Environmental Health and Safety

Vasilis Fthenakis, Ph.D. Senior Chemical Engineer/Principal Investigator
Charlie Kim, Ph.D., Materials Engineer/LCA Specialist
Wenming Wang, Ph.D., Metallurgical Engineer, Recycling Specialist

National Photovoltaic (PV) EHS Research Center

Brookhaven National Laboratory

DOE Solar Energy Technologies Program
Peer Review
Denver, CO, April 17-19, 2007

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Objectives

- Preserve the safe and environmentally friendly nature of PV and minimize EH&S risks and associated costs, to ensure the public support and economic viability of PV systems.
- Identify potential EH&S barriers of PV materials, processes, or applications and define strategies to overcome such barriers, with proactive research and rigorous industry outreach.
- Maintain the EH&S Research Center as the world's best source on PV EH&S, providing accurate information related to EH&S issues and perceptions.

Relevance

- Minimization of EH&S risks and costs is paramount for achieving the program's 2020 goal of $0.06/KWh while having the support of the public is a prerequisite for existence and growth that could support this price.
- The EH&S work also supports DOE's strategic mission objectives:
  - Reducing adverse environmental impacts associated with energy production, delivery, and use.
  - Helping industry shift from waste management to resource efficiency and pollution prevention

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FY06 Main Activities

HAZARD/ENVIRONMENTAL ASSESSMENT ($180K)

- Life Cycle Analysis (LCA) of Amonix Concentrating PV
- GHG emissions in solar electric and nuclear power life cycles
- Energy Payback, GHG emissions, and external costs of PV (mc-Si, pc-Si, ribbon, CdTe)
- Environmental metrics of roof-top and ground-based PV

HAZARD MANAGEMENT ($90K)

- CdTe PV Recycling: Recovery of 99.98% pure Cd at projected cost of 0.1 ¢/W
- Silane storage safety analysis

INDUSTRY OUTREACH ($39K)

- Assistance to First Solar, Unisolar, DayStart Tech and others
-

INFORMATION DISSEMINATION/ COMMUNICATIONS ($52K)

- Answered several requests from agencies, business and media
- Organized an MRS symposium on LCA
- Published and presented extensively

PROJECT MANAGEMENT/ REVIEWS / ASSISTANCE ($39K)

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Major Accomplishments

- Determined Energy Payback Times (EPBT), GHG and toxic emissions from PV
- Conducted comparative assessment of GHG emissions in PV and nuclear life cycles
- Optimized Cd recovery from defect/spent CdTe PV modules
- Spearheaded international collaborations on LCA and recycling
- Led expert workshops by the EU-JRC, BMU and the IEA

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Presentation Overview

- Life Cycle Analysis
  - Greenhouse Gas Emissions
  - Energy Payback Times (EPBT)
  - Toxic Emissions

Recycling

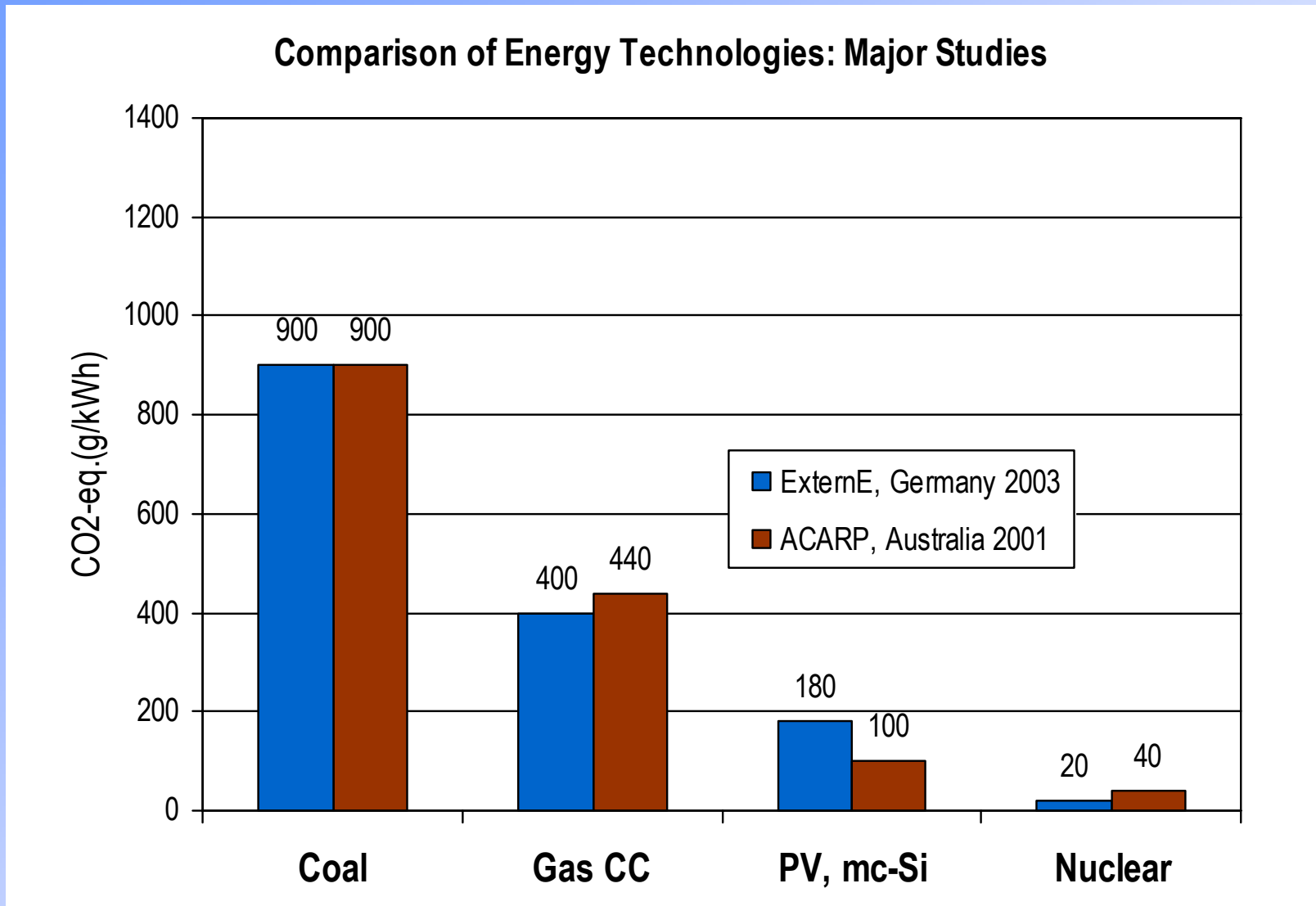
Silane Safety

Risk Estimates

Future Directions

GHG Emissions from Life Cycle Energy of Electricity Production

-ExternE & Australian Coal Association Research Programs-



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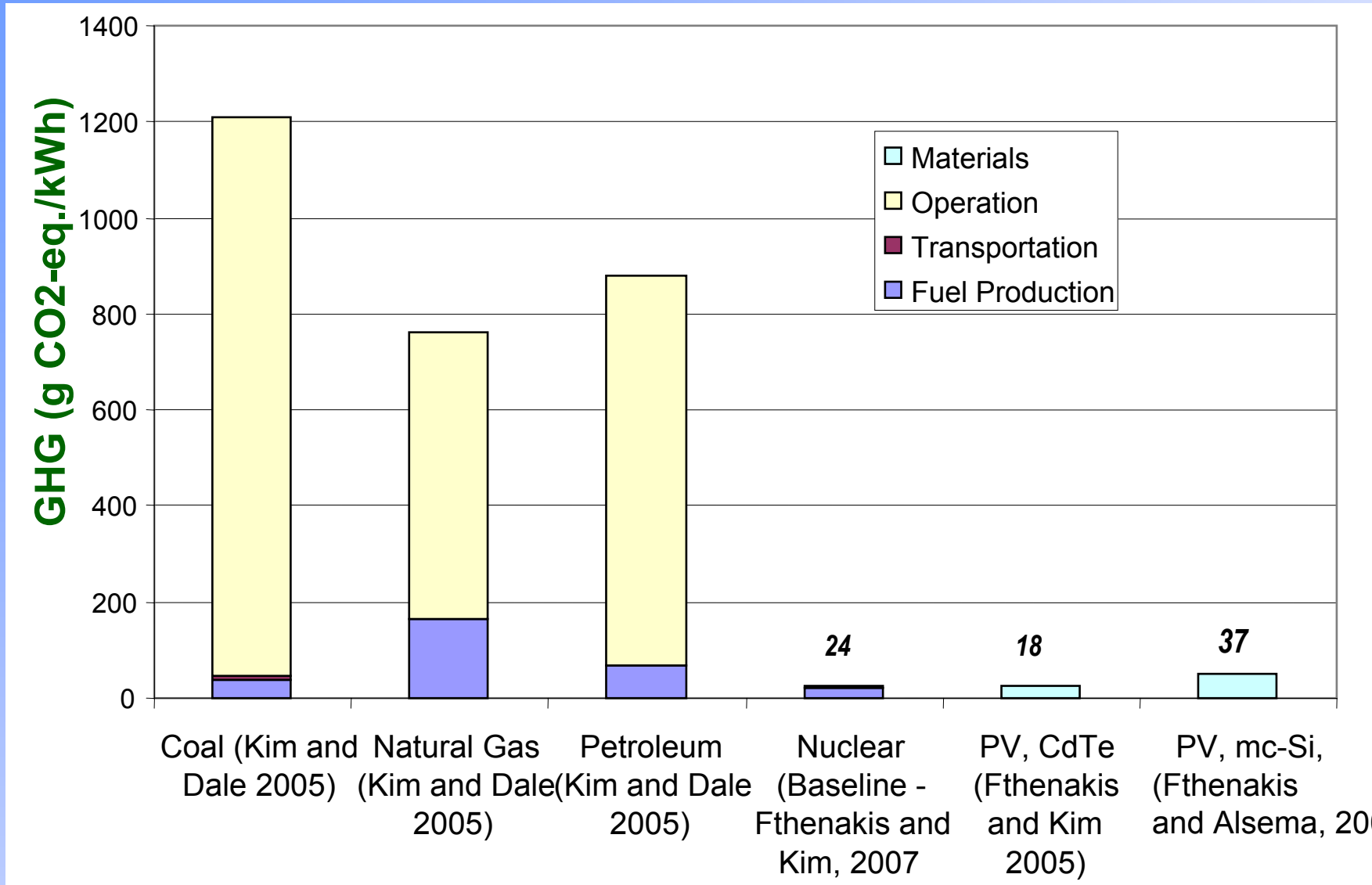
GHG Emissions from Life Cycle Energy of Electricity Production –*BNL et al. Estimates*



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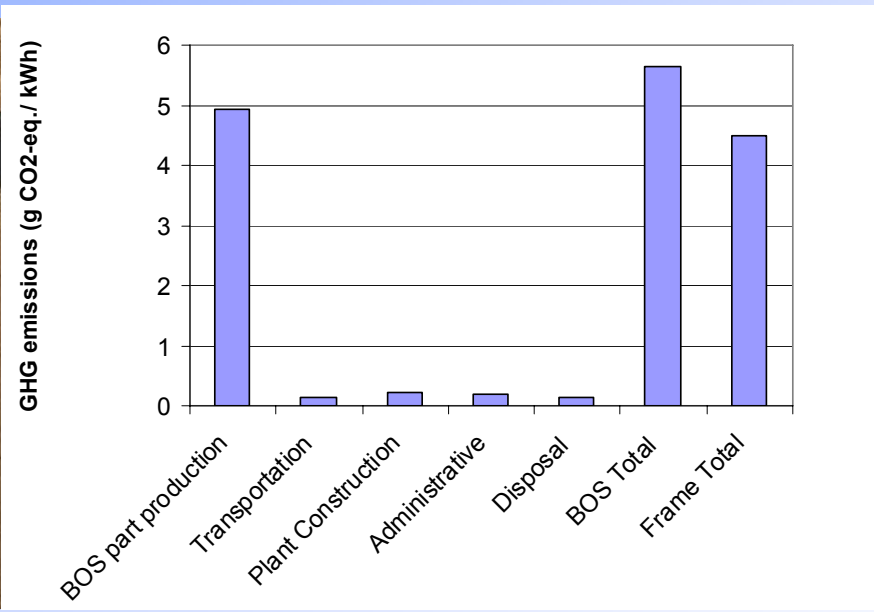
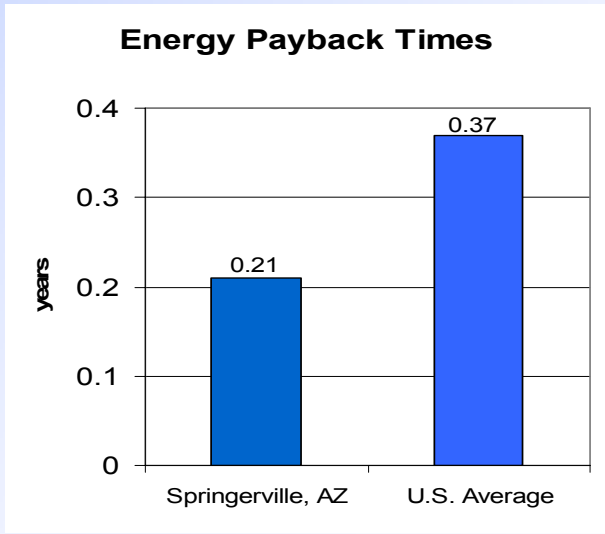
LCA of BOS of Tucson Electric's Springerville, AZ, PV plant



This is a 70% improvement from previous BOS designs (e.g., Sienna, Italy)



Mason, Fthenakis, Hansen, and Kim, Energy Pay-Back and Life Cycle CO2 Emissions of the BOS in an Optimized 3.5 MW PV Installation, ***Progress in Photovoltaics****, 2006*

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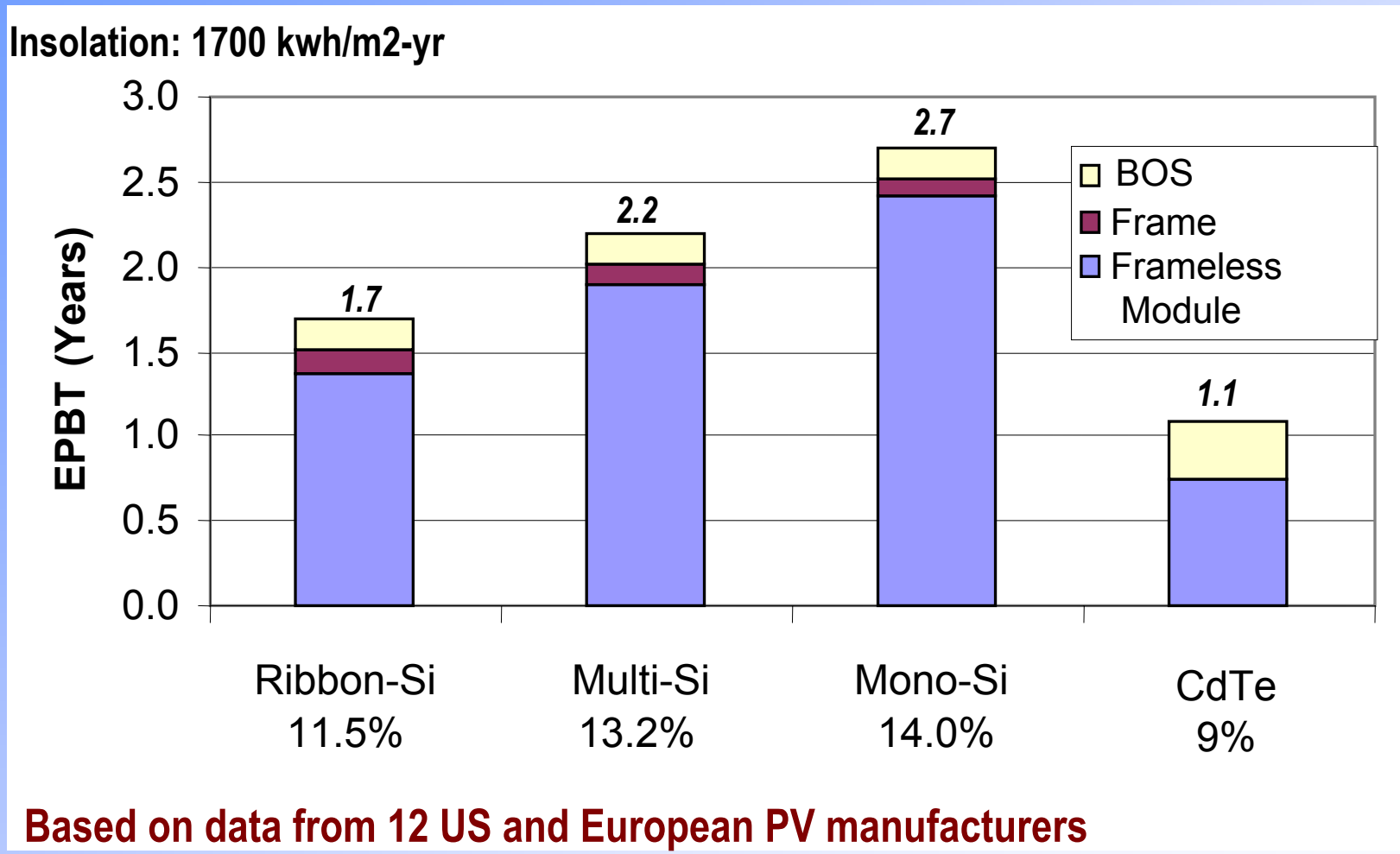
Energy Payback Times (EPBT)

Crystal Clear & BNL Studies



Based on data from 12 US and European PV manufacturers

-**Alsema & de Wild,** *Material Research Society, Symposium vol. 895, 73, 2006*

-**deWild & Alsema,** *Material Research Society, Symposium vol. 895, 59, 2006*

-**Fthenakis & Kim,** *Material Research Society, Symposium vol. 895, 83, 2006*

-**Fthenakis & Alsema,** *Progress in Photovoltaics, 14, 275, 2006*

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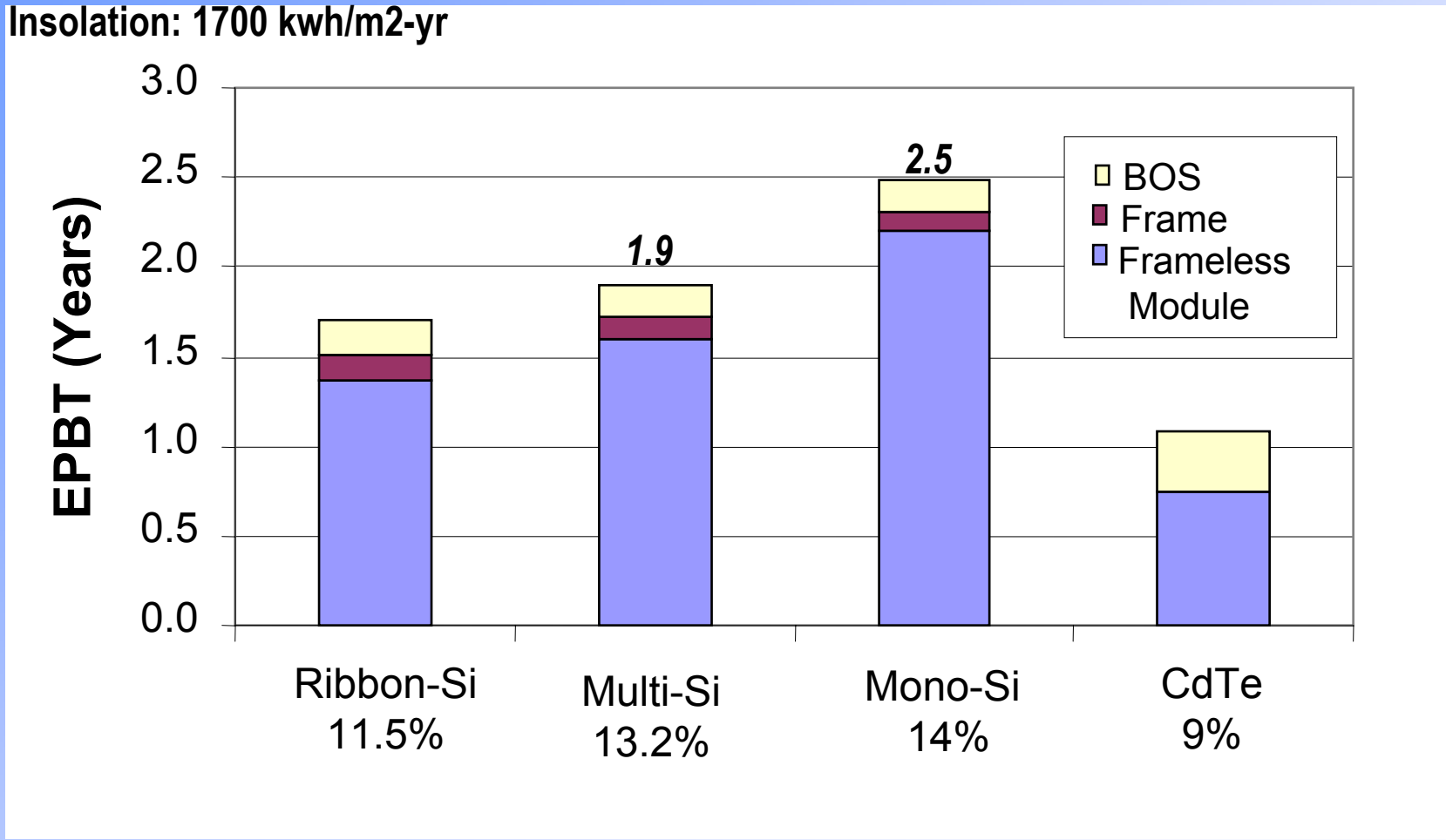
Energy Payback Times
Effect of Si Slurry Recycling



-Alsema , de Wild & Fthenakis, *21st EU-PV Conference,* *Aug., 2006*
-Fthenakis & Alsema, *Progress in Photovoltaics, 14, 275, 2006*

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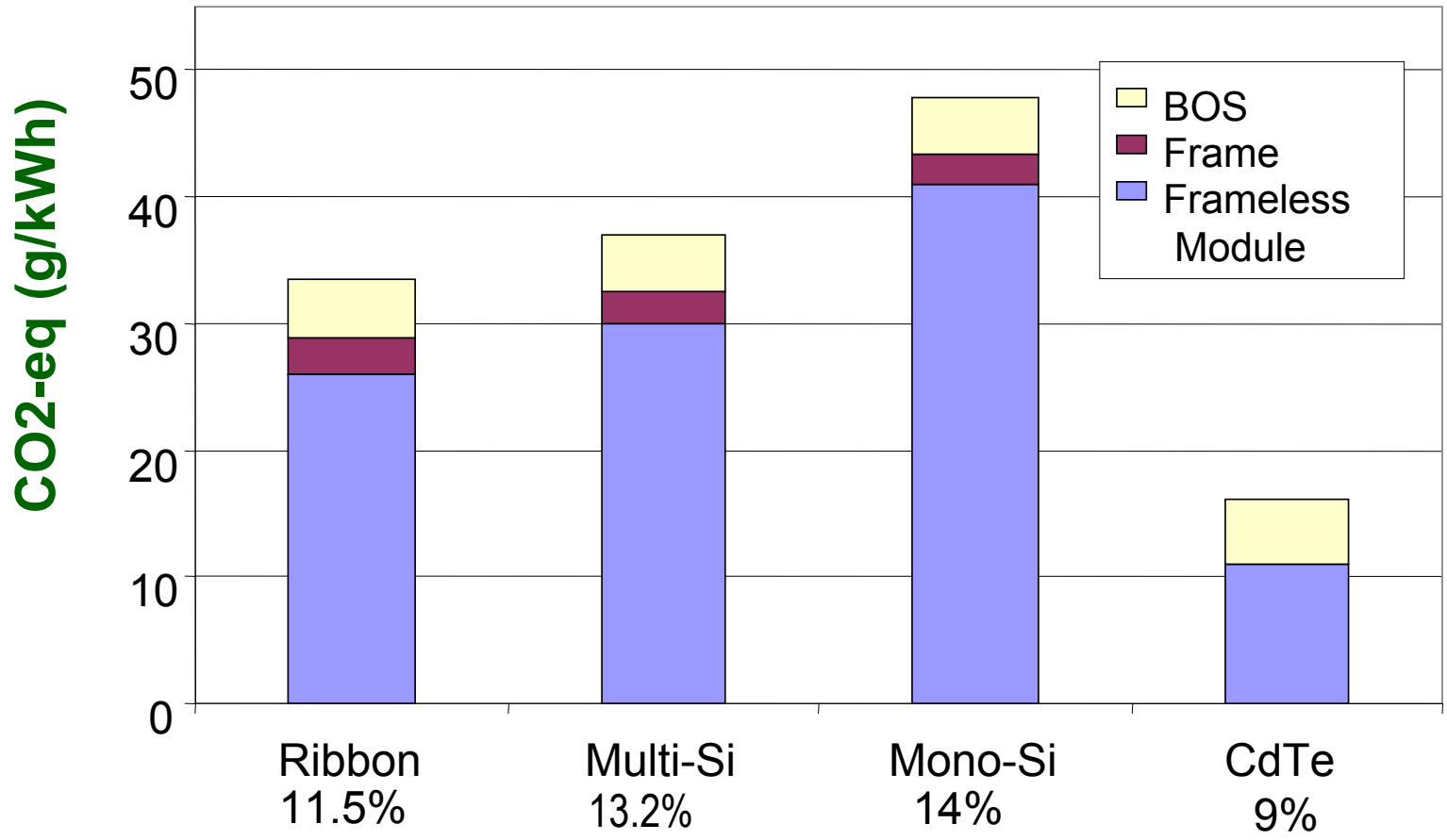
Life Cycle GHG Emissions –Europe

Insolation: 1700 kwh/m2-yr



Alsema & de Wild, *Material Research Society, Symposium vol. 895, 73, 2006*
deWild & Alsema, *Material Research Society, Symposium vol. 895, 59, 2006*
Fthenakis & Kim, *Material Research Society, Symposium vol. 895, 83, 2006*
Fthenakis & Alsema, *Progress in Photovoltaics, Accelerated Publication, 14, 275, 2006*

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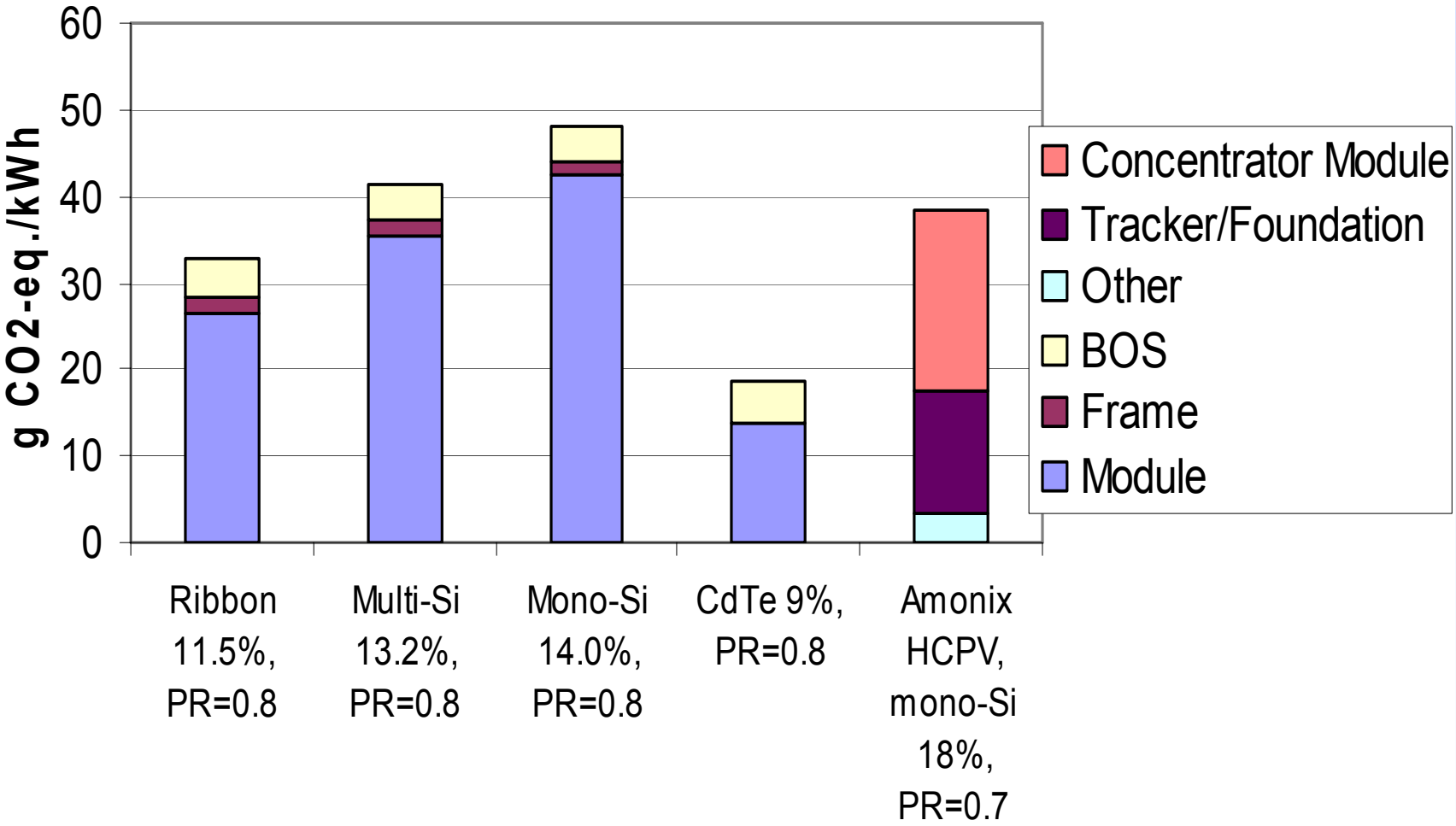
Life Cycle GHG Emissions –Phoenix, AZ



Normalized for Phoenix, AZ. Insolation = 2370 kWh/m2/yr for longitude optimal, = 2480 kWh/m2/yr for direct normal with 2-axis tracker.

Kim & Fthenakis, *IEEE WCPEC, May 11, 2006*

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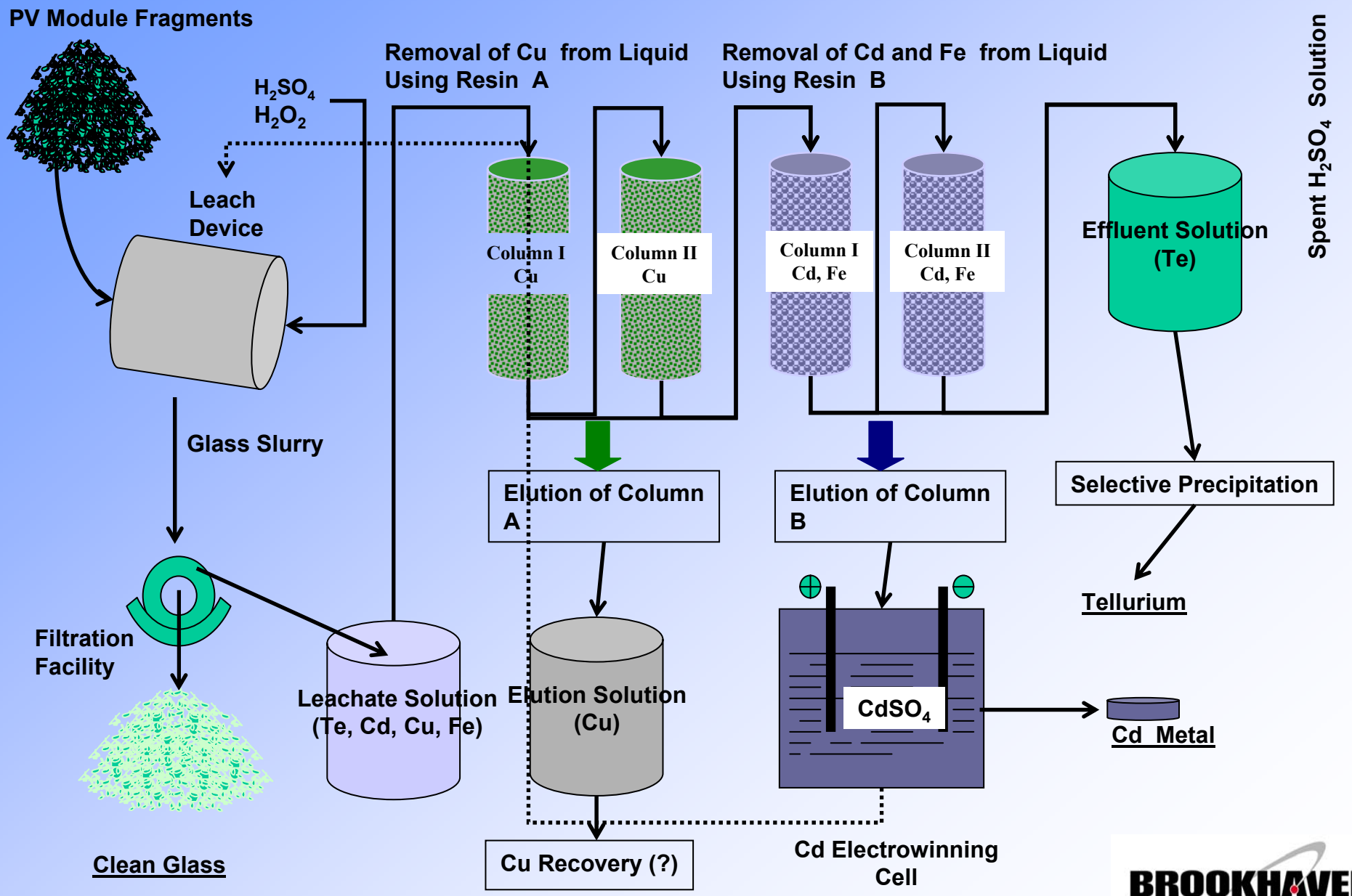
Recycling of Cd and Te from Spent CdTe PV Modules

Recycling of Spent Electrolyte



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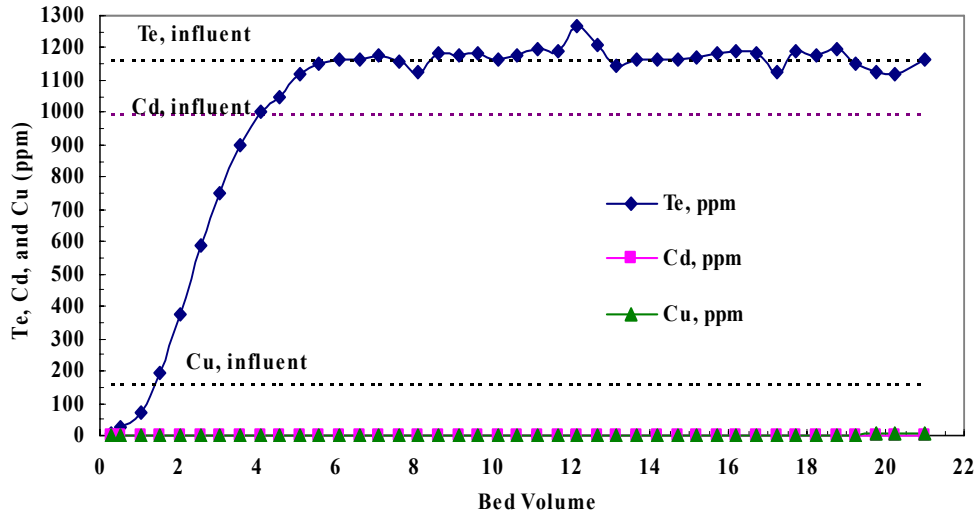
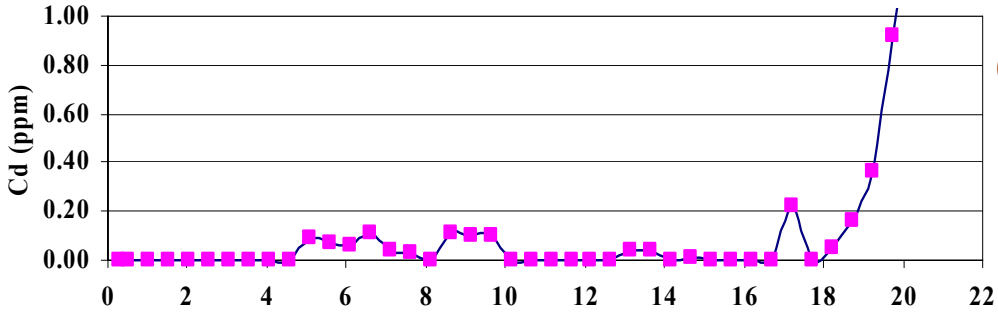
Separation of Cd from Te in CdTe Recycling



Cd separation 99.99%



Cd effluent concentration <0.3 ppm

RESULT: Cd, Te extraction & separation completed at a projected cost of 1 ¢/W_p

PATENT application #11/421,343

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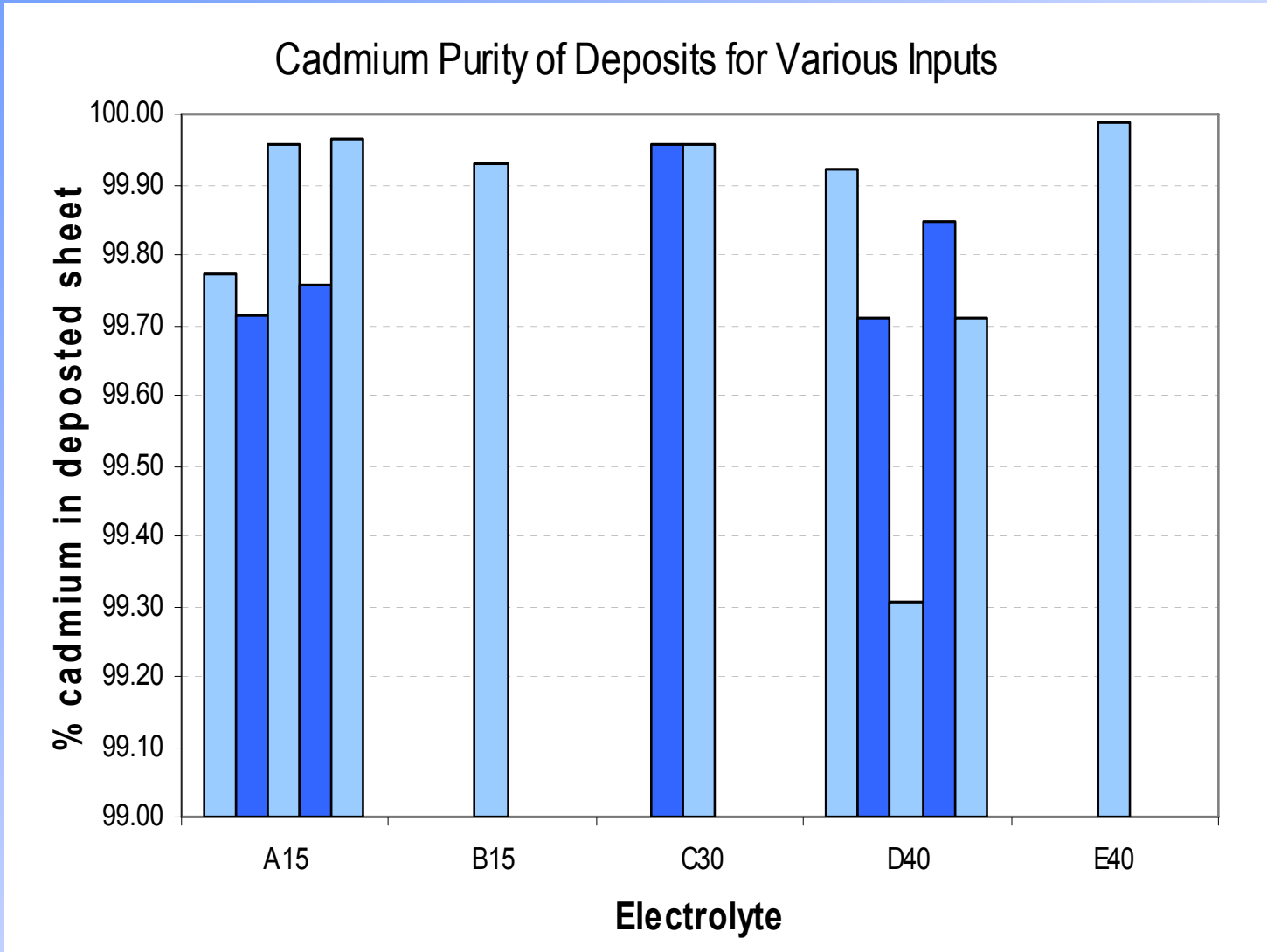
Cd Recovery by Electrowinning



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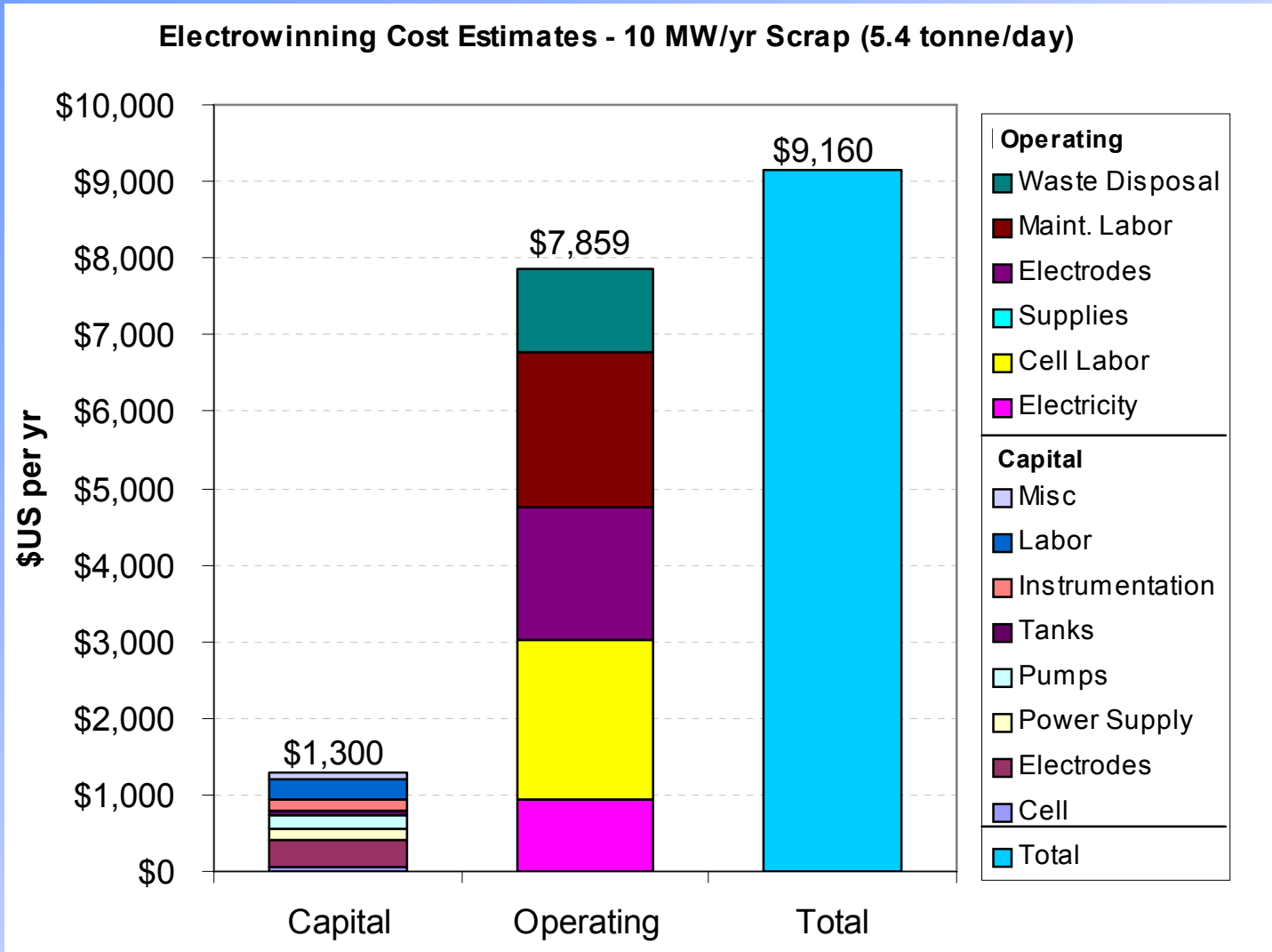
Cd Electrowinning Estimated Cost



Incremental cost of electrowinning = 0.1 ¢/Wp

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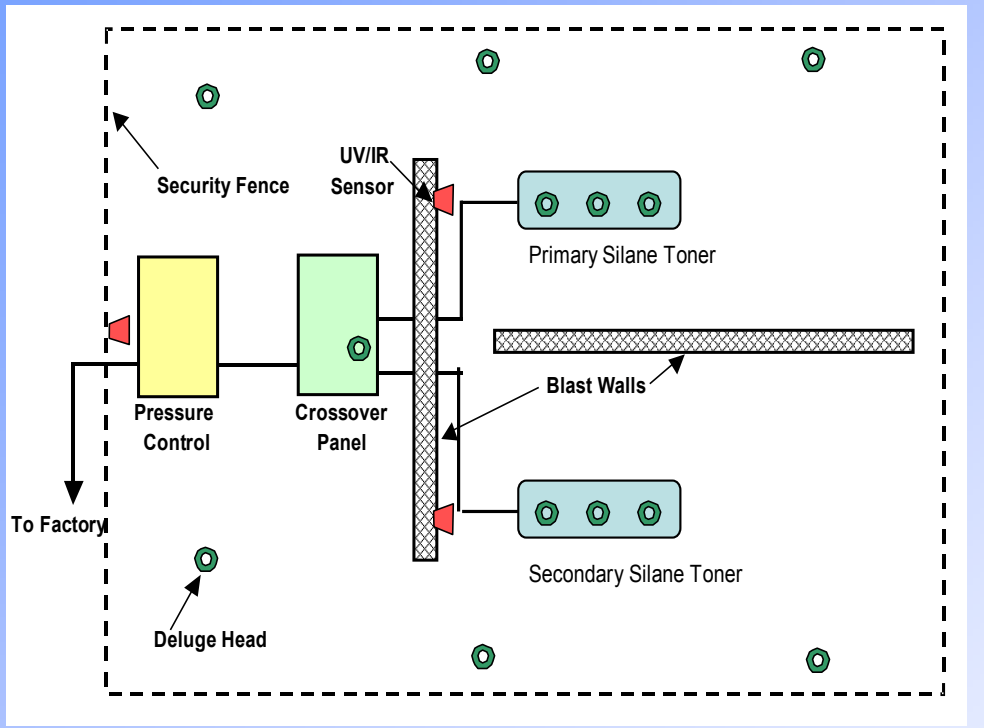
Silane Safety

Silane Bulk Storage

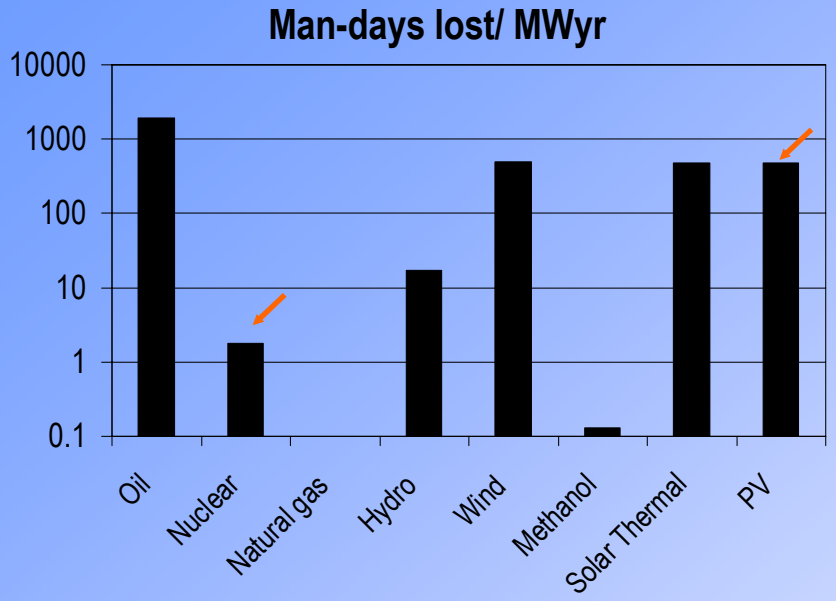


LAYERS OF PROTECTION

- Flow restrictors and pressure transducers for cylinder- and delivery-pressures.
- UV/IR detectors in storage
- Hybrid sensors in the tools
- Personnel training/safe procedures are extremely important.
- The potential for loss is reduced by blast walls, spacing the tanks, having a deluge system, secure, fenced, separation zones.

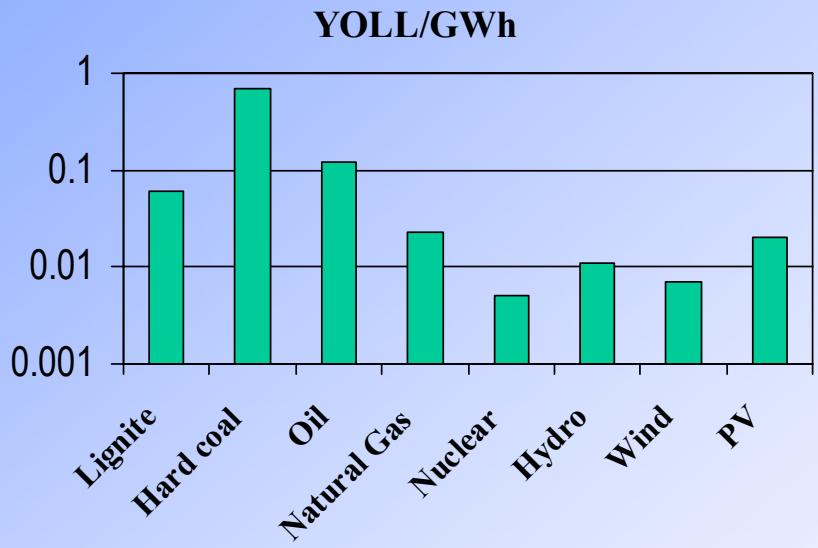
SILANE SAFETY IN AMORPHOUS SILICON AND SILICON NITRIDE OPERATIONS , Dresden, 2006
V..Fthenakis, C. Carlisle and W. Chan
Brookhaven National Laboratory, Upton, NY
United Solar Ovonic, Auburn Hills, MI

PV Risks: Studies by Others

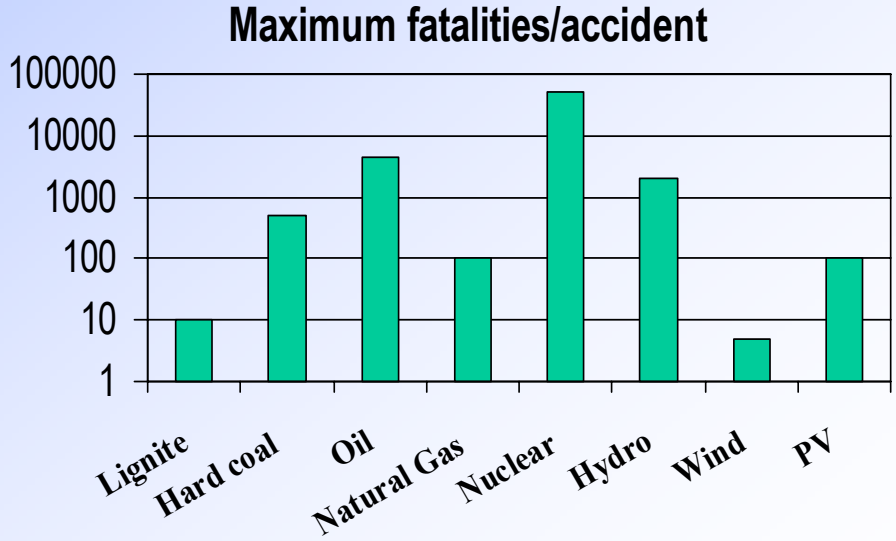


"Solar energy systems have greater material requirements .., so public risks from emissions will be greater"(Inhaber, *Science,* 1979*)*

"Commercial nuclear power is 10-15 times less risky than PV" (Bezdek, *Energy, 1993)*



ExternE German Implementation, 1999
(YOLL= years of life lost)



Paul Scherrer Institute (PSI) Report
(Hirschberg et al., 2004)

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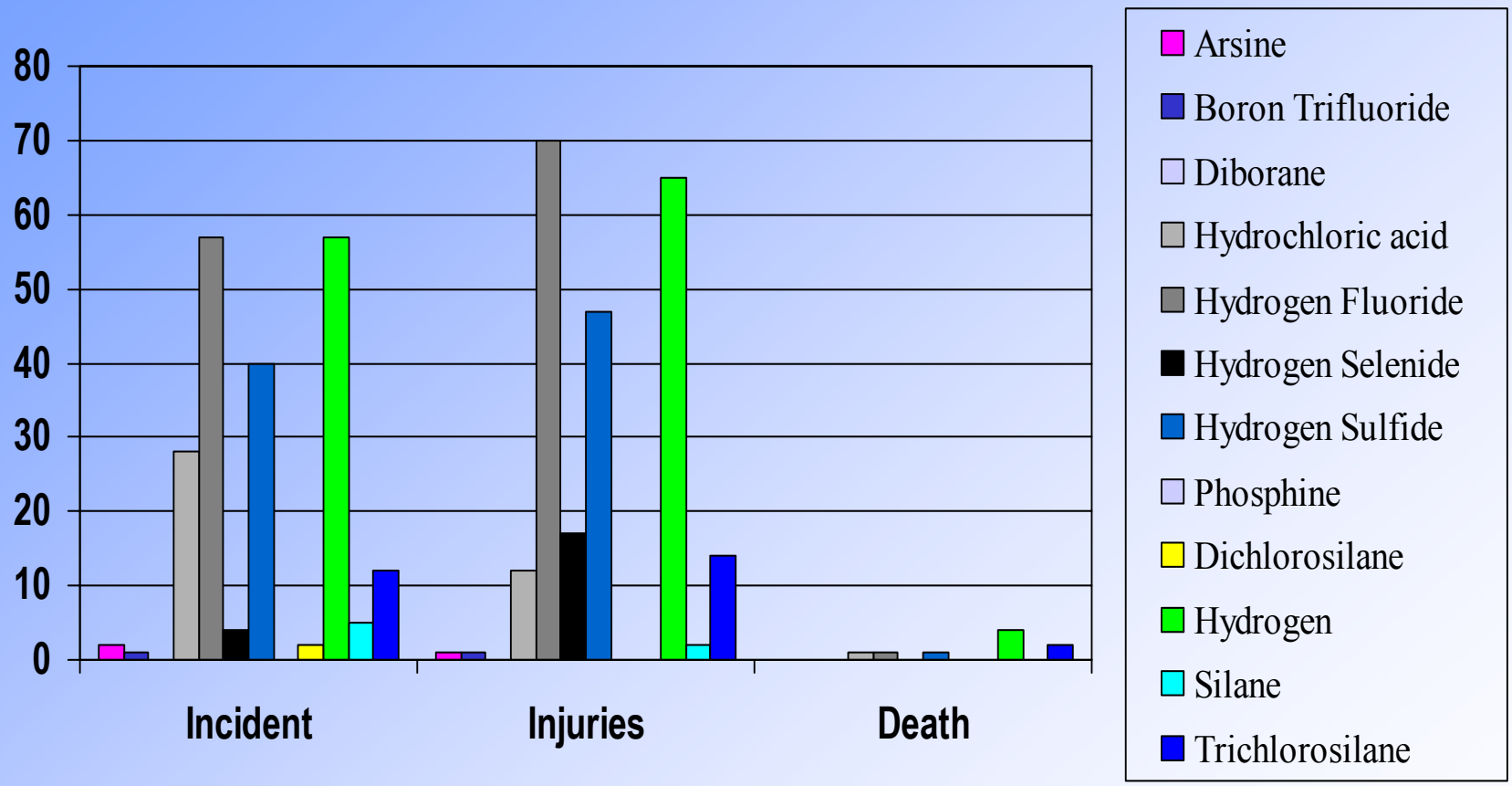
Estimating Accidental Risks

- We examined the risks related to the production, distribution and use of hazardous materials used in PV, based on the EPA Risk Management Program (RMP) databases for the U.S. industry

Hazardous Substances in PV Module Manufacturing (OSHA PSM & EPA RMP)

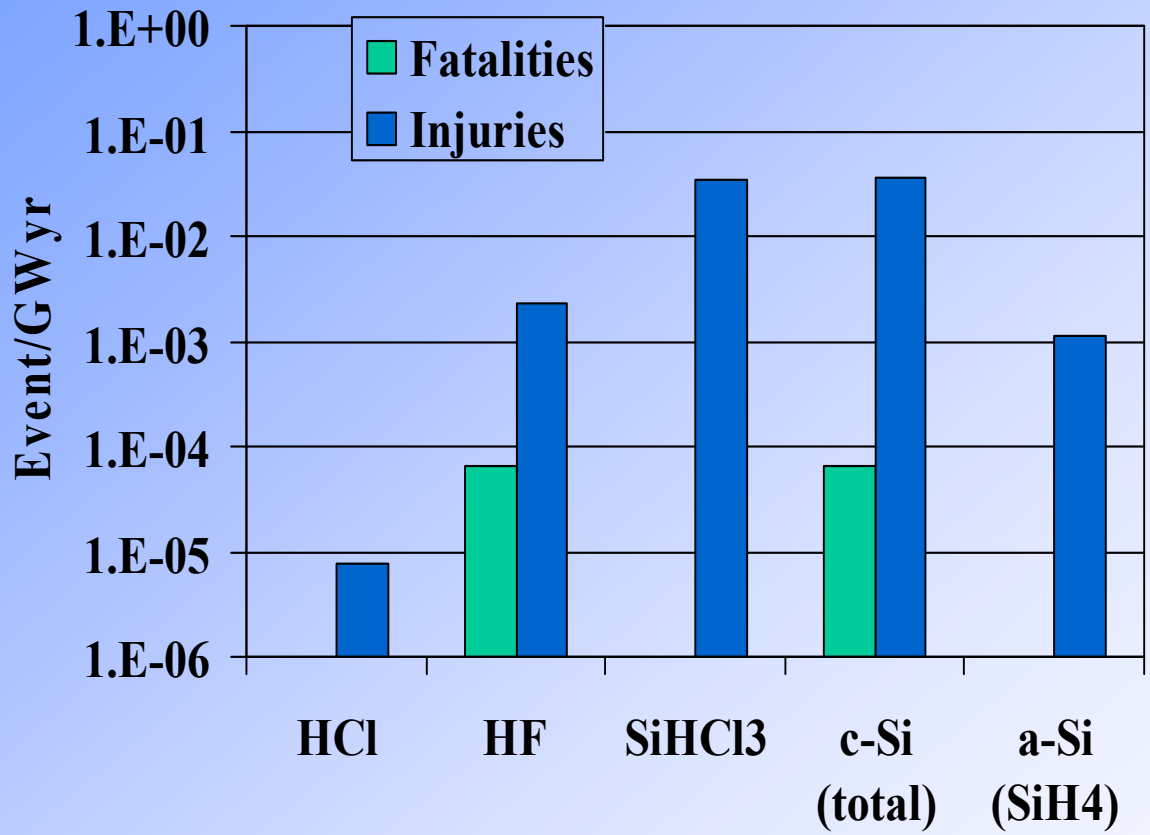
Substance	Source
Arsine	GaAs MOCVD
Boron Trifluoride	Dopant
Diborane	a-Si dopant
Hydrochloric acid	Cleaning agent – c-Si
Hydrogen Fluoride	Etchant – c-Si
Hydrogen Selenide	CIGS selenization
Hydrogen Sulfide	CIS sputtering
Phosphine	a-Si dopant
Hydrogen	a-Si deposition/GaAs
Silane	a-Si deposition
Trichlorosilane	Precursor - c-Si

Number of Reported Events in the U.S.
US-EPA RMP Database (1994-2004)



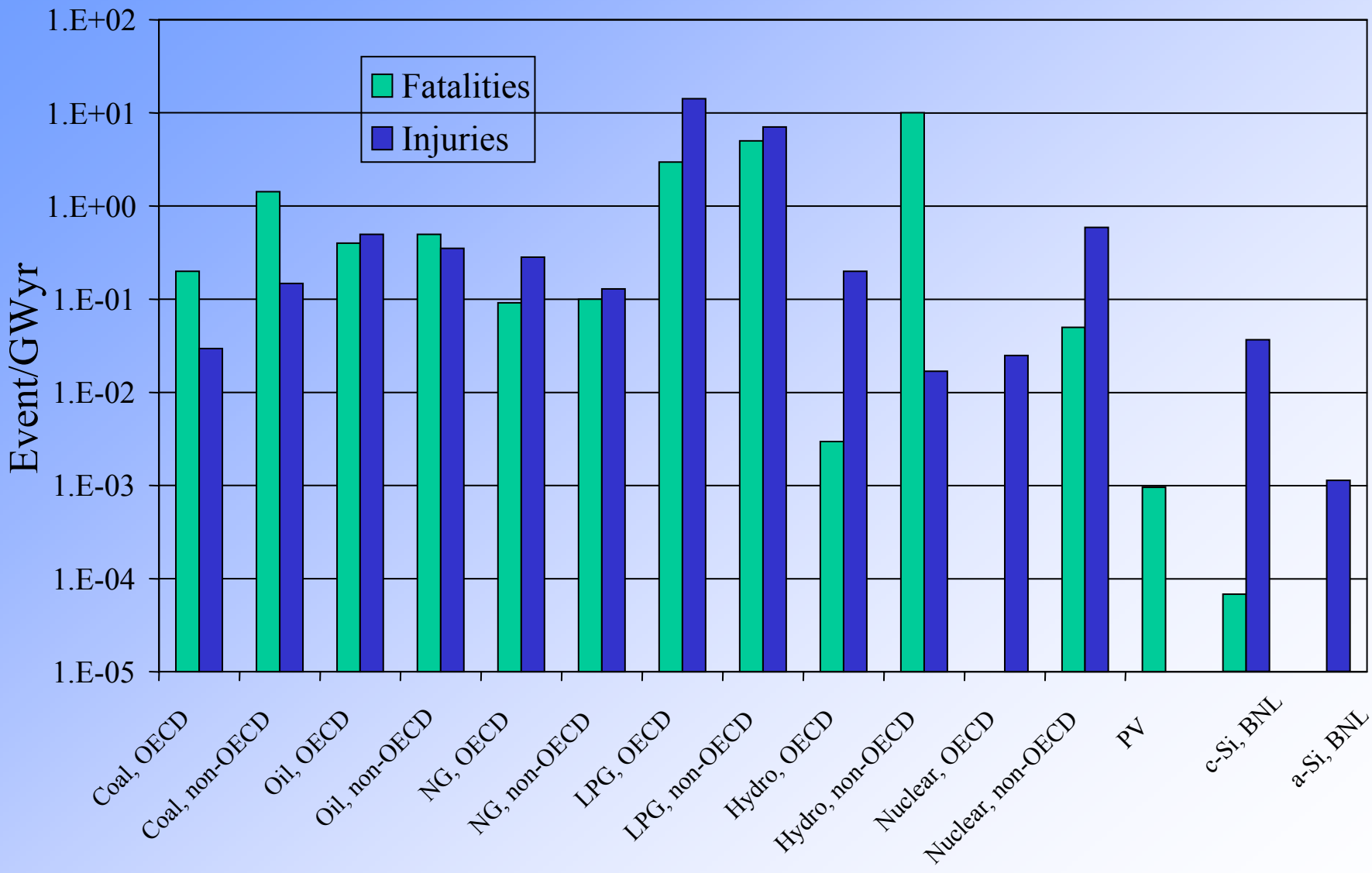
Estimated PV Risks by Chemical

Derived from US-EPA RMP Database (1997-2004)



Insolation = 1800 kWh/m2/yr; performance ratio = 0.8.

Comparison of Risk Estimates



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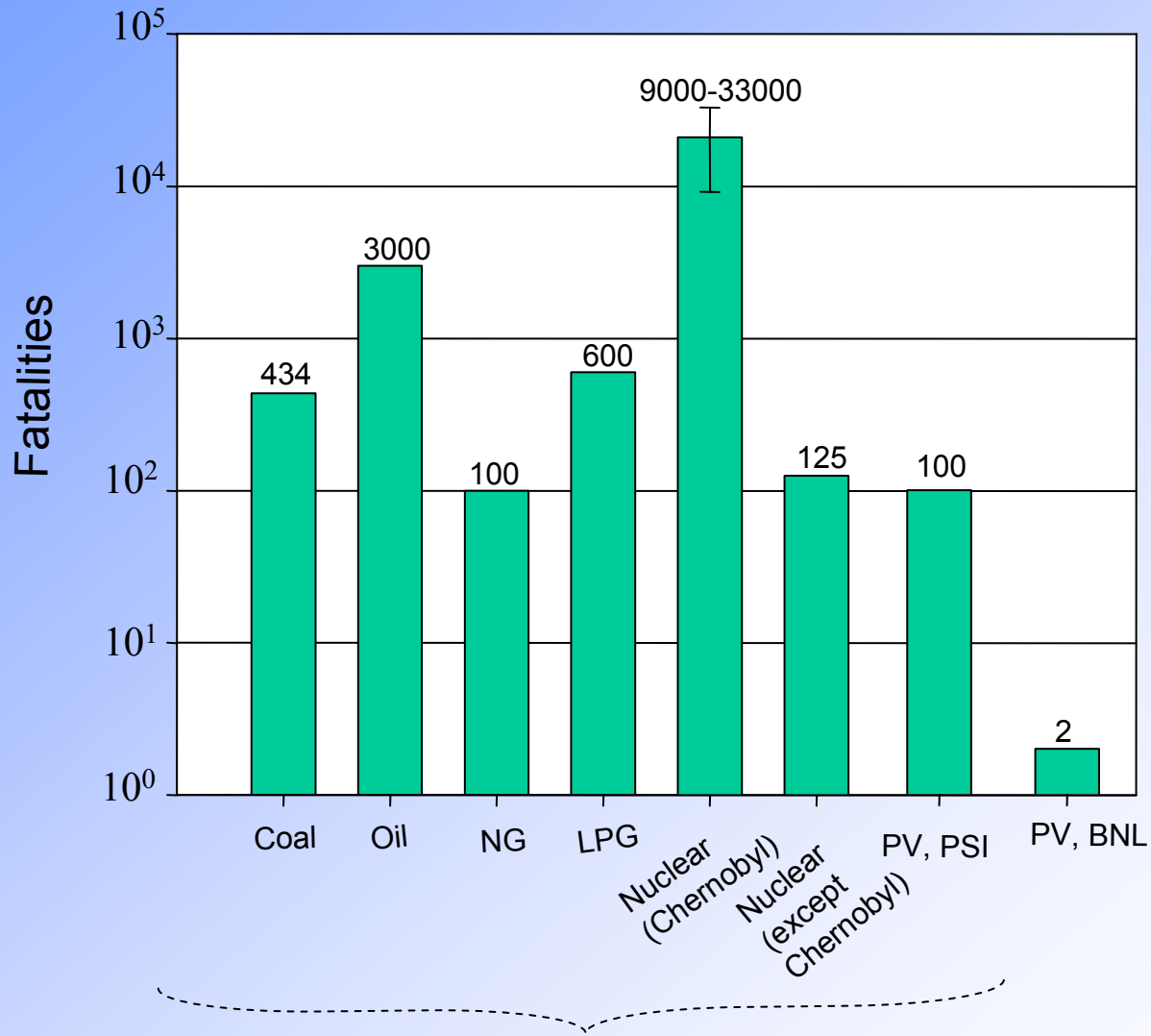
Comparisons of Estimated Maximum Consequences



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FY 2006 Publications

1. Fthenakis V.M. and Kim H.C., Greenhouse Gas Emissions from Solar Electric and Nuclear Power, A life Cycle Study, Energy Policy, 35, 2549-2557, 2007
2. Fthenakis V.M., et al., , Emissions and Redistribution of Elements in CdTe PV Modules during Fires, Progress in Photovoltaics: Research and Applications, 13: 713-723, 2005.
3. Mason J., Fthenakis V.M., Hansen T. and Kim C. Energy Pay-Back and Life Cycle CO2 Emissions of the BOS in an Optimized 3.5 MW PV Installation, Progress in Photovoltaics: Research and Applications, 14, 179-190, 2006.
4. Fthenakis V.M and Wang W., Extraction and Separation of Cd and Te from Cadmium Telluride Photovoltaic Manufacturing Scrap, Progress in Photovoltaics: Research and Applications, 14:363-371, 2006.
5. 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.
6. Kim H.C. and Fthenakis V.M, Amonix High-Concentrator Photovoltaic system: Life cycle energy demand and greenhouse gas emissions, Proceedings IEEE 4th World Conference on Photovoltaic Energy Conversion, Hawaii, May 8-12, 2006, pp. 628-631.
7. Fthenakis V.M., Quantifying the life-cycle environmental profile of photovoltaics and comparisons with other electricity-generation technologies, Proceedings IEEE 4th World Conference on Photovoltaic Energy Conversion, Hawaii, May 8-12, 2006, pp. 2477-2480.
8. de Wild-Scholten M.J., Alsema E., ter Horst E.W., Bachler M. and Fthenakis V.M., A Cost and Environmental Impact Comparison of Grid-Connected Rooftop and Ground-Mounted PV Systems, Proceedings 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September 2006, pp. 3167-3172.
9. Alsema E., de Wild-Scholten M.J. and Fthenakis V.M., Environmental Impacts of PV Electricity Generation - A Critical Comparison of Energy Supply Options, Proceedings 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September 2006, pp. 3201-3207.
10. Fthenakis V.M., Colli A., Arellano A., Kirchsteiger C., and Ale B., Evaluation of Risks in the life Cycle of Photovoltaics in a Comparative Context, Proceedings 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September 2006, pp. 3194-3201.
11. Fthenakis V.M., CdTe Photovoltaics: Life-cycle Environmental Profile, Thin Solid Films, in press.
12. Fthenakis V.M. Photovoltaics Life Cycle Analysis, Invited Plenary Presentation, Renewable Energy 2006, Chiba, Japan, October 11, 2006.
13. Wang W. and Fthenakis V., Recovery of tellurium from CdTe PV manufacturing scrap and other sources, EPD Congress, TMS (The Minerals, Metals & Material Society, 2006.
14. Fthenakis V.M., Carlisle C. and Chan W., Silane Safety in amorphous silicon and silicon nitride operations, Proceedings 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September 2006, 1761-1783.
15. Fthenakis V.M., Wang W., Meader A., and Squires K., Recycling of CdTe Photovoltaic Modules: Recovery of Glass, Cadmium and Tellurium, Proceedings 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September 2006, pp. 2539-2541
16. Fthenakis V.M., Kim H.C., Emissions from Photovoltaic Life Cycles, Environmental Sciences & Technology, Submitted.

Future Directions: FY07-09 Key EHS Targets

FY07

- Industry Outreach/ EHS Vigilance in manufacturing facilities; On-going effort
- Compare CdS buffer options for CIGS PV
- Assist industrialization of PV recycling
- GHG use in c-Si etching operations
- LCA of different manufacturing efficiencies

FY08

- EHS and LCA production of silicon feedstock
- Joint studies for increasing material utilization/ decreasing EHS risks and costs in a-Si PV manufacturing
- Dye-sensitized solar cells Life Cycle Analysis
- Risk-based LCA-based Comparisons of Energy Technologies Collaborative Work

FY09

- Organic solar cells EHS and LCA
- Concentrating Solar Power Life Cycle Analyses
- PV Nanomaterials Toxicity & Life Cycle Analysis

Collaborative work –5-yr IEA Task 12- kick off meeting March 16, 2006

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