Holistic Life Cycle Analysis: Focus on CdTe Photovoltaics

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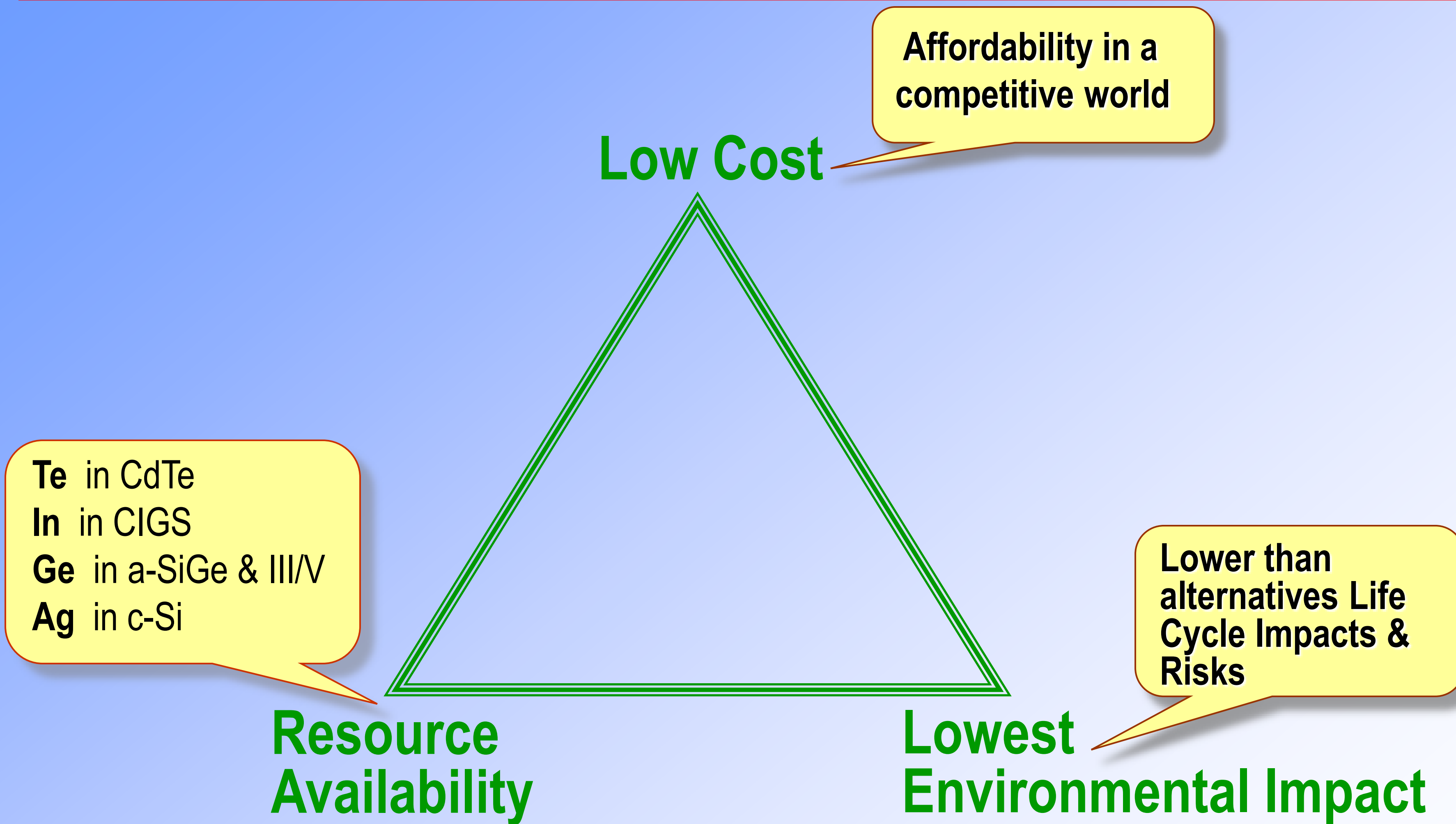
Presentation at the SwissPhotonics Workshop,
Environmental and Economic Impact of PV Energy Production
EMPA, Zurich, 22 October 2013

CU-BNL: Outcomes from LCA research

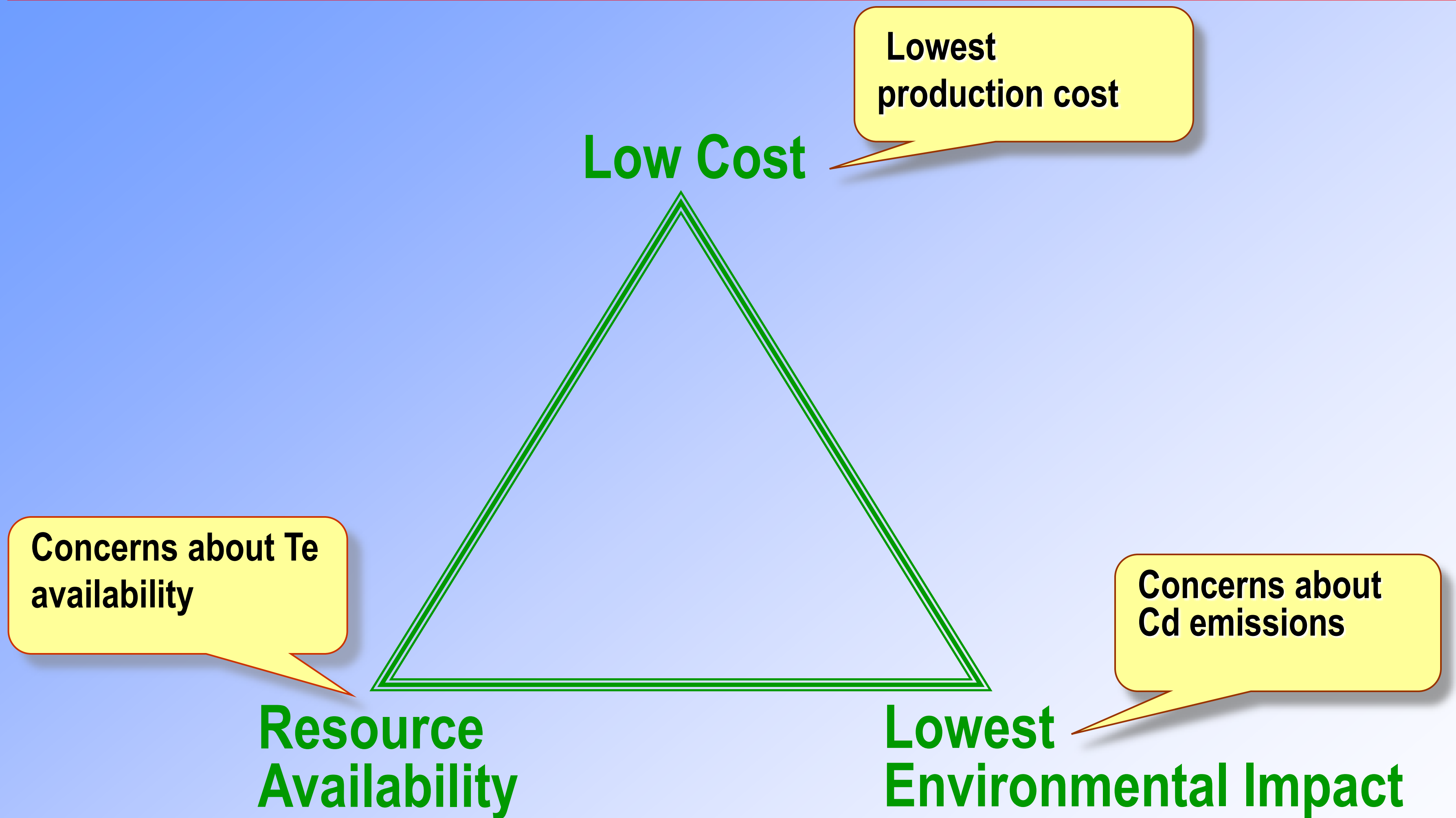
- Original, data-based LCA on current & emerging PV technologies
  - CdTe PV
  - High-efficiency mono-crystalline PV
  - High Concentration PV (Si and III/V)
  - GIGS PV
  - Advanced c-Si PV
  - Organic PV
- Corrected misrepresentations of PV environmental profiles
  - Emissions
  - Energy Payback Times–Energy Return on Investment
  - Land use
  - Risks
- Addressing sustainability of large-scale deployment
  - Materials availability
  - Recycling technologies
  - PV variability –Grid integration
- Effective Dissemination of research results
  - Bibliography of 300 articles, ~60 on LCA
  - www.bnl.gov/pv www.clca.columbia.edu

Large Scale PV –Sustainability Criteria



Zweibel, Mason & Fthenakis, A Solar Grand Plan, Scientific American, 2008
Fthenakis, Mason & Zweibel, The technical, geographical and economic feasibility for solar energy in the US, Energy Policy, 2009
Fthenakis, The sustainability of thin-film PV, Renewable & Sustainable Energy Reviews, 2009
Fthenakis, Sustainability metrics for extending thin-film PV to terawatt levels. MRS Bulletin, 2012.

Large Scale PV –Sustainability Criteria: Focus on CdTe PV



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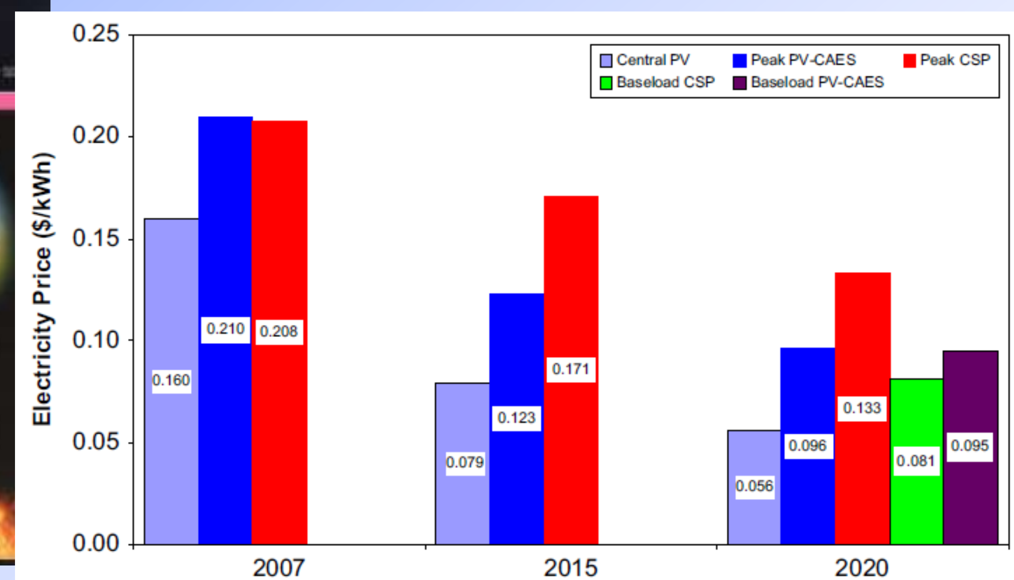
Fthenakis, Sustainability metrics for extending thin-film PV to terawatt levels. MRS Bulletin, 2012.

A Solar Grand Plan

By 2050 solar power could provide 69% of electricity & 35% of total energy demand in the U.S. *Sci. American, January 2008*



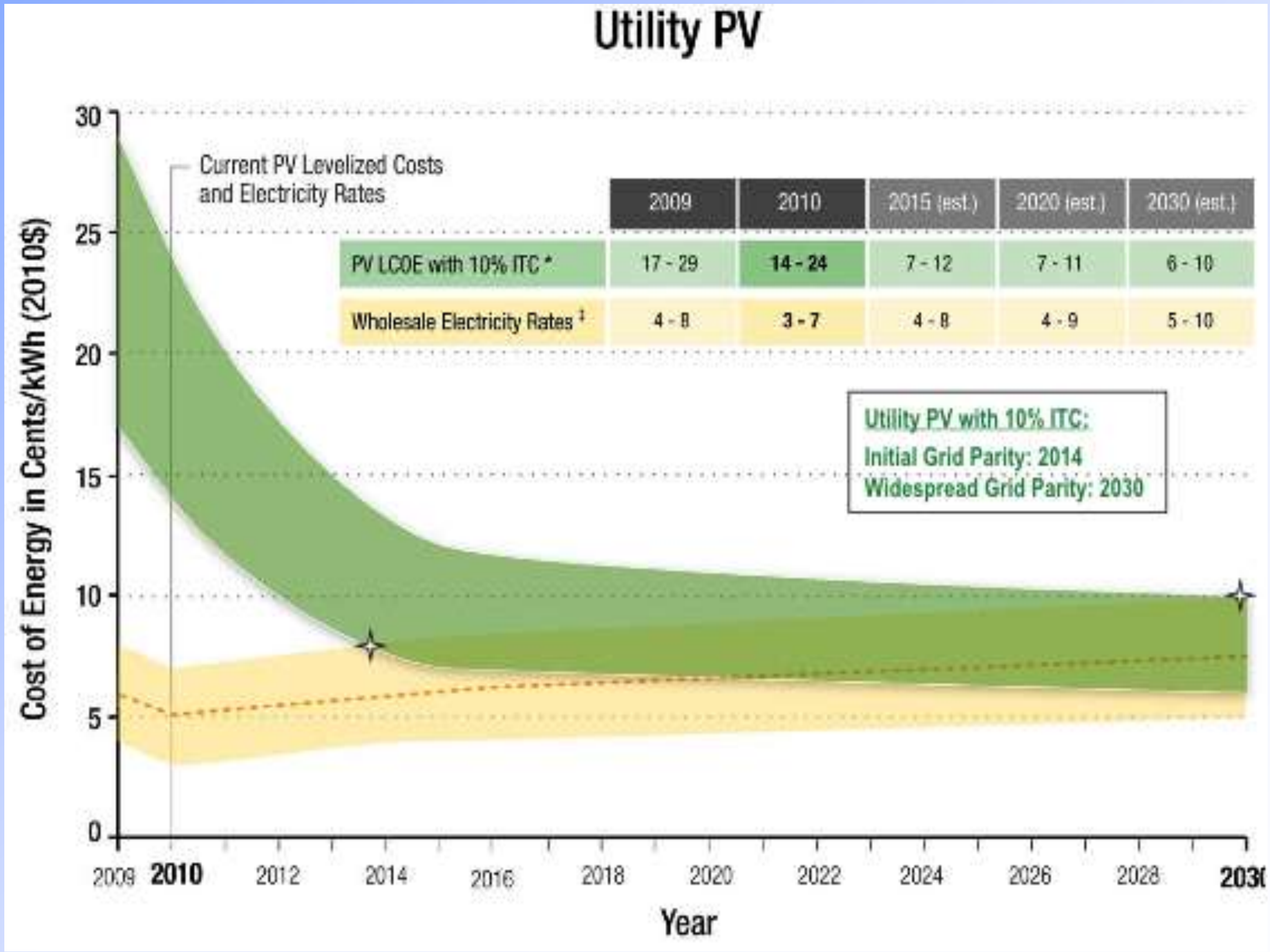
The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US

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

Affordability: Projected PV Growth and Electricity Price Targets

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

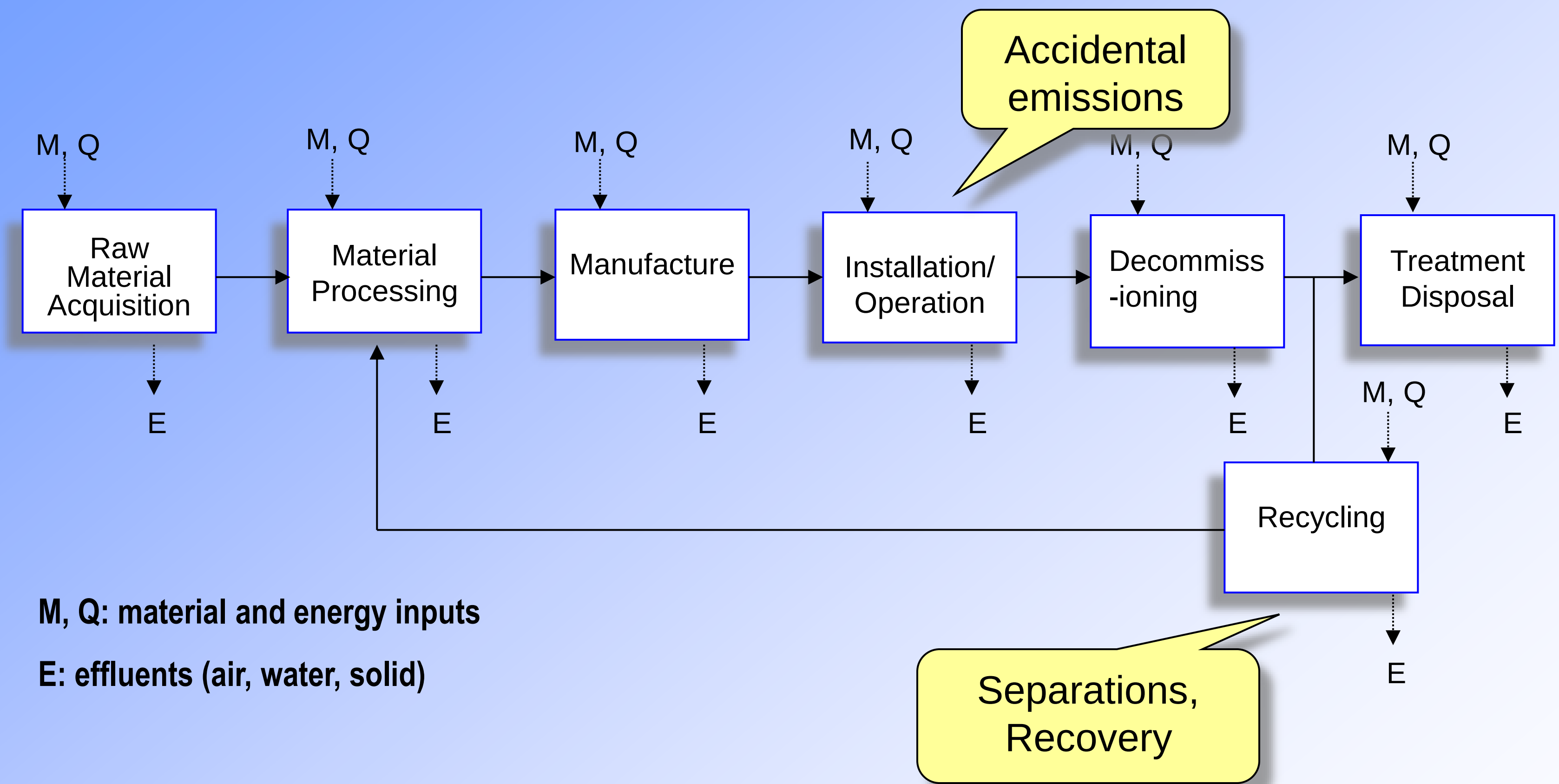
Financing Conditions
- Low: 8.2%
- High: 9.9%



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

Life Cycle Analysis

Experimental Research at BNL



M, Q: material and energy inputs

E: effluents (air, water, solid)

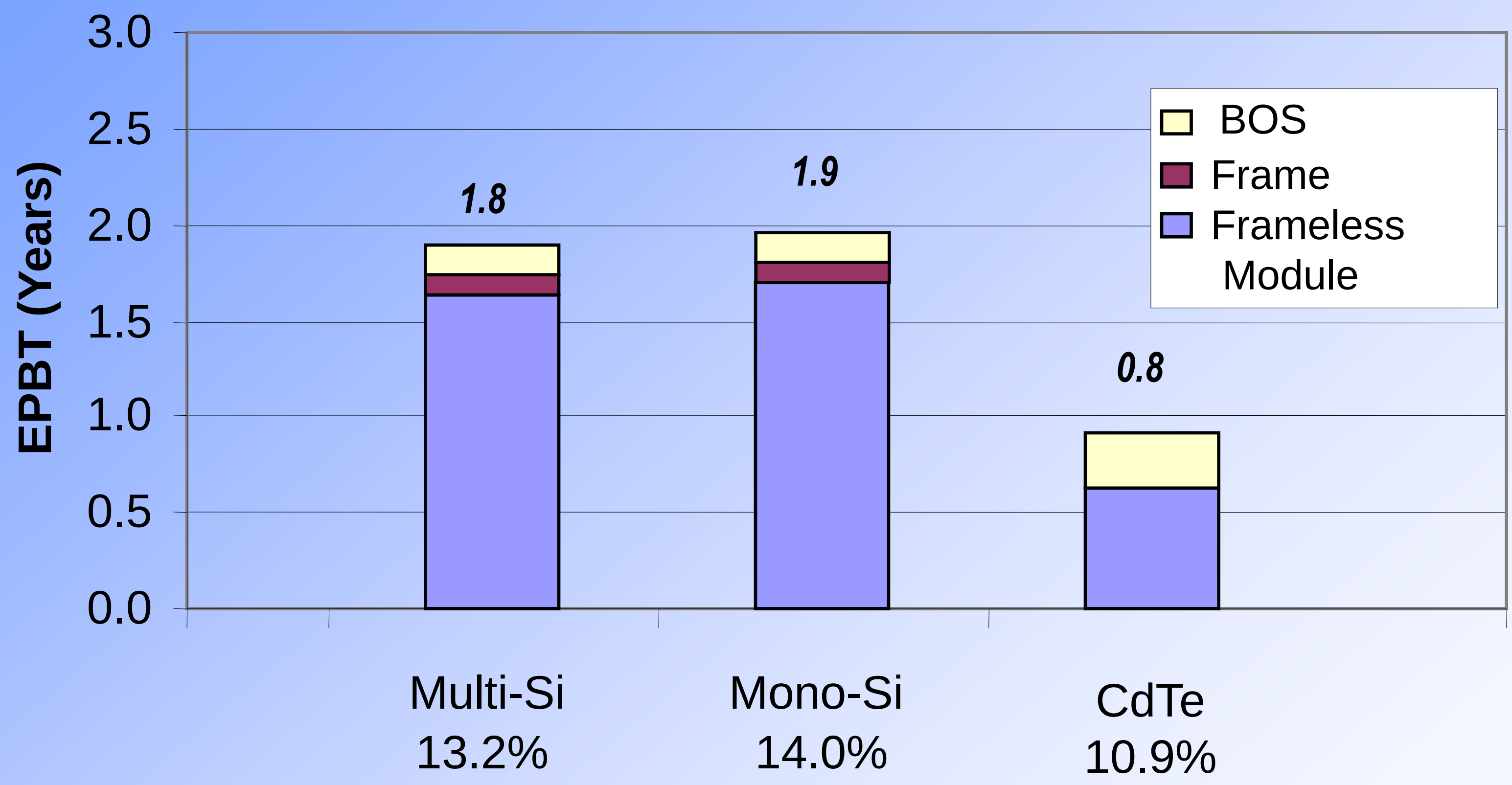
Comparative Life-Cycle Analysis Metrics

- Energy Payback Times (EPBT) and Energy Return on Investment (EROI)
- Greenhouse Gas Emissions
- Toxic 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)

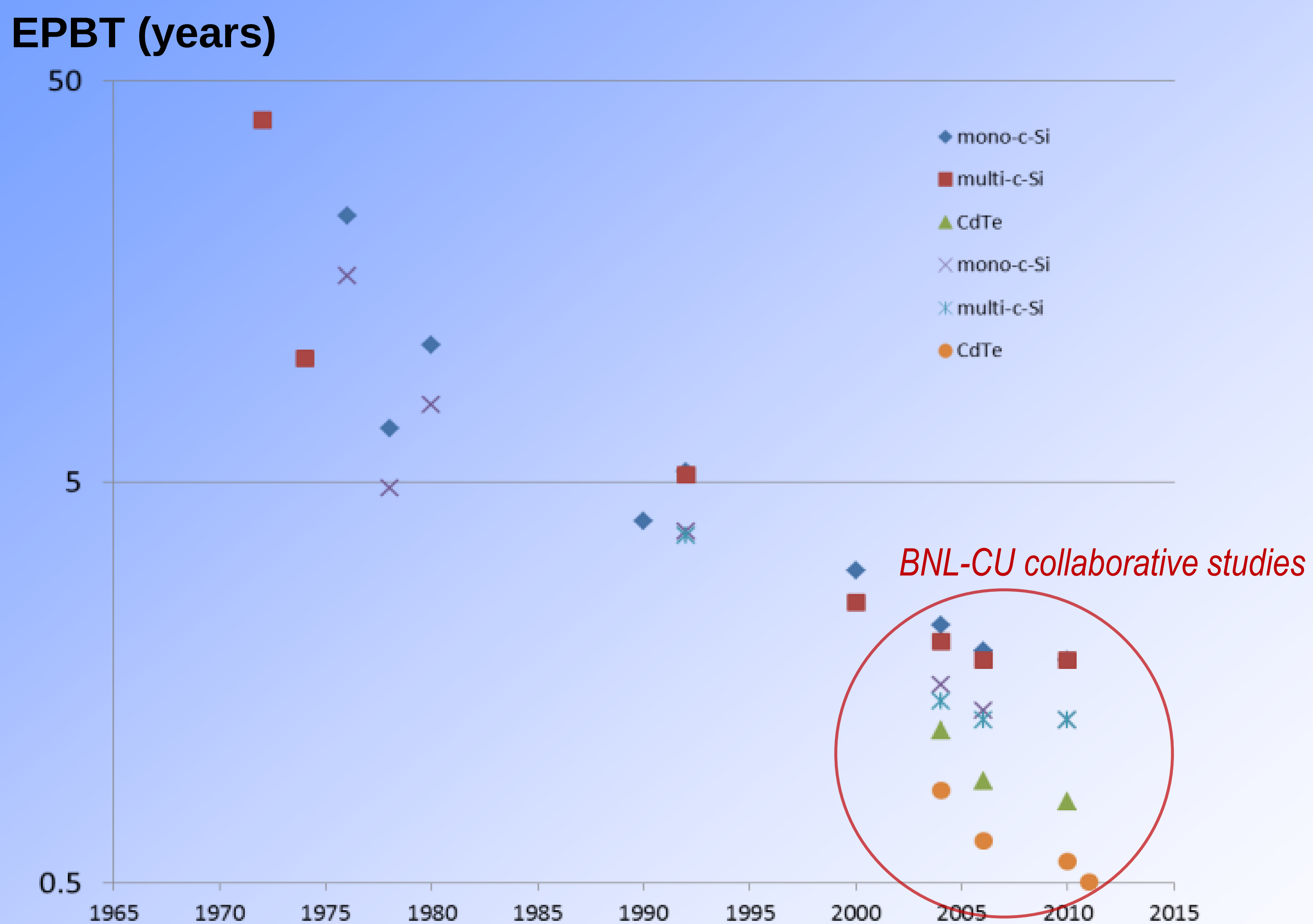
Insolation: 1700 kWh/m^2-yr (Southern Europe)



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*

EPBT Historical Evolution

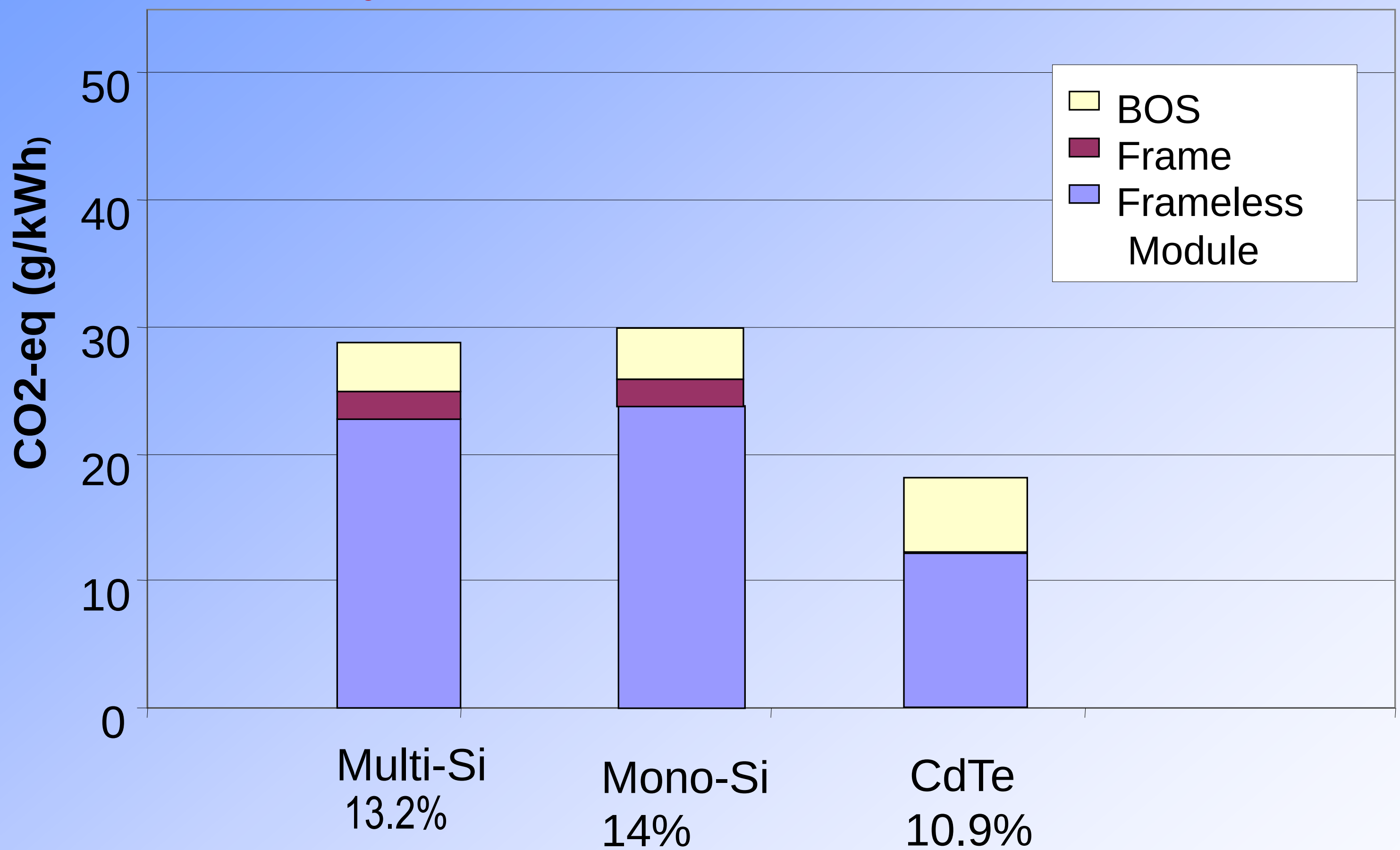


Irradiation of 1700 and 2400 kWh/m^2/yr

Fthenakis, PV Energy ROI Tracks Efficiency Gains, *Solar Today*, 2012

Greenhouse Gas (GHG) Emissions

Insolation: 1700 kWh/m2-yr



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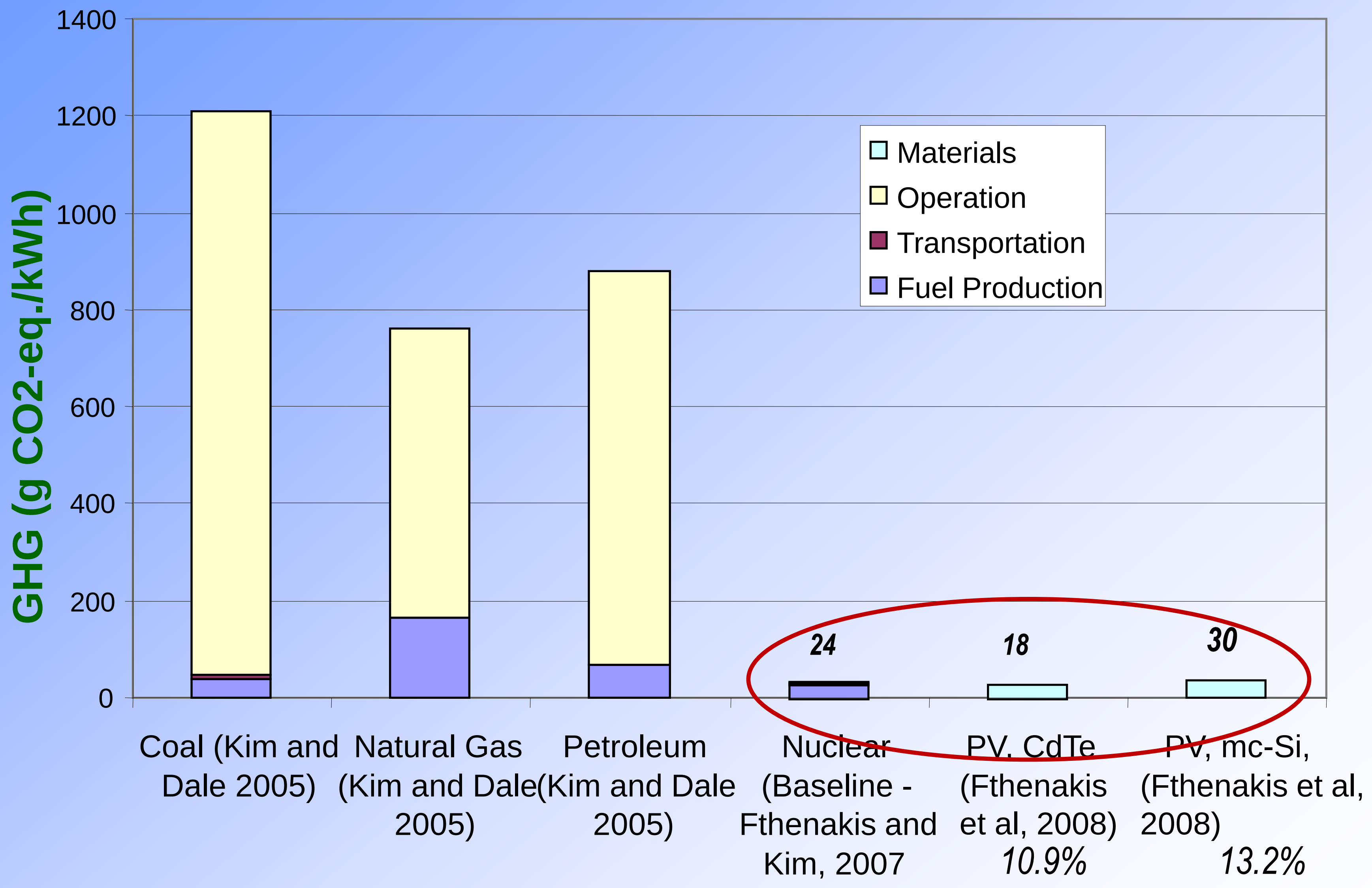
- ***Fthenakis et al.,*** *EUPV, 2009*
- **deWild 2009**, *EUPV, 2009*
- **Fthenakis, Kim & Alsema,** *ES&T, 42, 2168, 2008*
- **Alsema & deWild,** *Material Research Society, Symposium, 895, 73, 2006*
- **deWild & Alsema,** *Material Research Society, Symposium, 895, 59, 2006*
- **Fthenakis & Kim,** *Material Research Society, Symposium, 895, 83, 2006*
- **Fthenakis & Alsema,** *Progress in Photovoltaics, 14, 275, 2006*

GHG Emissions from Life Cycle of Electricity Production: Comparisons

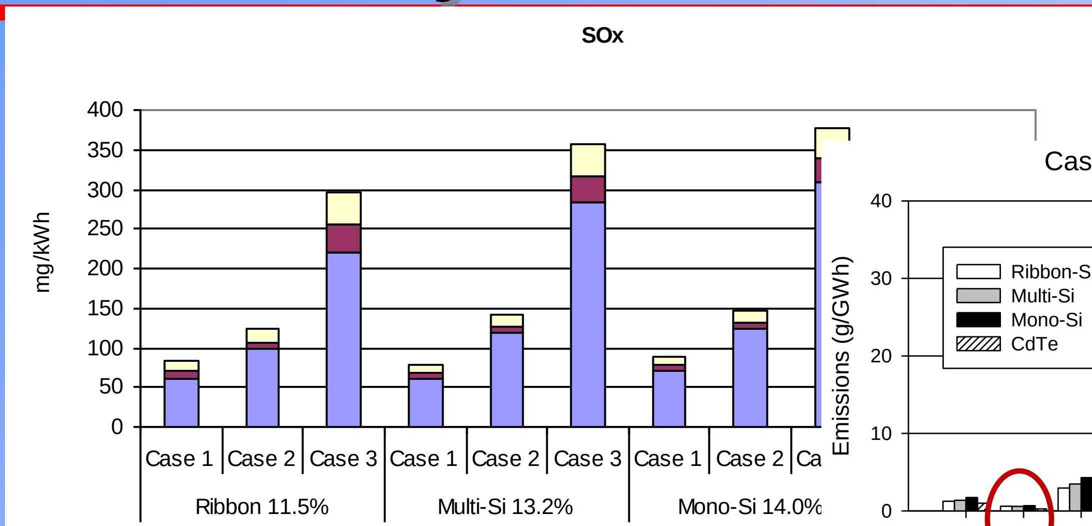


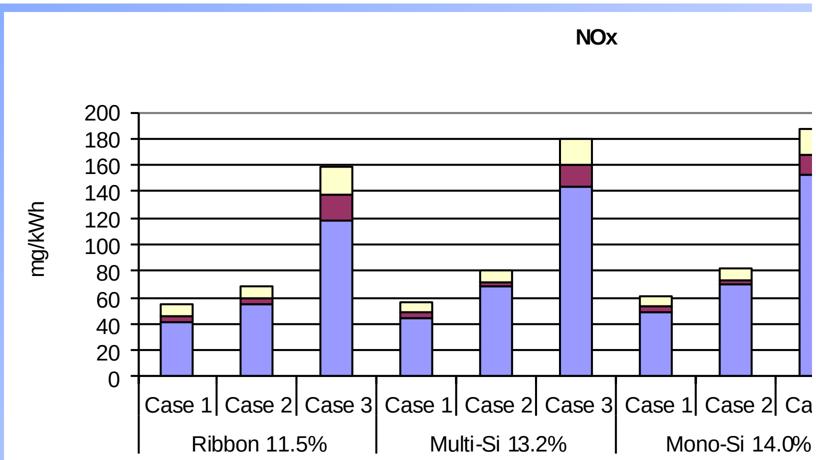
Fthenakis, California Energy Commission, *Nuclear Issues Workshop*, June 2007

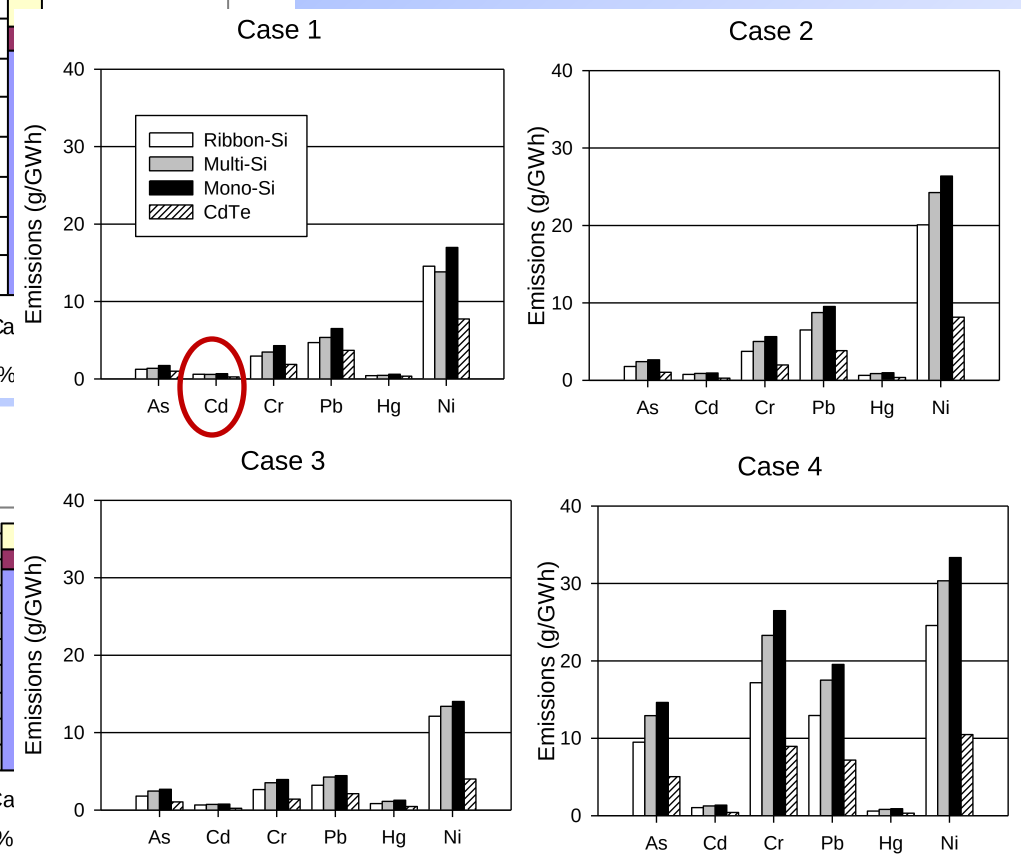
Fthenakis & Kim, Life Cycle Emissions…, *Energy Policy, 35, 2549, 2007*

Fthenakis & Kim*, ES&T, 42, 2168, 2008*

Life-cycle Toxic Emissions







Case 1- 2006 electricity mixture in Si production-Crystal Clear project;

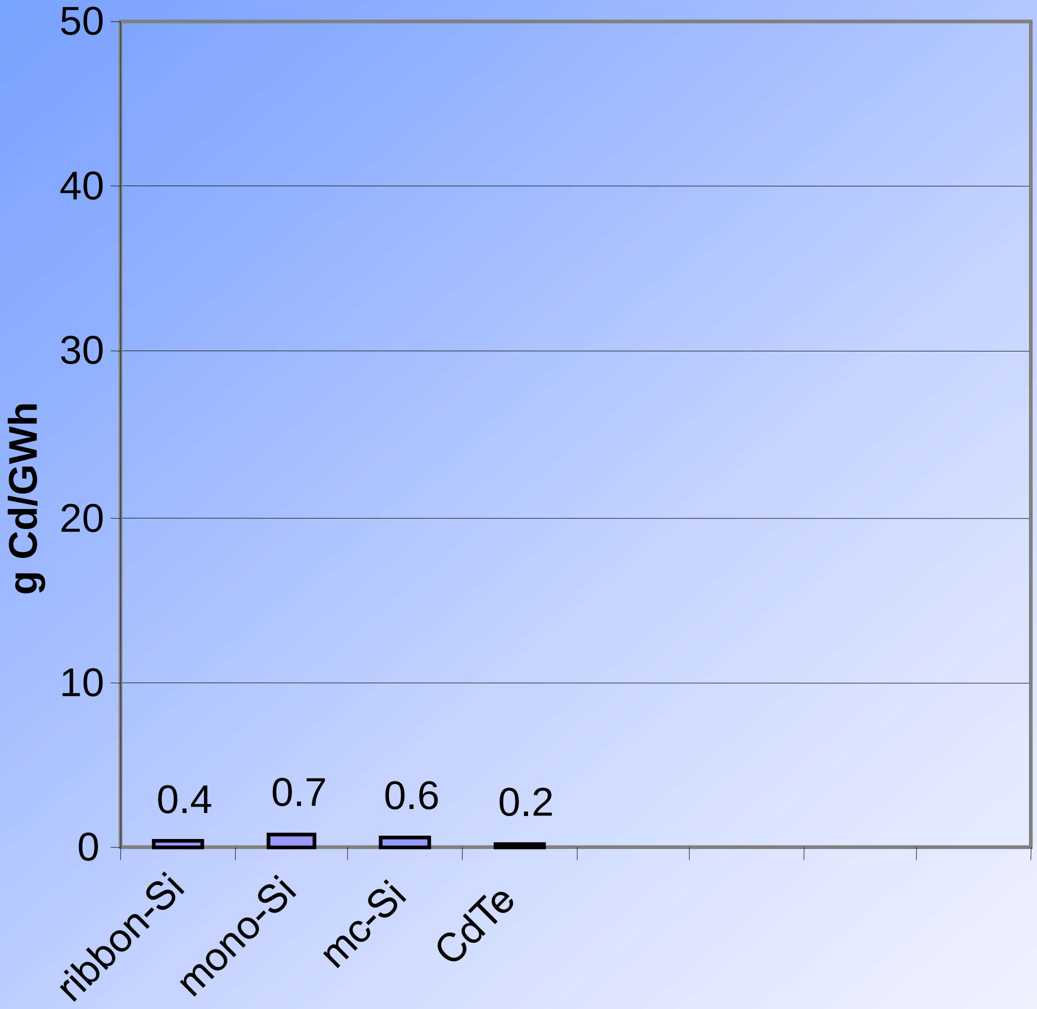
Case 2- UCTE grid mixture & EcoInvent database;

Case 3- US grid mixture & Franklin database.

Ground-mounted, Southern European insolation, 1700 kWh/m2/yr, performance ratio =0.8, lifetime=30 years

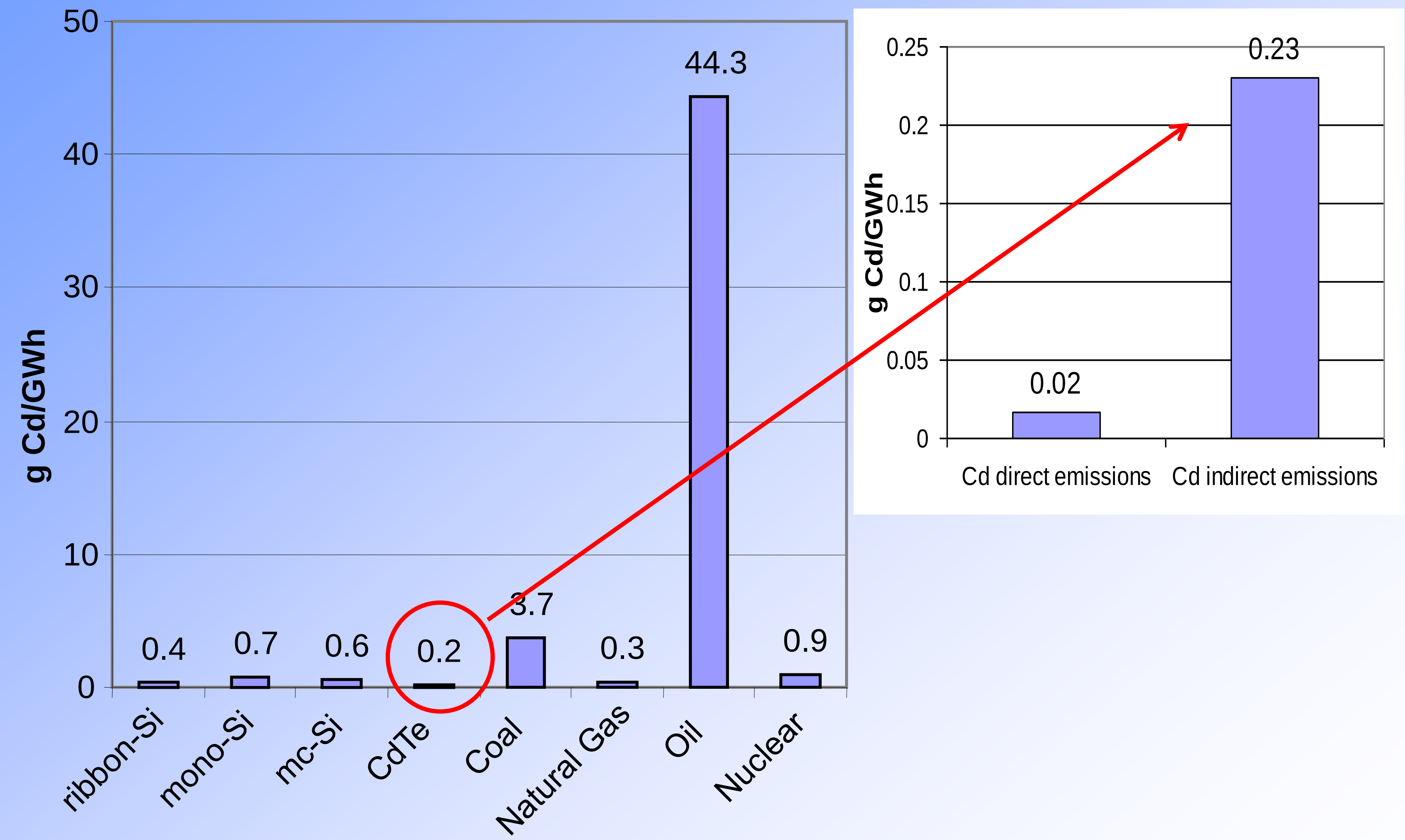
Fthenakis, Kim and Alsema, *Environmental Science & Technology,* 2008

Life-Cycle Cd Atmospheric Emissions



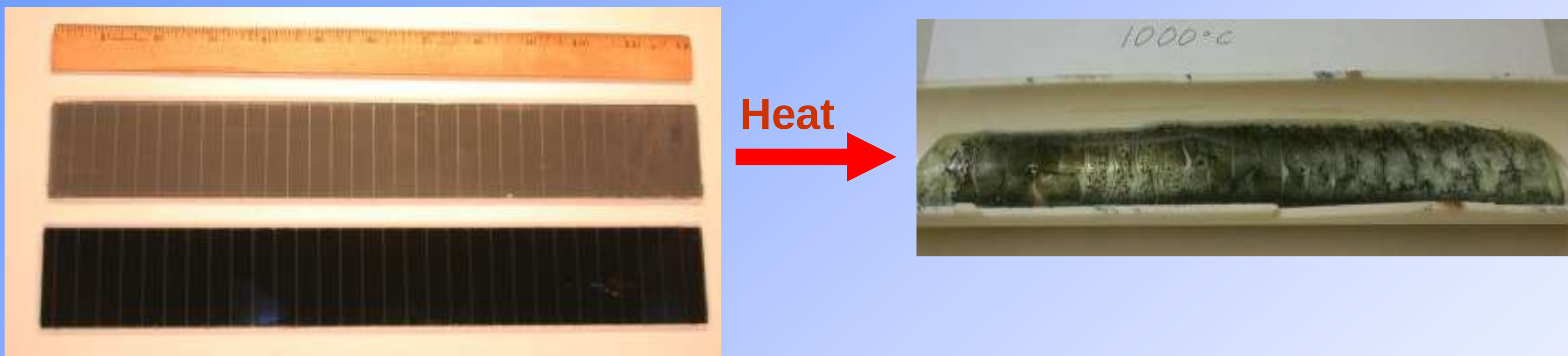
Fthenakis and Kim, *Thin-Solid Films*, 515(15), 5961, 2007
Fthenakis, Kim & Alsema, *Environ. Sci. Technol*, 42, 2168, 2008

Life-Cycle Cd Atmospheric Emissions



Fthenakis and Kim, *Thin-Solid Films*, 515(15), 5961, 2007
Fthenakis, Kim & Alsema, *Environ. Sci. Technol*, 42, 2168, 2008

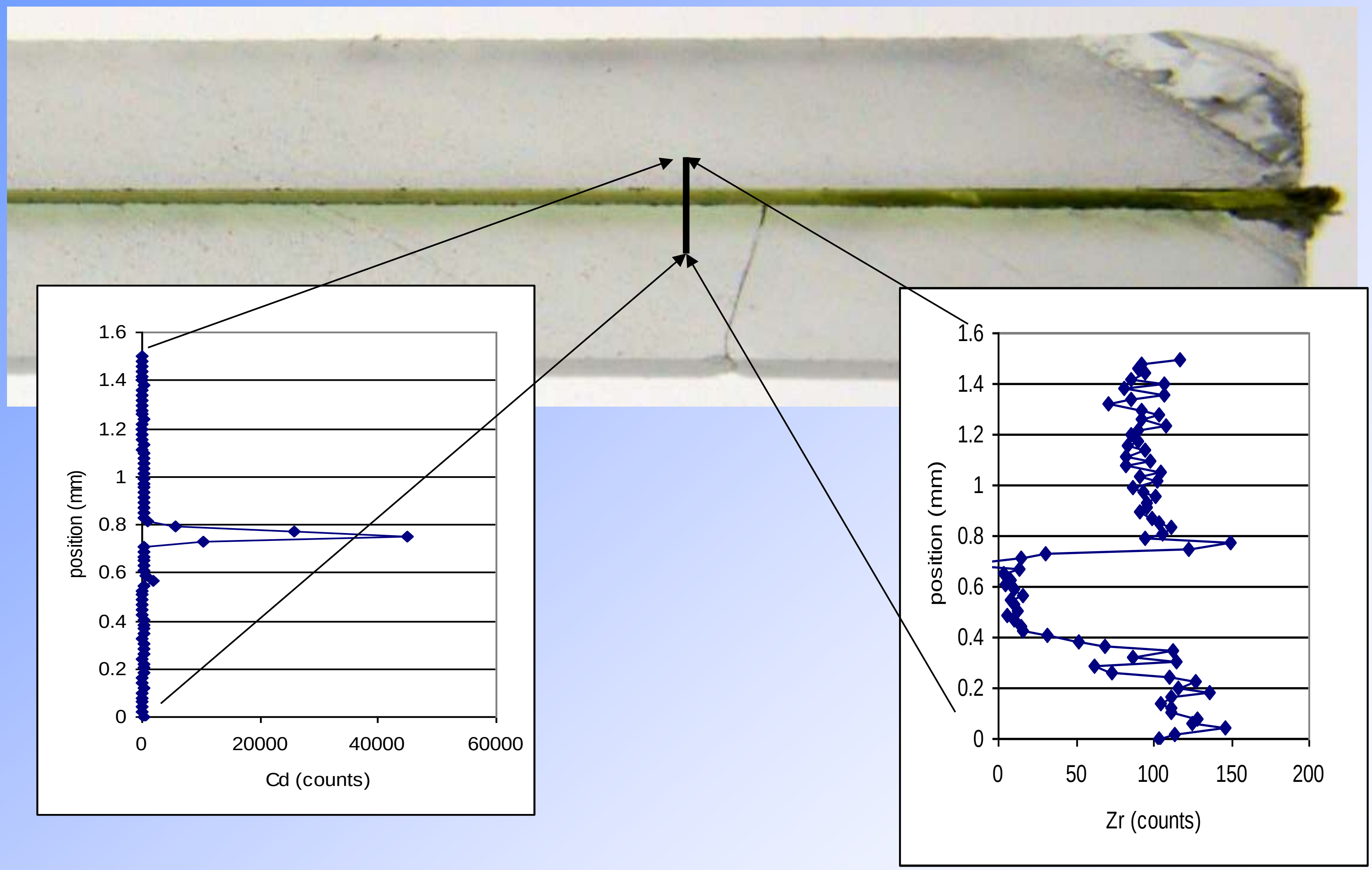
Simulations of Accidental Releases during Fires



- Weight Loss Measurements
- ICP Analysis of Cd & Te Emissions
- ICP Analysis of Cd & Te in Molten Glass
- X-ray Fluorescence Micro-Spectrometry of Cd in Molten Glass

Based on 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

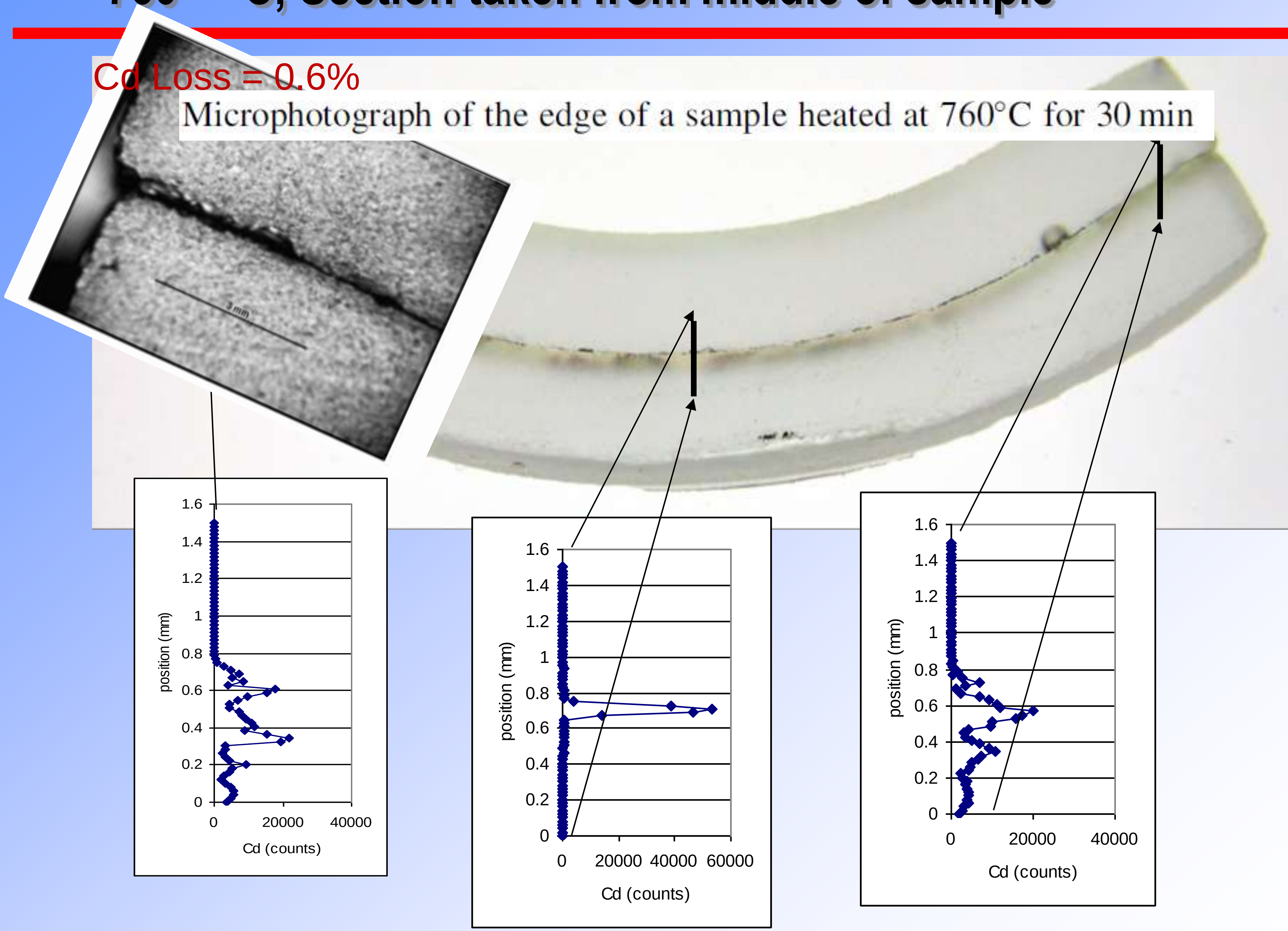
XRF-micro-probing -Cd & Zr distribution in PV sample
Unheated Sample -Vertical Cross Section



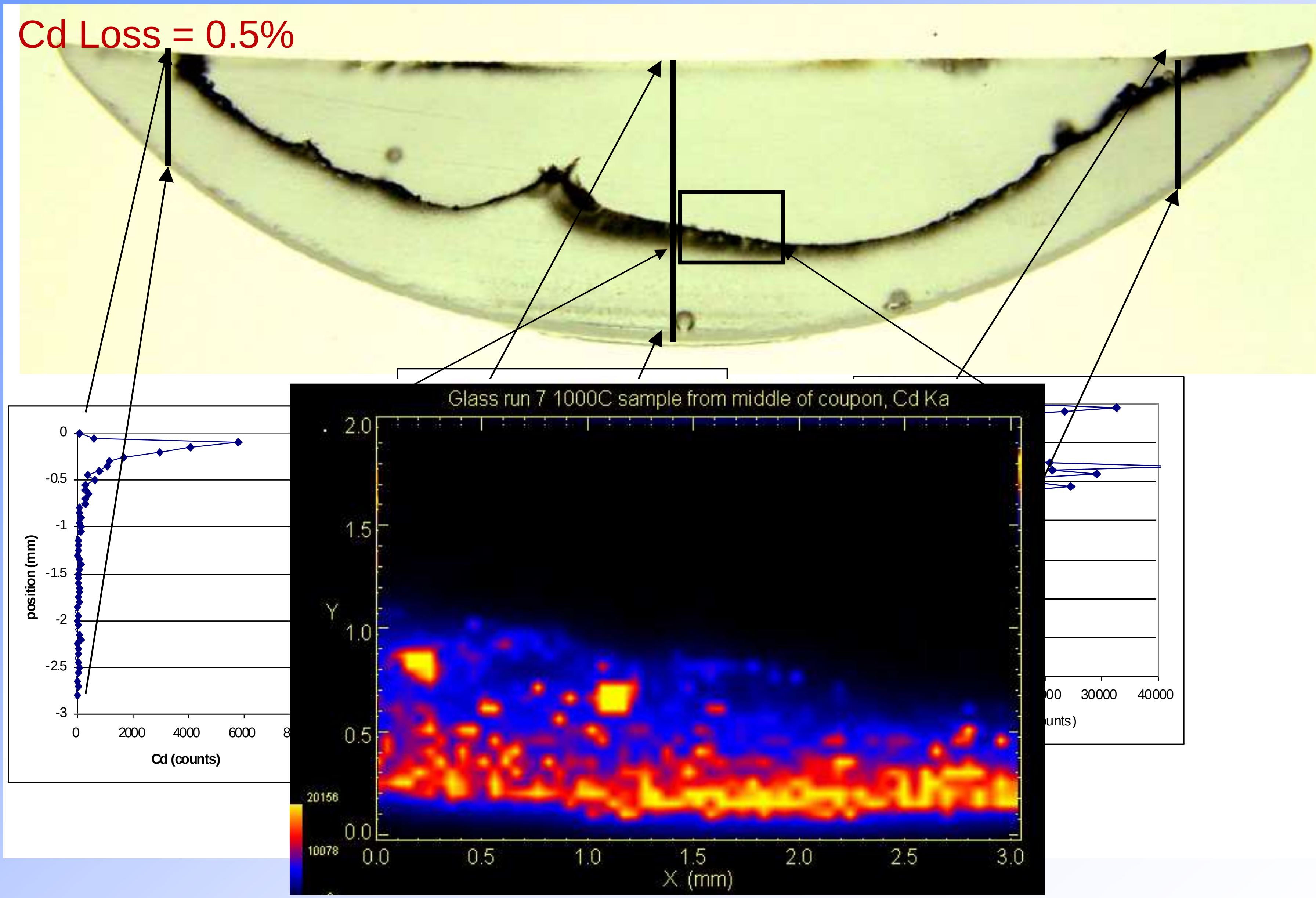
Fthenakis, *Renewable and Sustainable Energy Reviews,* 2004

Fthenakis, Fuhrmann, Heiser, Lanzirotti, Wang*, Progress in Photovoltaics,* 2005

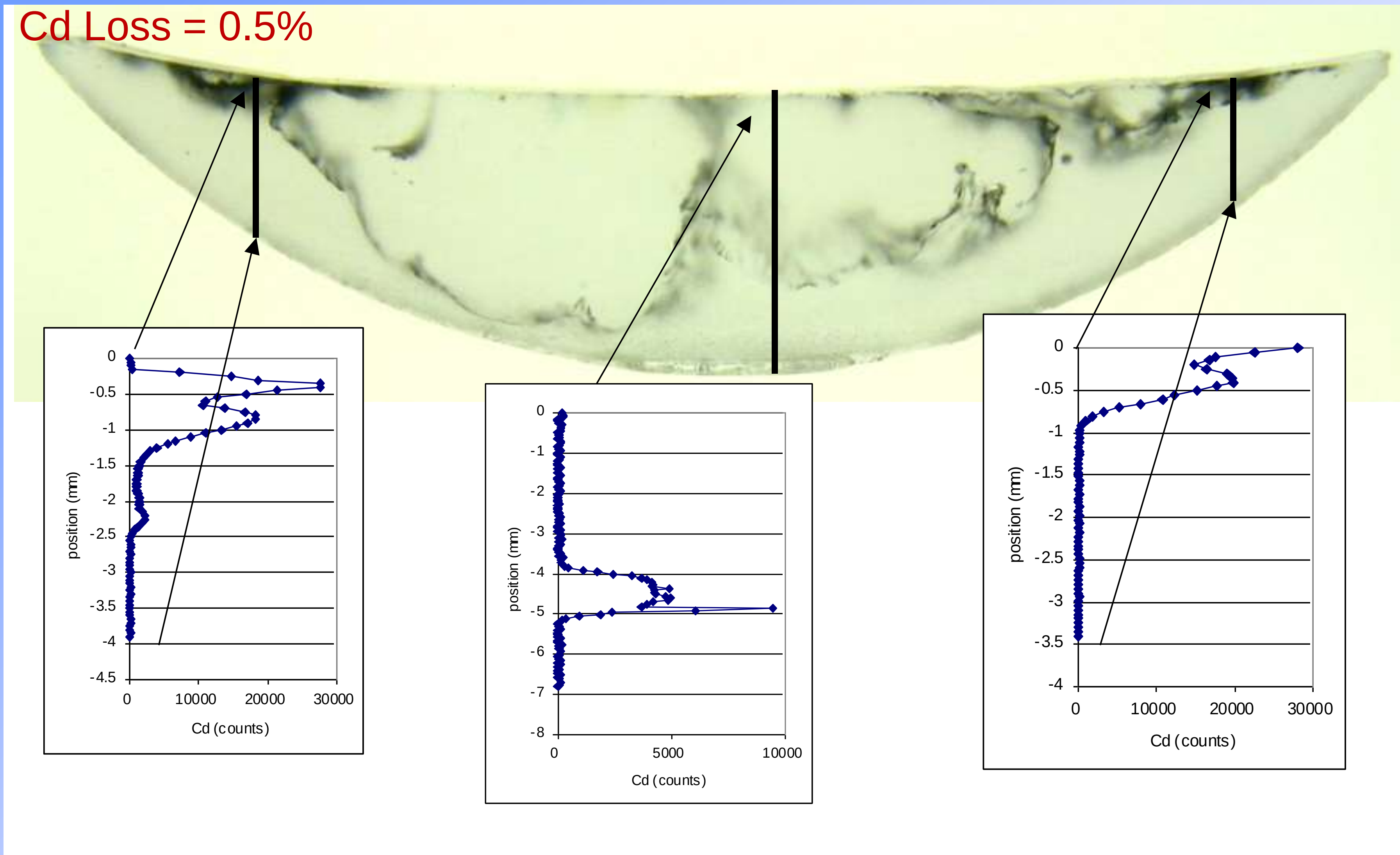
XRF-micro-probe -Cd distribution in PV sample 760 ° C, Section taken from middle of sample



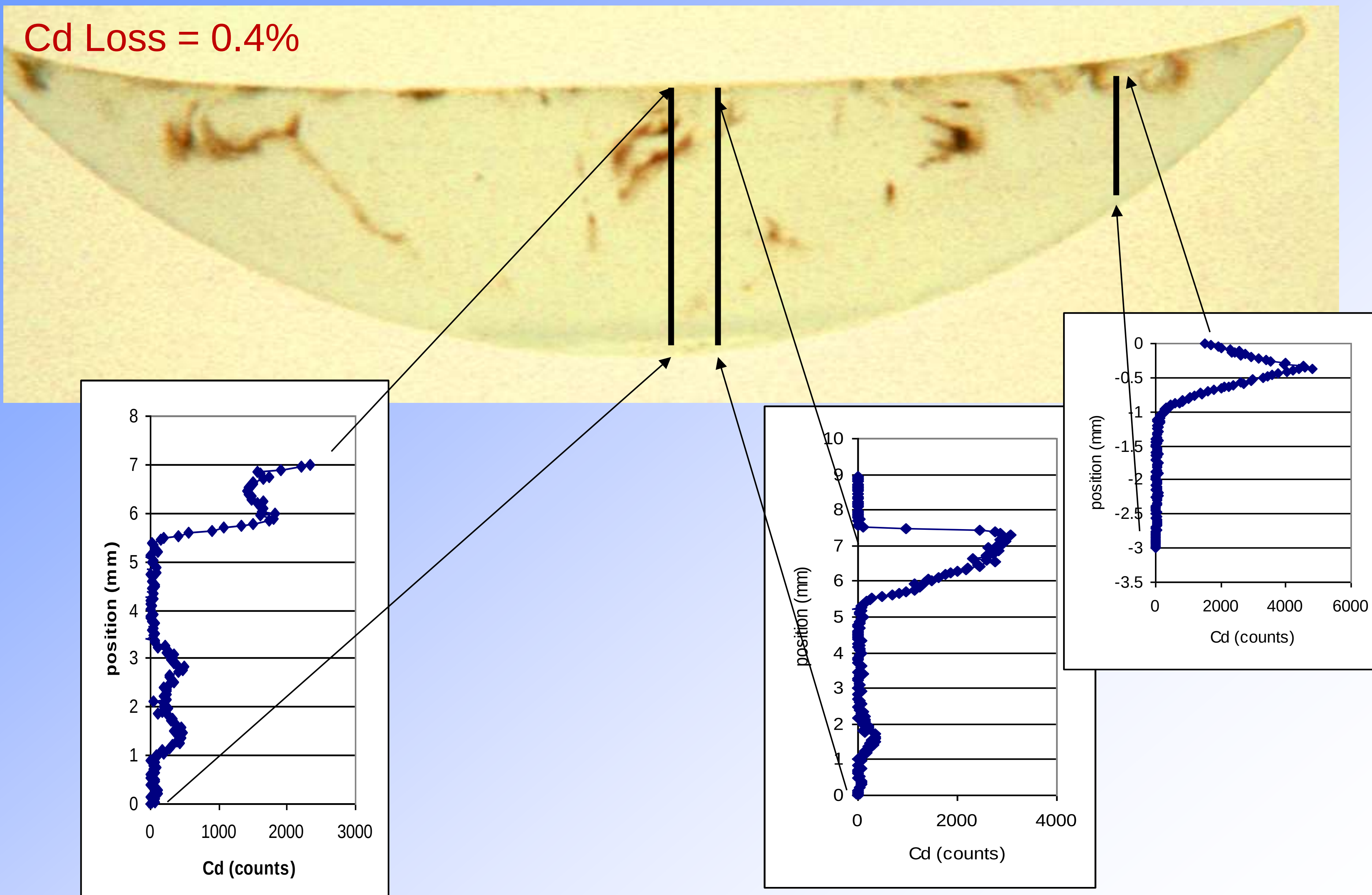
XRF-micro-probe -Cd distribution in PV sample 1000 ° C, Section taken from middle of sample



XRF-micro-probing -Cd distribution in PV sample 1000 ° C, Section taken from right side of sample

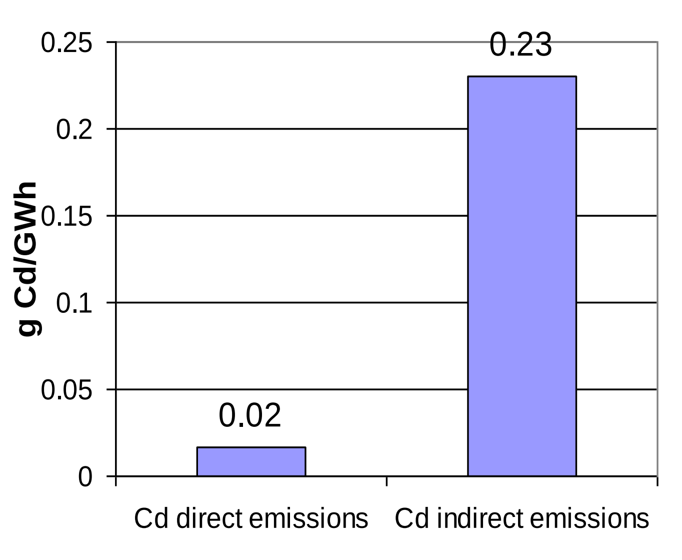


XRF-micro-probing -Cd distribution in PV sample 1100 ° C, Section taken from middle of sample



Direct 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

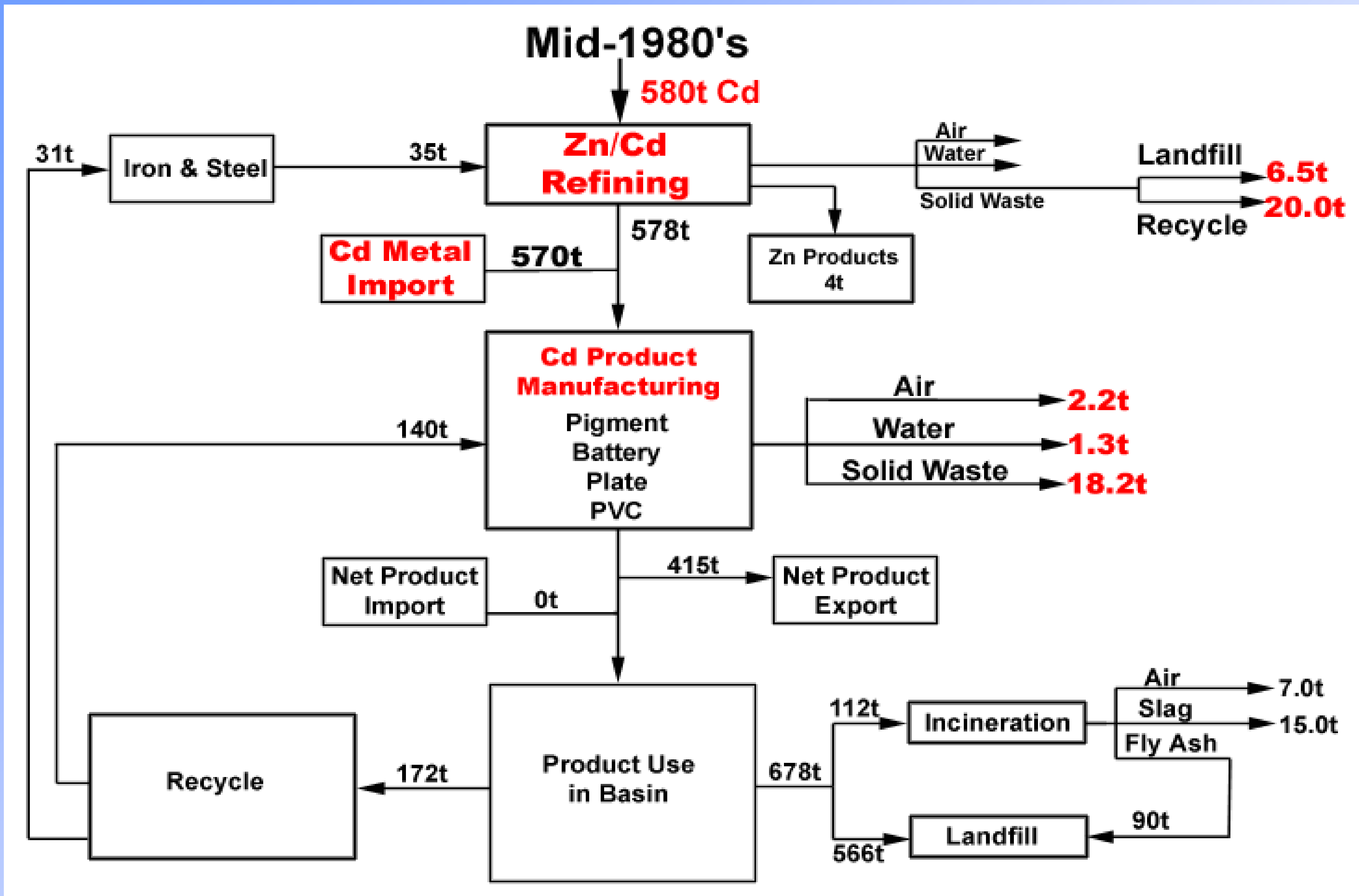
Cd Use in CdTe PV Production

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)

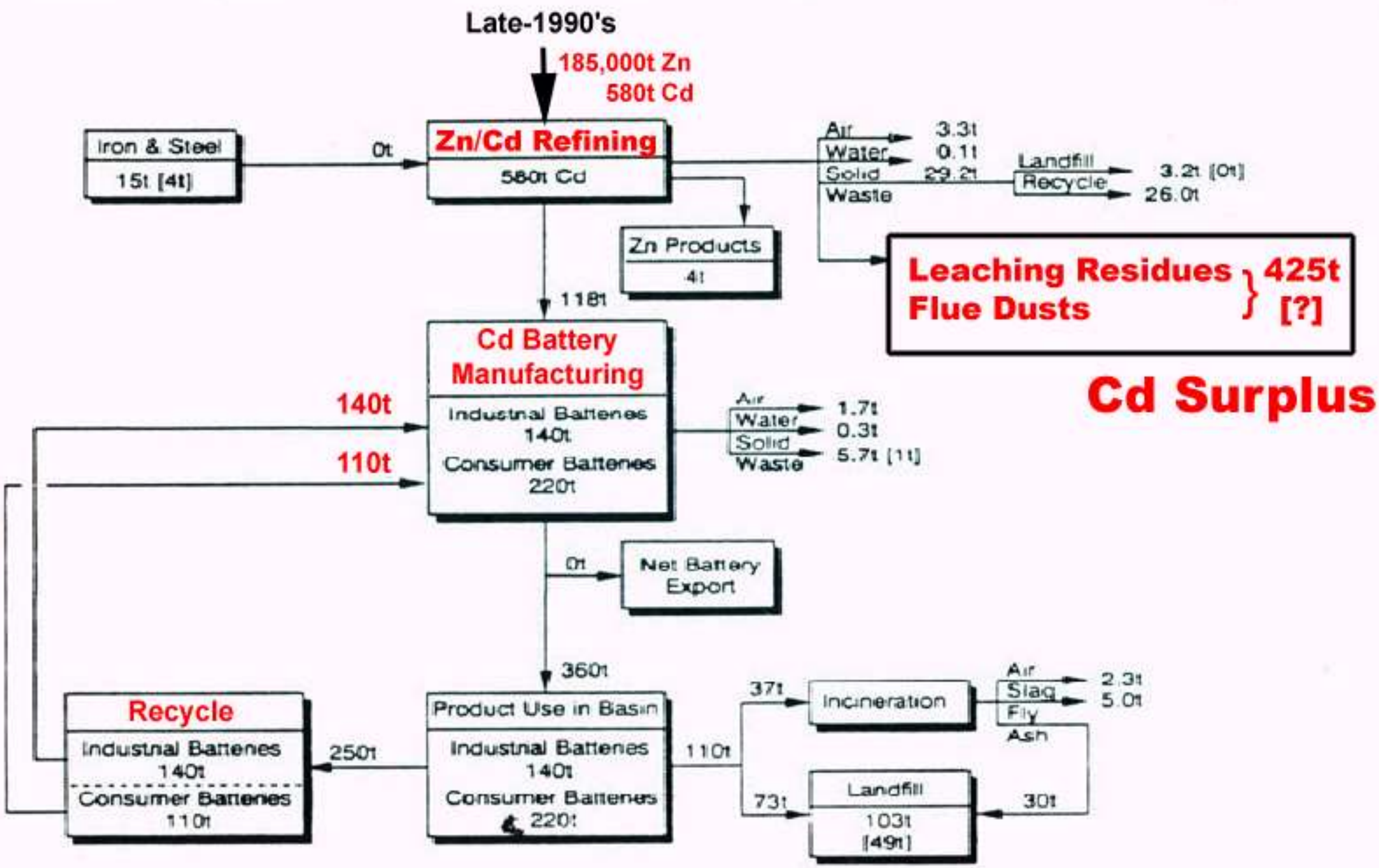
- Liewellyn T. Cadmium , **Bureau of Mines** Information Circular 1994, US Department of the Interior.
- Plachy J., **U.S. Geological Survey Minerals Yearbook**—2001, Cadmium—Chapter 17.
- Stigliani W, Anderberg S. Chapter 7. In: Ayres R, Simonis U, editors. **Industrial metabolism**. Tokyo, Japan: The United Nations University Press; 1994.

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. 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!**

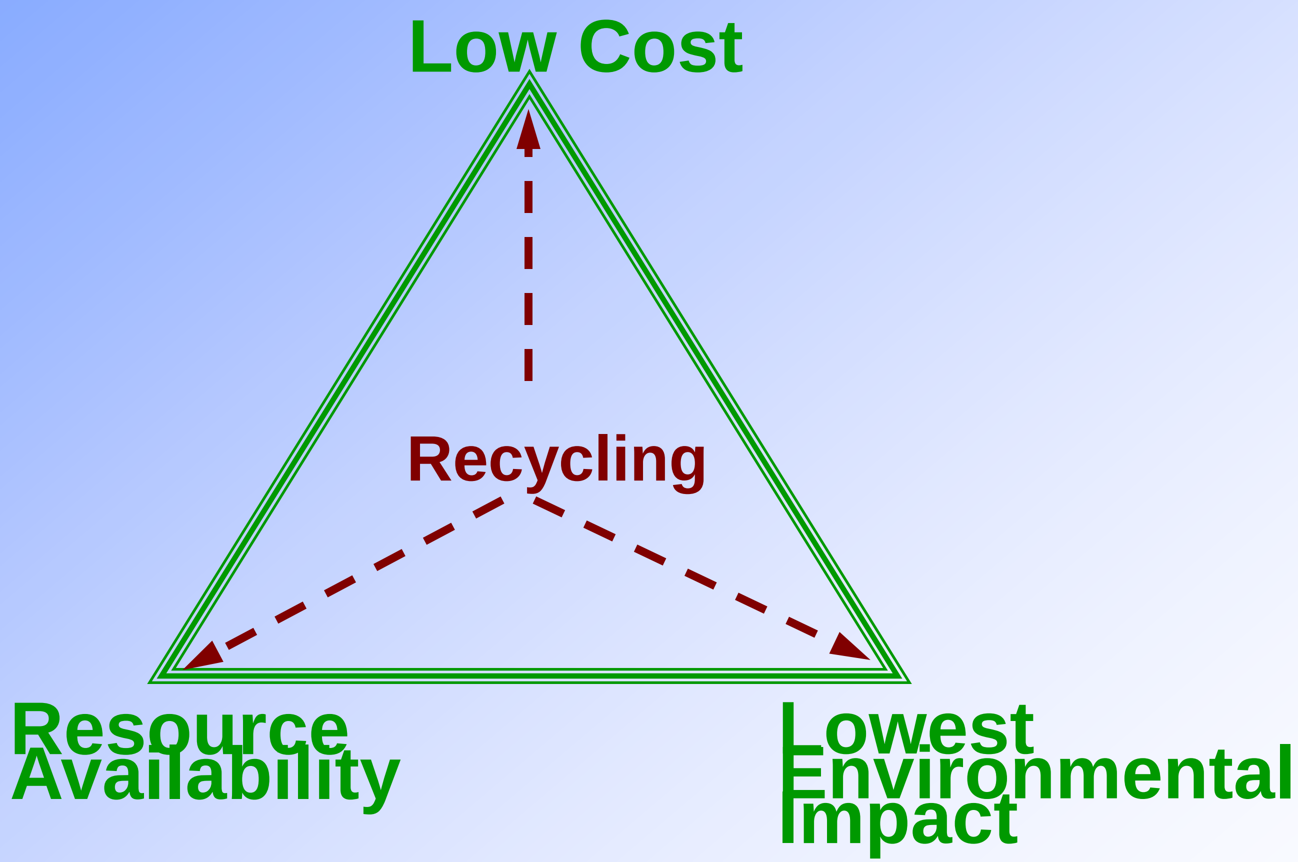
One possible option would be to allow the production and use of Cd-containing products with inherently low availability for leaching.

The other option, depositing the Cd-containing wastes in safely contained landfills, has other risks "

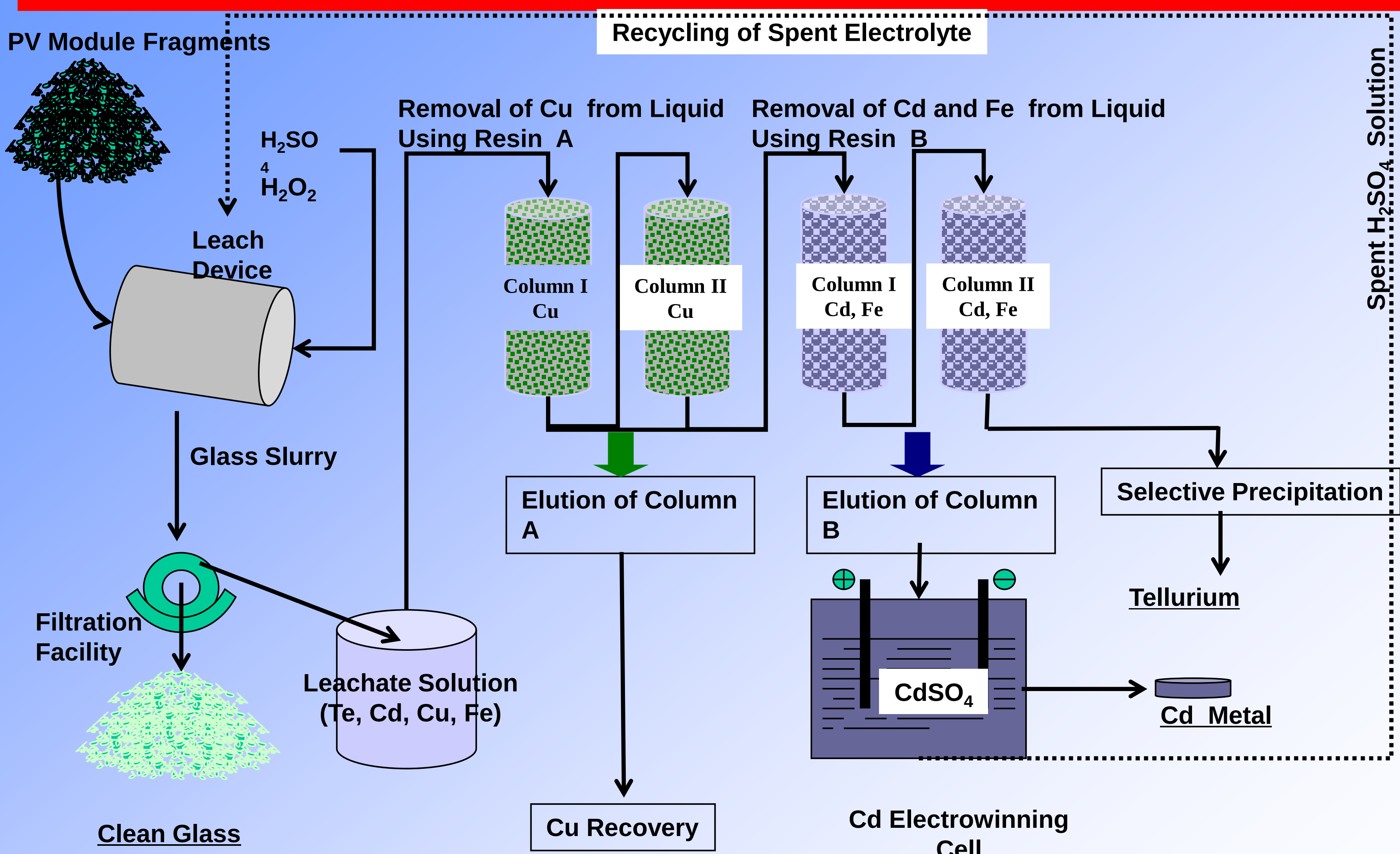
Source: *Stigliani & Anderberg, Chapter 7, Industrial Metabolism, The United Nations University, 1994*

Recycling of Spent Modules

- Resolves environmental issues related to end-of-life
- Provides a source of materials



Recycling R&D at BNL: CdTe PV Modules



Fthenakis V. and Wang W., Separating Te from Cd Waste Patent No 7,731,920, June 8, 2010

Wang W. and Fthenakis V.M. Kinetics Study on Separation of Cadmium from Tellurium in Acidic Solution Media Using Cation Exchange Resin, Journal of Hazardous Materials, B125, 80-88, 2005

Fthenakis V.M and Wang W., Extraction and Separation of Cd and Te from Cadmium Telluride Photovoltaic Manufacturing Scrap, Progress in Photovoltaics, 14:363-371, 2006.

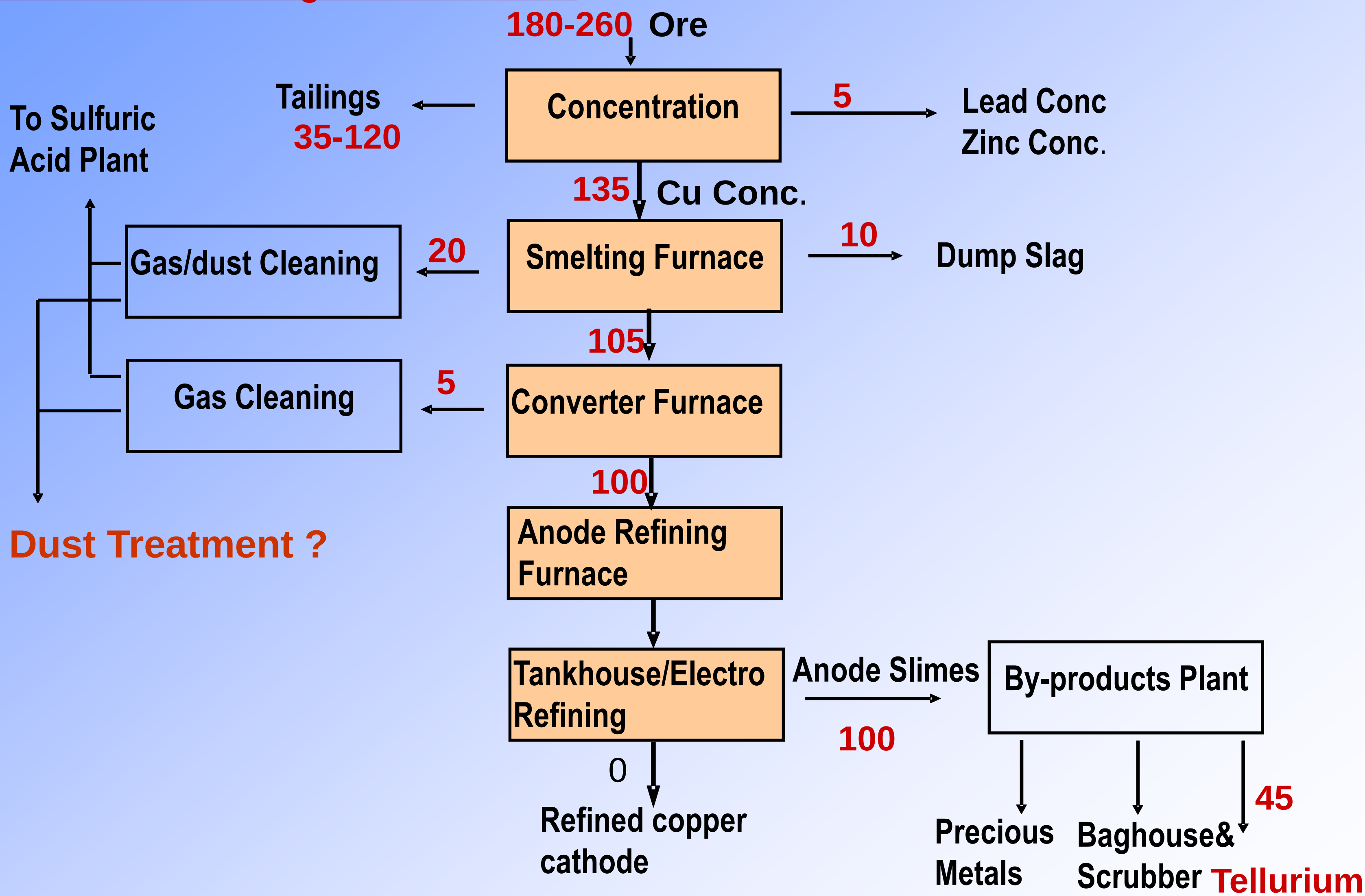
Studies of Te Availability for CdTe PV

- **Green M**., Improved estimates of Te and Se availability from Cu anode slimes and recent price trends, Progress in Photovoltaics, 14(8), 743-751, 2006.
- **Green M.** , Estimates of Te and In prices from direct mining of known ores, Progress in Photovoltaics, 17(5), 347-359, 2009
- **Fthenakis V.M.**, Sustainability of photovoltaics: The case for thin-film solar cells, Renewable and Sustainable Energy Reviews, 13, 2746-2750, 2009.
- **Zweibel K.,** The impact of Te supply on CdTe PV, Science, 328, 699, 2010
- **Green M.,** PV Velocity Forum: *Supply and Economics in Thin-film PV Materials*, IEEE PVSC, Hawaii, June 23, 2010
- **Fthenakis V.,** PV Velocity Forum: *Supply and Economics in Thin-film PV Materials*, IEEE PVSC, Hawaii, June 23, 2010
- **Fthenakis V**., Sustainability metrics for extending thin-film photovoltaics to terawatt levels. MRS Bulletin, 37(4), 425-430, 2012
- **Marwede M., Reller A.,** Future recycling flows of Te from CdTe Pv waste, Resources, Conservation and Recycling, 69, 35-49, 2012
- **Woodhouse M.**, et. al., Perspectives on the pathways for CdTe PV module manufacturers to address expected increase in the price of Te, IEEEPV Journal, 2012
- **Houari Y., Speirs J., Candelise C., Gross R**., A system dynamic model of Te availability for CdTe PV**,** Progress in Photovoltaics, 2013.

Te from Copper Sulfide ores*

Approximate Global Distribution in Copper Circuits

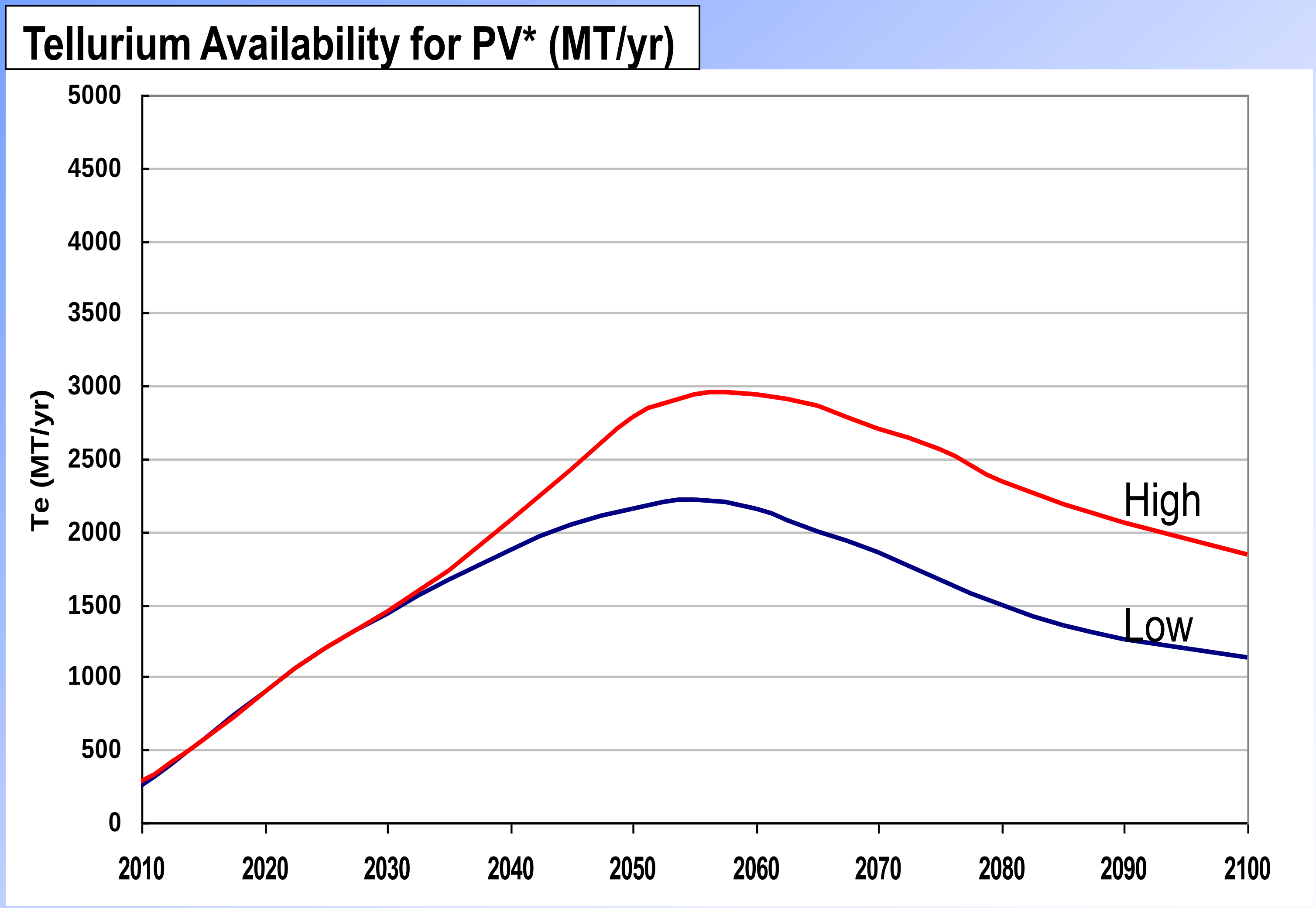
Numbers refer to kg of Tellurium:



*Cu, Cu-Mo, Cu-Au & polymetallic ores, e.g., Pb-Cu-Zn-Ag ores

Ojebuoboh, *Proceedings EMC*, 2007; *Nagaraj*, 2010; *Fthenakis update* 2010

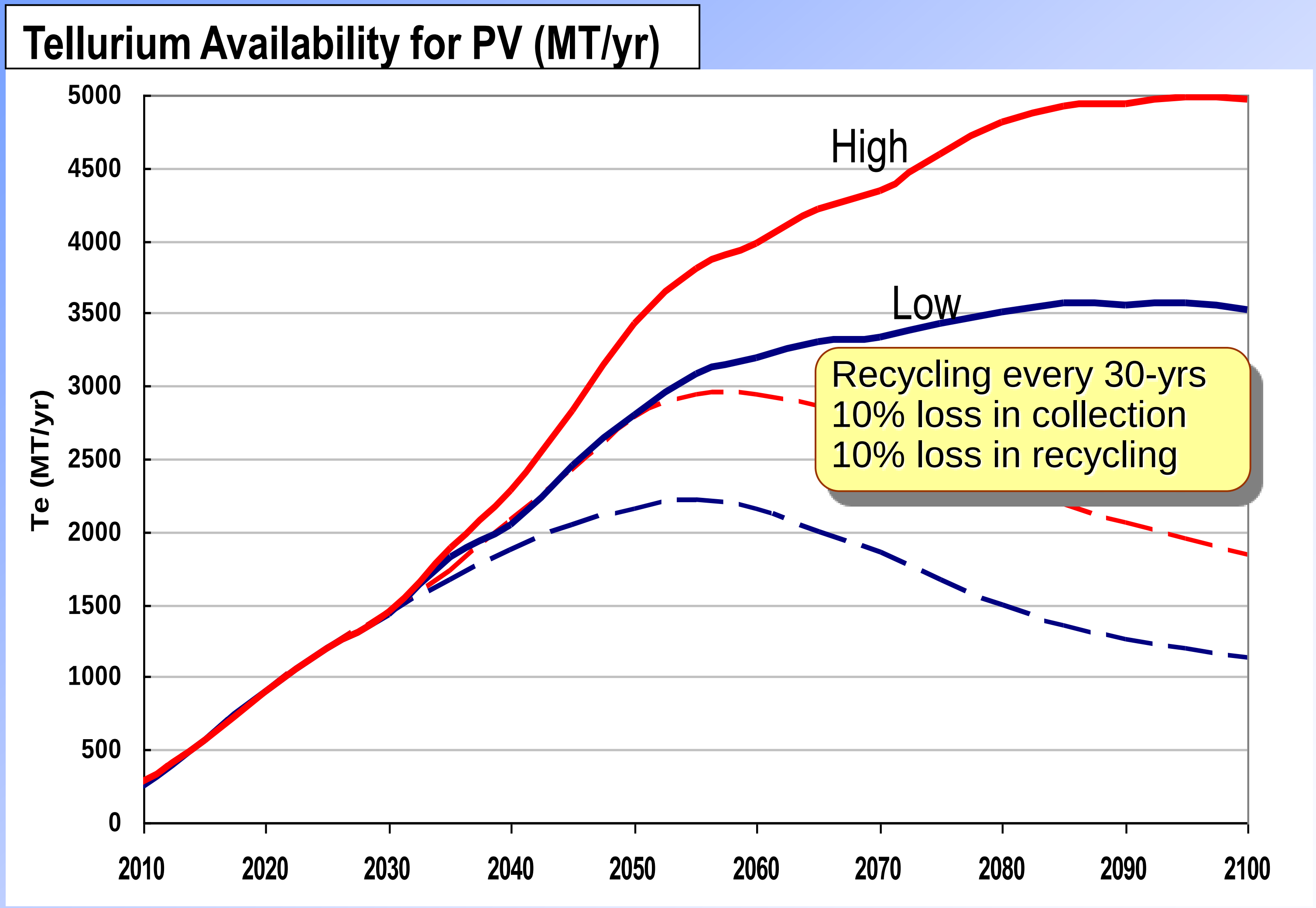
Tellurium for PV* from Copper Smelters



•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 future growth in Te production is allocated to PV

Te Availability for PV:
Primary + Recycled



Fthenakis V., *Renewable & Sustainable Energy Reviews* 13, 2746, 2009
Fthenakis V., *MRS Bulletin*, 37, 425, 2012

Te Utilization in thin-film PV

		2010
PV	Metal	Required (MT/GW)
CdTe	Te	**106**

Material Losses & Utilization	**(%)**
Deposition loss	-30
Collected for recycling	24
Module scrap loss	-3.5
Collected for recycling	3.1
Loss in purification & CdTe synthesis	-7
Total losses	-13.4
Material Utilization	86.6

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

Te Needs in CdTe PV

		2010	Expected 2020
PV	Metal	**Required (MT/GW)**	**Required (MT/GW)**
CdTe	Te	106	**38-74**

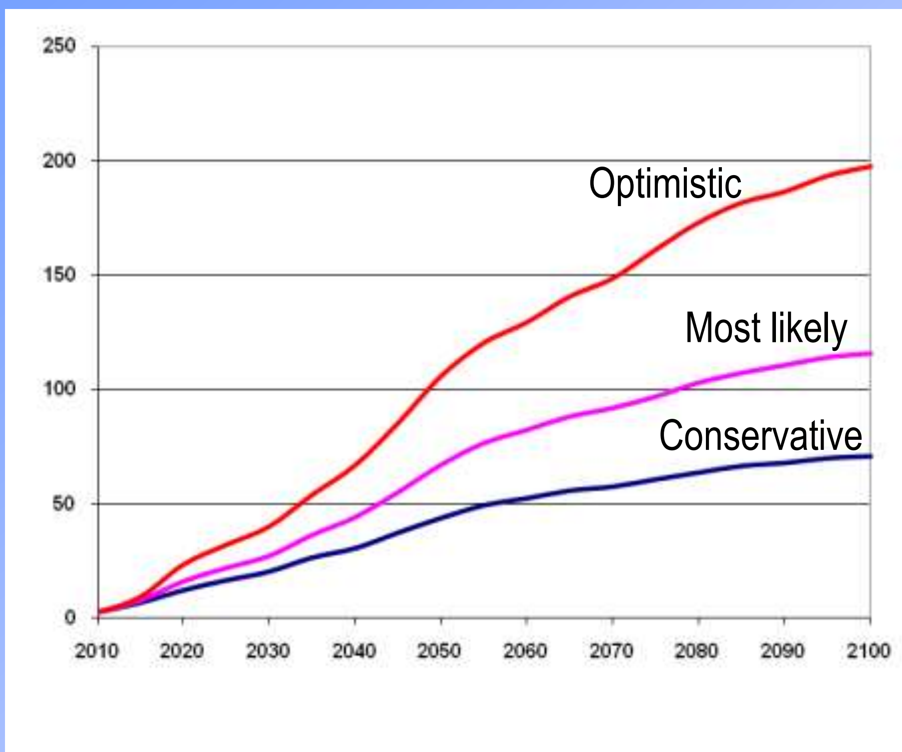
Table I. Assumptions for thin-film photovoltaic (PV) efficiencies and layer thicknesses discussed in the text.

PV type	Efficiency (%)				Layer thickness (μm)			
	2010	2020			2010	2020		
		Conservative	Most likely	Optimistic		Conservative	Most likely	Optimistic
CdTe	11.7	13	13.2	14	3	2.5	1.5	1
CIGS	11.5	14	15.9	16.3	1.6	1.2	1.	0.8
a-SiGe	6.8	9	9.7	10	1.2	1.2	1.1	1

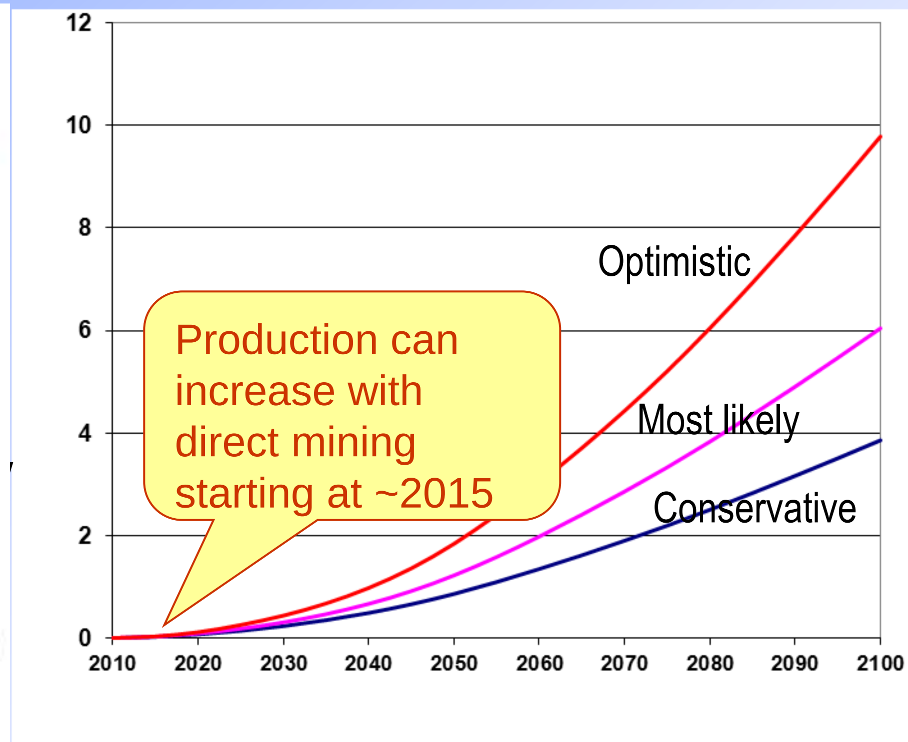
Fthenakis V., *Renewable & Sustainable Energy Reviews* 13, 2746, 2009
Fthenakis V., *MRS Bulletin*, 37, 425, 2012

CdTe PV Production Constraints

Annual (GW/yr)



Cumulative (TW)



Fthenakis V., *Renewable & Sustainable Energy Reviews* 13, 2746, 2009
Fthenakis V., *MRS Bulletin*, 37, 425, 2012

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.
  - Examples: Land use comparisons between coal and PV; Cd emission comparisons between coal and various PV technologies; risk comparisons among power life cycles
- Every PV technology has some EHS issues, but the industry is proactive in controlling them.
- The environmental issues related to CdTe PV are outweighed by the environmental benefits that PV displacement of fossil would generate.

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www.clca.columbia.edu
www.pv.bnl.gov

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, Frauhoffer 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, Norgegian 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 IEEEPVSC, 1997; Eberspacher 1998

We advocate for all PV modules to be recycled at the end of their life

Extraction Efficiencies from Slimes for Te, Se and In

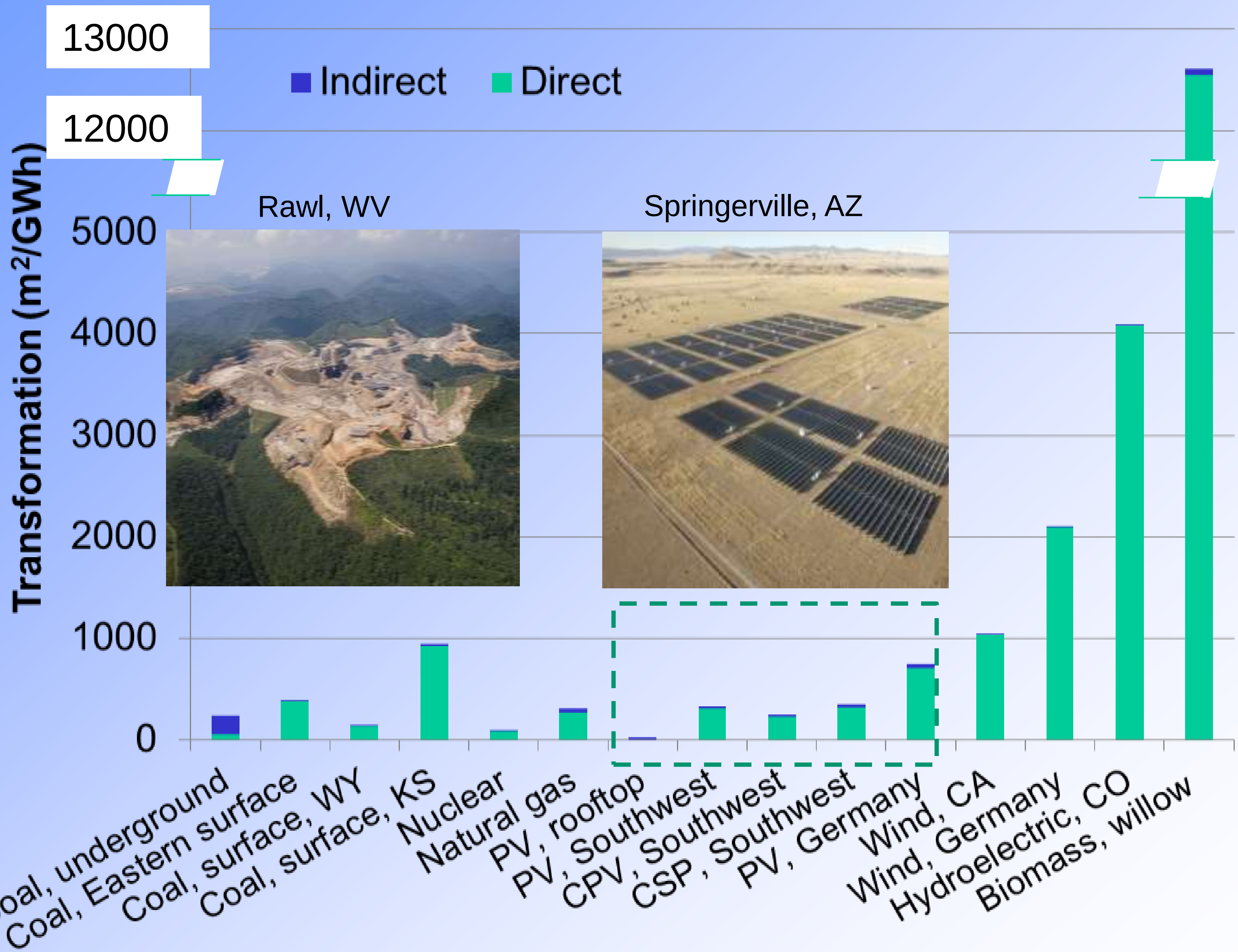
Year	Extraction Efficiency (%)		
	Tellurium	Selenium	Indium
2002	33	52	30
2006	40	80	70-80
2009	45	80	80

Main reason for lower Te than Se recovery rates

- **Several refineries recover Se but not Te**

Anderson 2002; USGS 2004, 2006; Ogebuoboh, 2007;
Fthenakis update 2010

Land Use in Energy Life Cycles



Fthenakis and Kim, Renewable and Sustainable Energy Reviews (2009); Burkhardt et al (2011)

Corrected Misrepresentations of PV Environmental Profiles

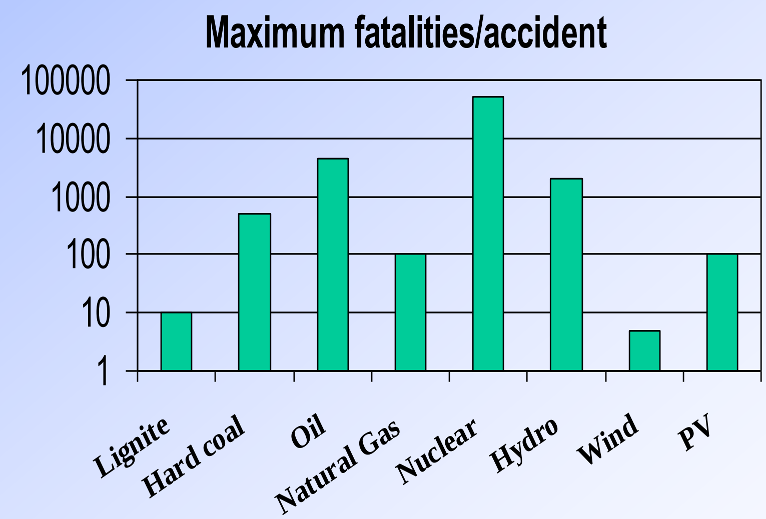
ExternE: Environmental Damage Costs

QUANTIFIED MARGINAL EXTERNAL COSTS OF ELECTRICITY PRODUCTION IN GERMANY[2]
(IN € CENT PER KWH)

	Coal	Lignite	Gas	Nuclear	PV	Wind	Hydro
Damage costs							
Noise	0	0	0	0	0	0.005	0
Health	0.73	0.99	**0.34**	**0.17**	**0.45**	0.072	0.051
Material	0.015	0.020	0.007	0.002	0.012	0.002	0.001
Crops	0	0	0	0.0008	0	0.0007	0.0002
Total	0.75	1.01	0.35	0.17	0.46	0.08	0.05
Avoidance costs							
Ecosystems	0.20	0.78	0.04	0.05	0.04	0.04	0.03
Global Warming	1.60	2.00	0.73	**0.03**	**0.33**	[illegible]	0.03

Report to European Commission, 2004

PV Risks



Hirschberg et al. 2004
Paul Sherrer Institute Report

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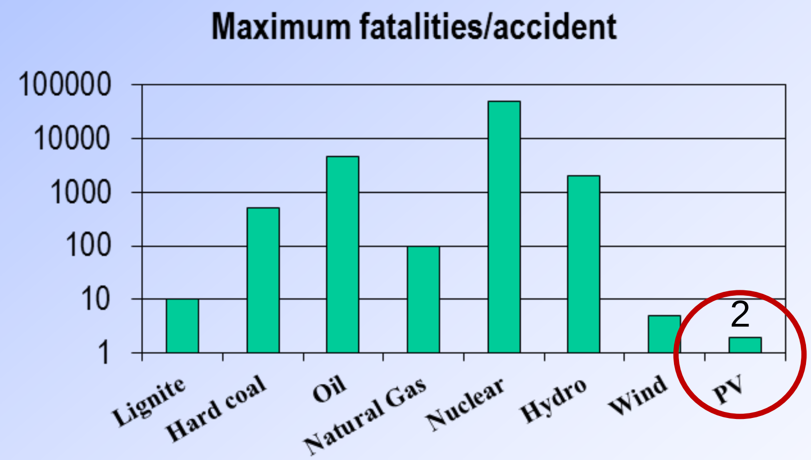
Noise	0	0	0	0	0	0.005	0
Health	0.73	0.99	0.34	0.17	0.08	0.072	0.051
Material	0.015	0.020	0.007	0.002	0.012	0.002	0.001
Crops	0	0	0	0.0008	0	0.0007	0.0002
Total	0.75	1.01	0.35	0.17	0.46	0.08	0.05
Avoidance costs							
Ecosystems	0.20	0.78	0.04	0.05	0.04	0.04	0.03
Global Warming	1.60	2.00	0.73	0.03	0.05	[illegible]	0.03

Fthenakis V.M. and Alsema E., Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004-early 2005 Status, Progress in Photovoltaics Research and Applications, 14:275-280, 2006

PV Risks



Fthenakis V.M., Colli A., Arellano A., Kirchsteiger C., Ale B. Evaluation of Photovoltaics in a Comparative Context, Proceedings 21st European PV Solar Energy Conference, Dresden, Germany, 4-8 September 2006