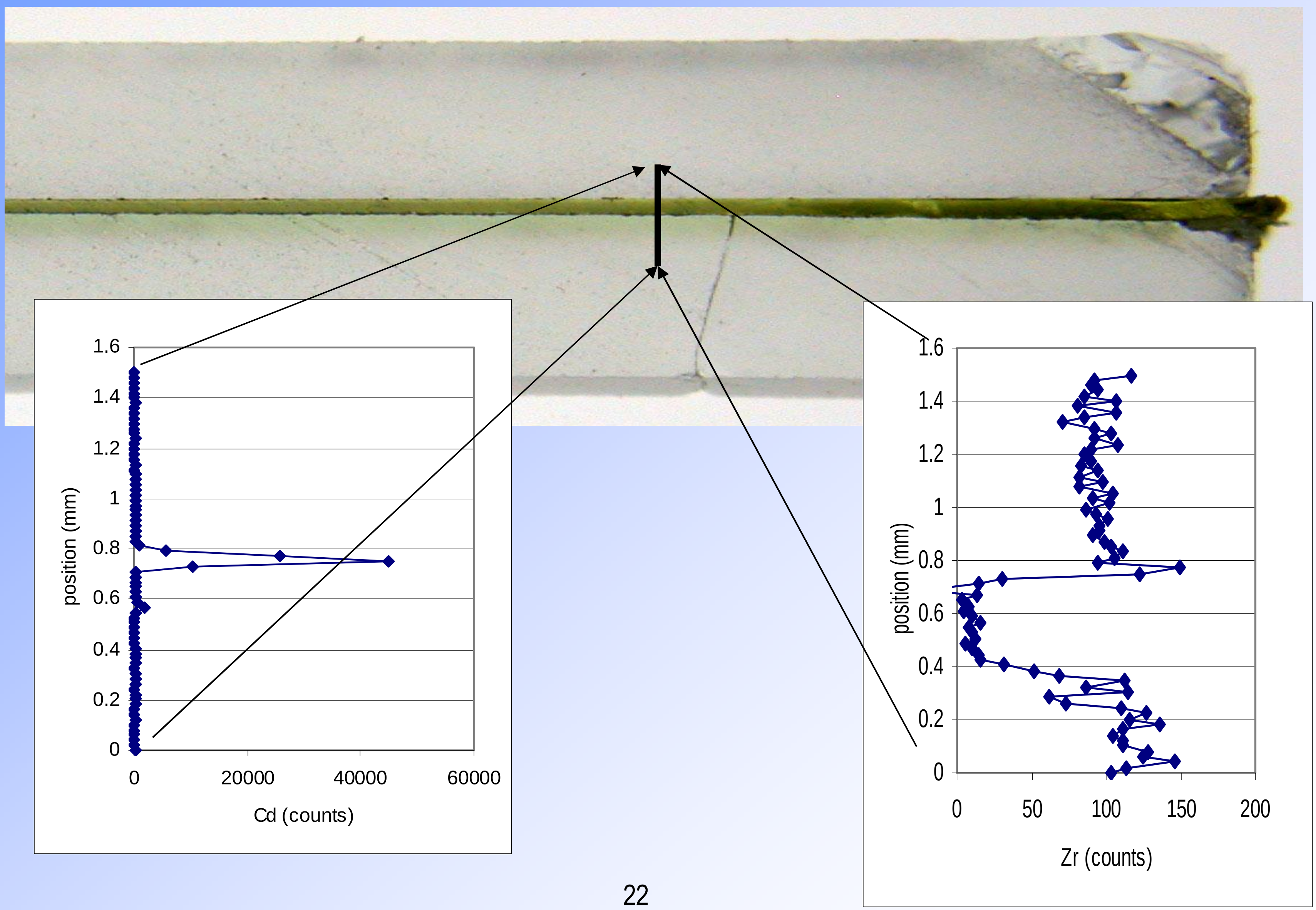
XRF-micro-probing –
Cd Distribution in PV Glass
1000 °C, right end of sample



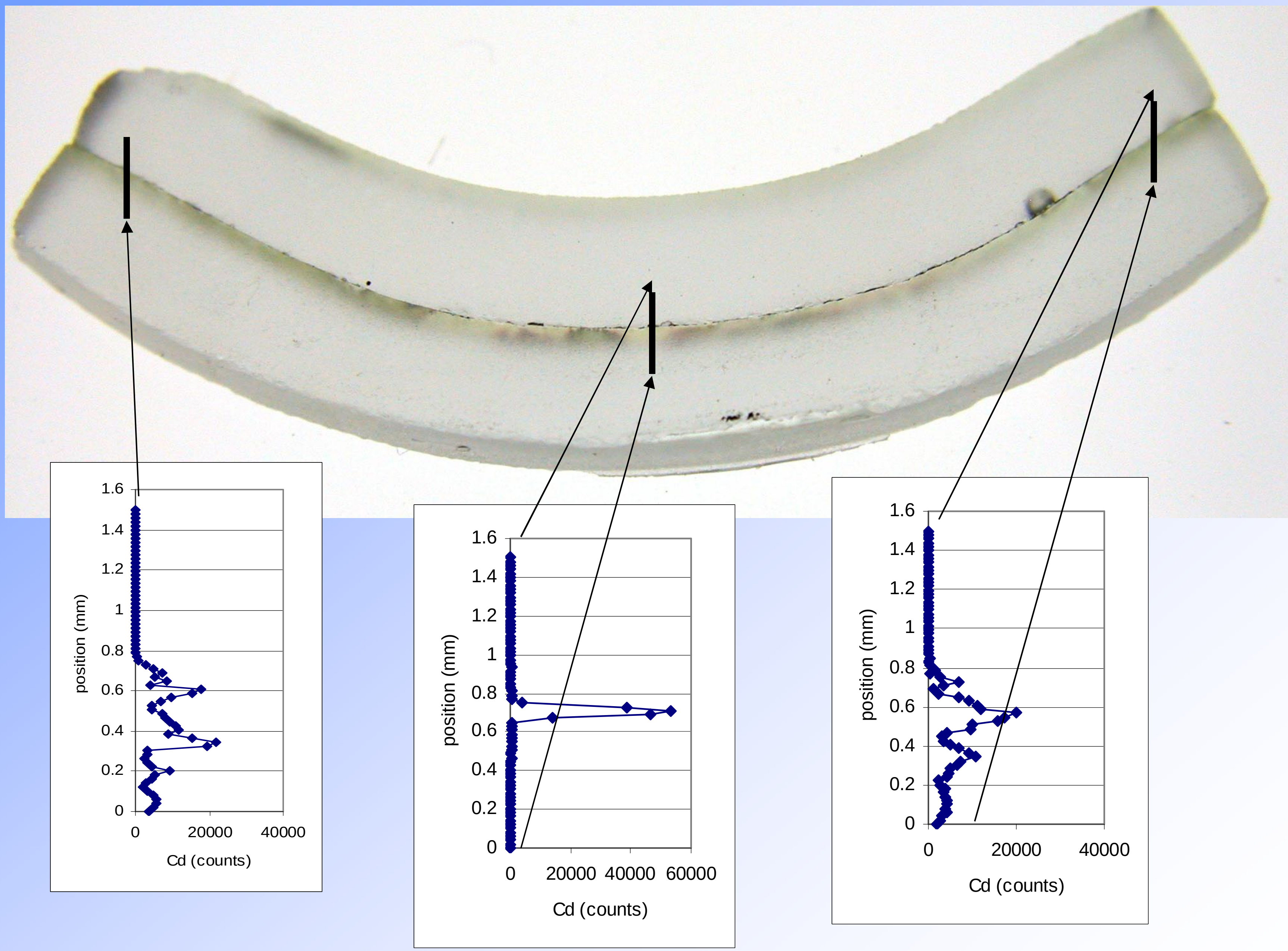


Fthenakis, Fuhrman, Heiser, Lanzirotti, Fitts and Wang, *Progress in Photovoltaics, 2005*

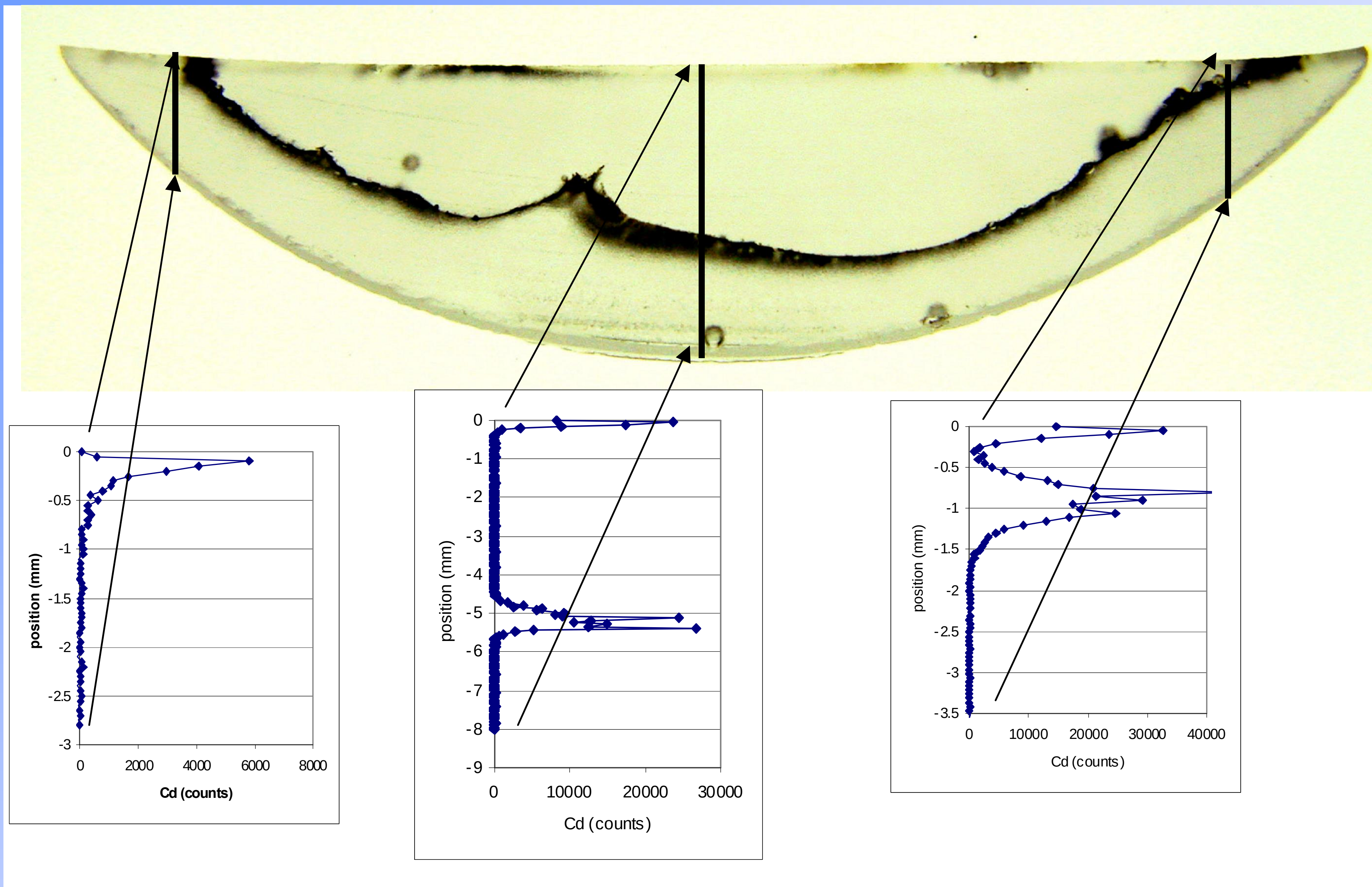
XRF-micro-probing -Cd & Zr distribution in PV sample
Unheated Sample -Vertical Cross Section



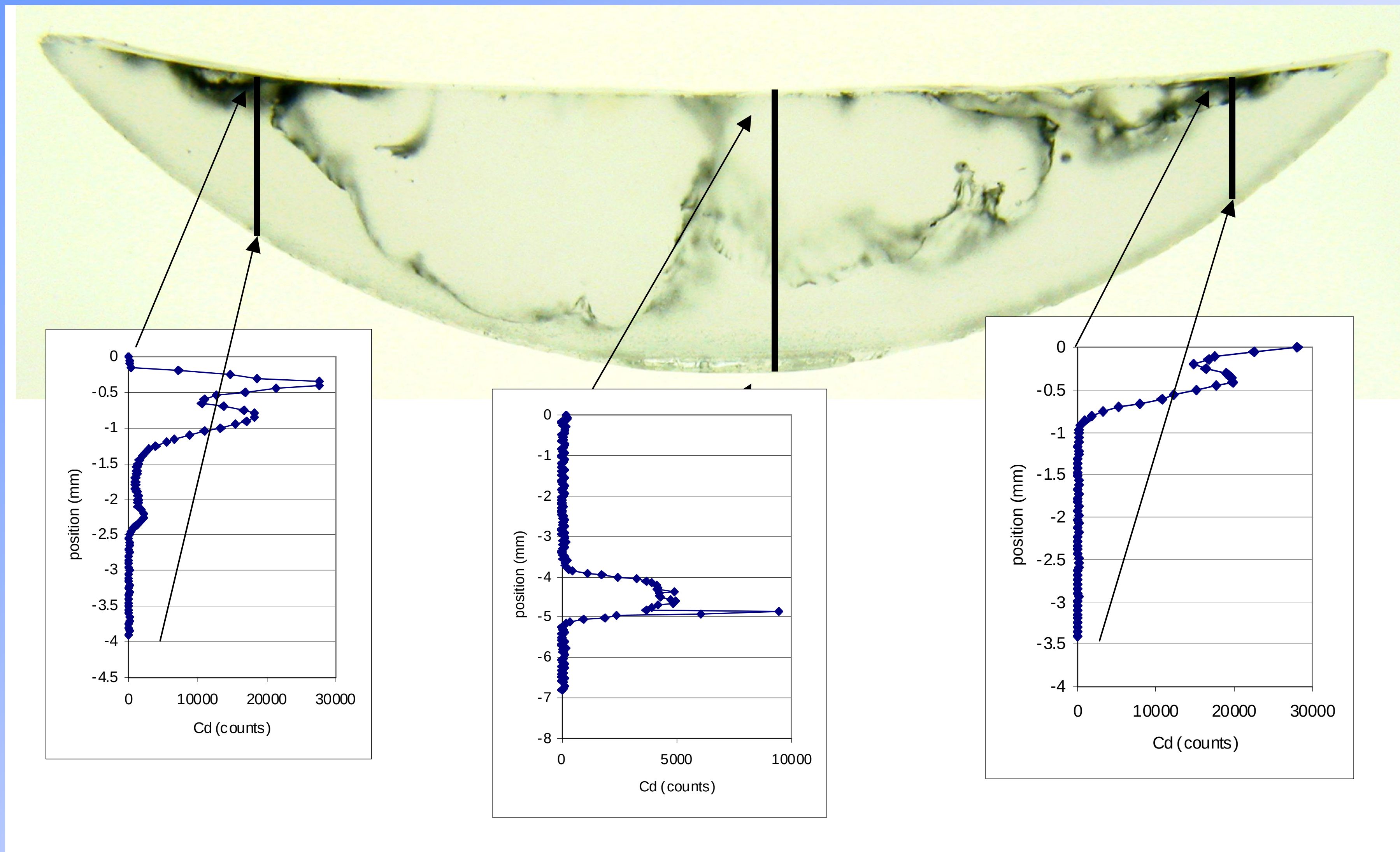
XRF-micro-probe -Cd distribution in PV sample 760 ° C, Section taken from middle of sample



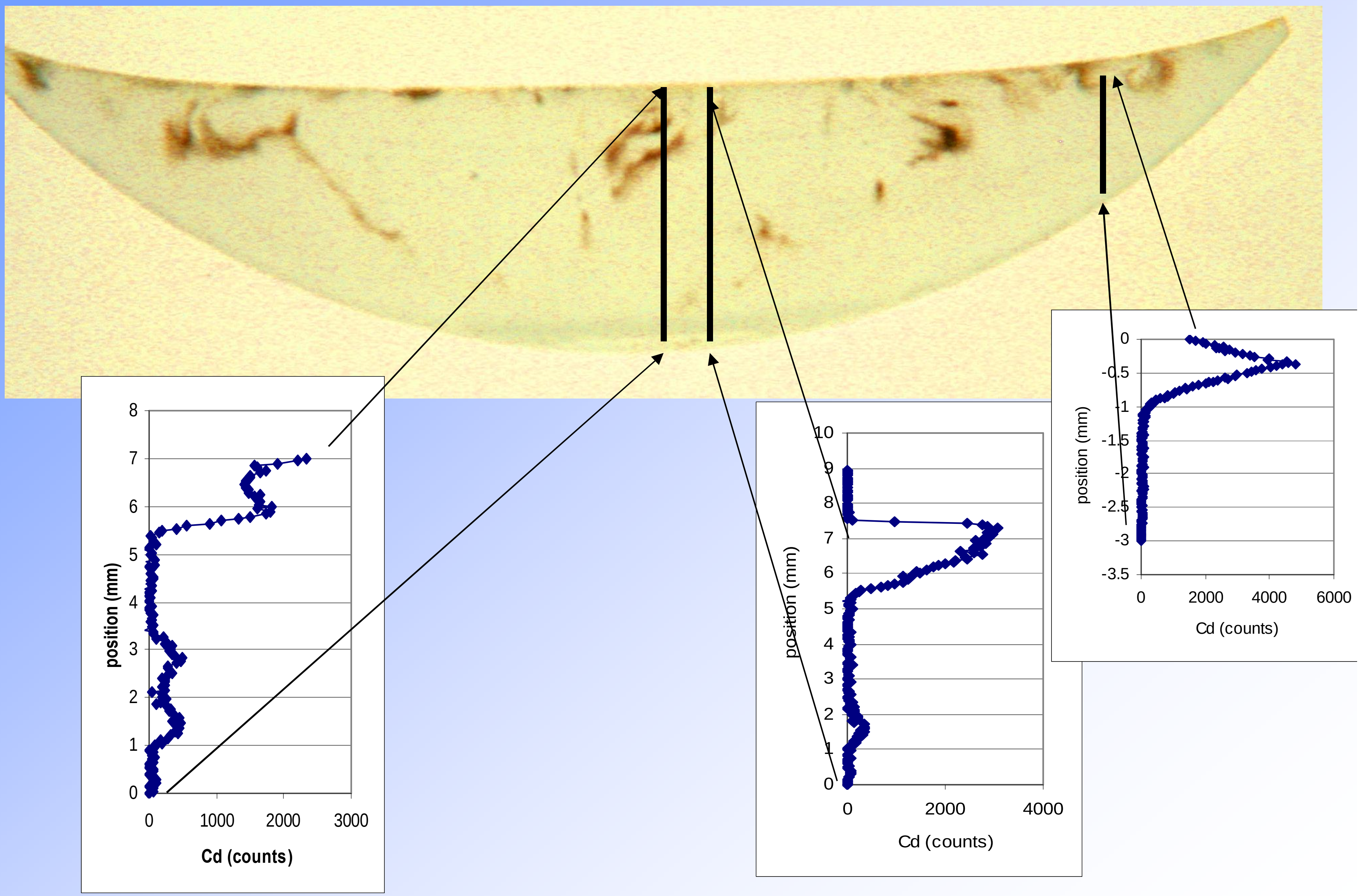
XRF-micro-probe -Cd distribution in PV sample 1000 ° C, Section taken from middle of sample



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

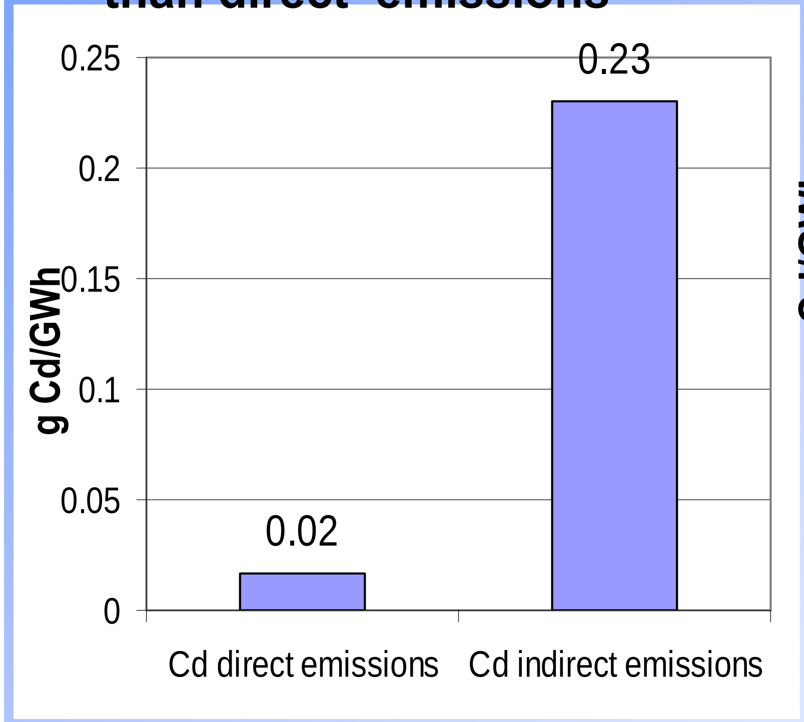
Process	(g Cd/ton Cd*)	(%)	(mg Cd/GWh)
1. Mining of Zn ores	2.7	0.58	0.02
2. Zn Smelting/Refining	40	0.58	0.30
3. Cd purification	6	100	7.79
4. CdTe Production	6	100	7.79
5. CdTe PV Manufacturing	0.4*	100	0.52*
6. CdTe PV Operation	0.05	100	0.06
7. CdTe PV Recycling	0.1*	100	0.13*
TOTAL EMISSIONS			16.55

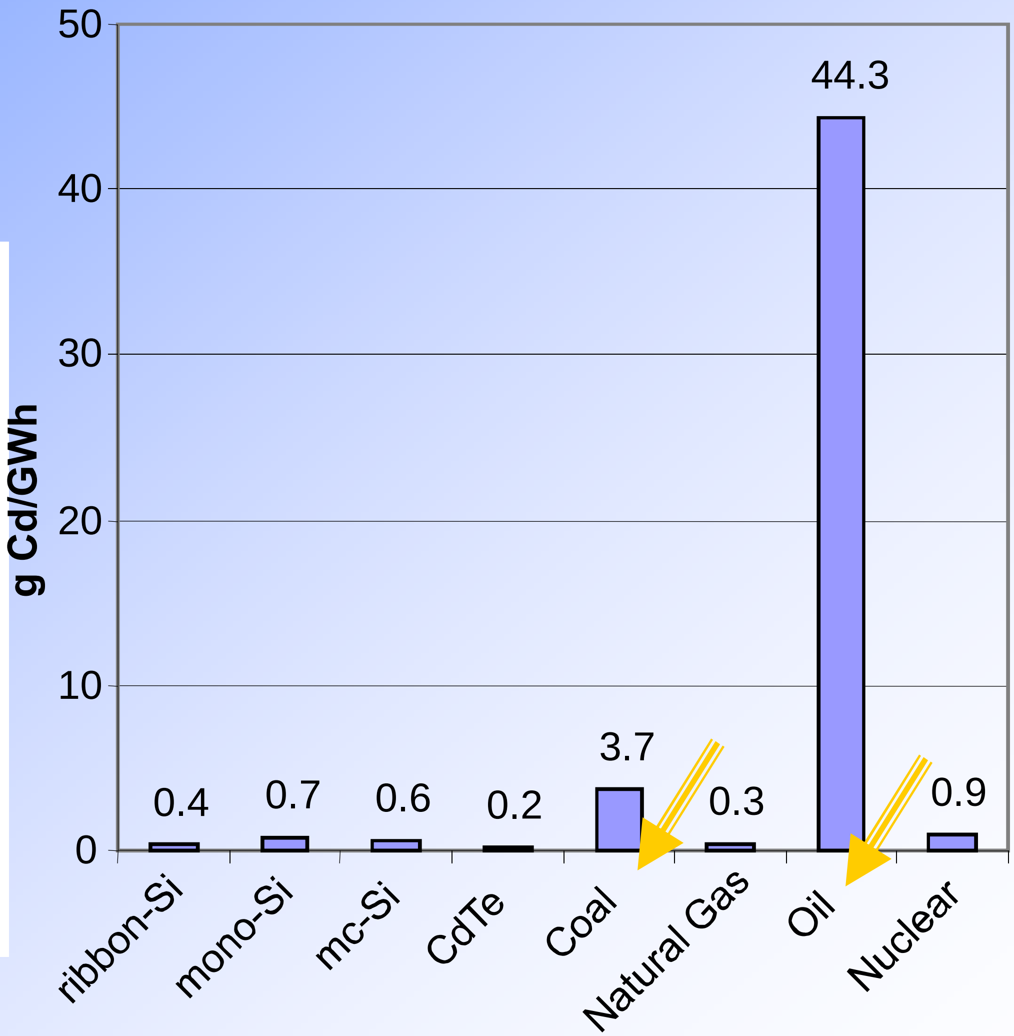
* 2009 updates

Fthenakis V. Renewable and Sustainable Energy Reviews, 8, 303-334, 2004

Total Life-Cycle Cd Atmospheric Emissions

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





Fthenakis and Kim, *Thin-Solid Films*, 515(15), 5961, 2007

Fthenakis, Kim & Alsema, Environ. Sci. Technol, 42, 2168, 2008

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

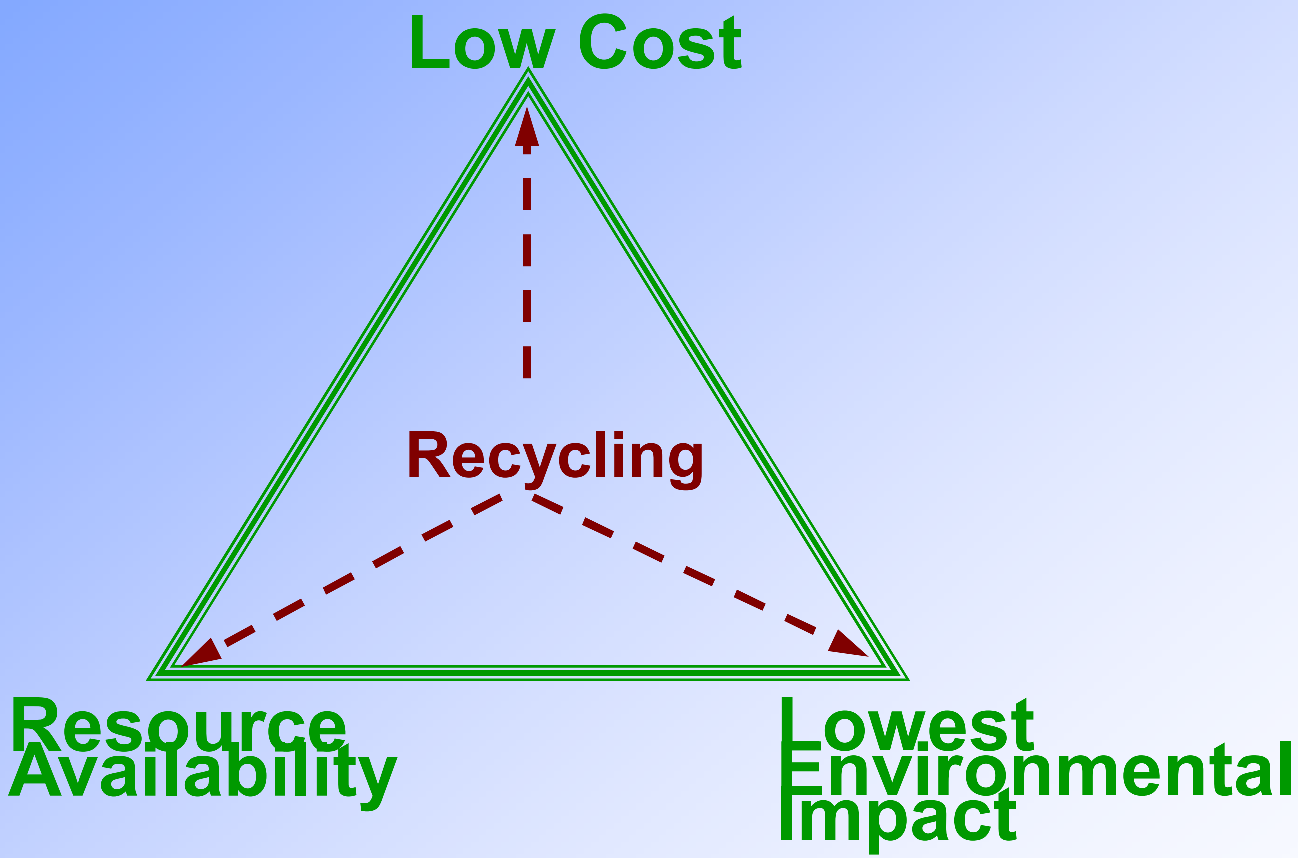
- Potential of environmental impacts from uncontrolled disposal of PV

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



Conclusion

- 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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