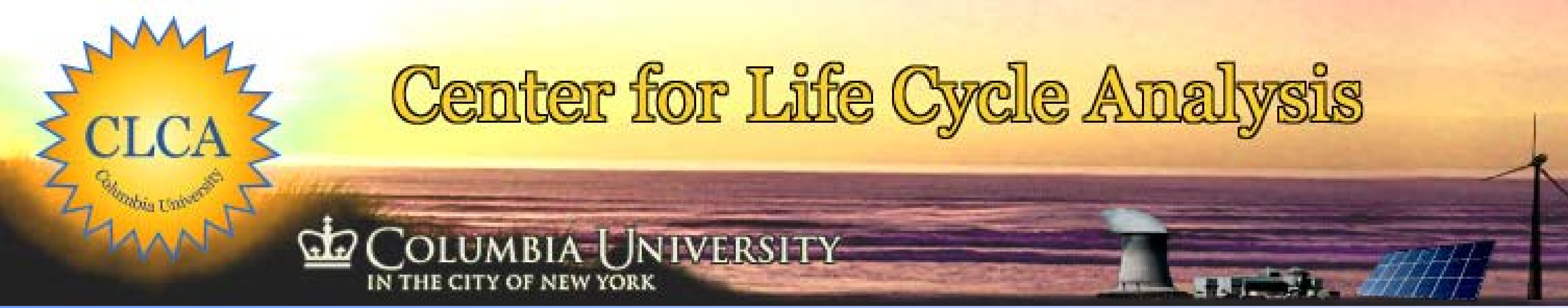

Life Cycle Analysis of PV

Vasilis Fthenakis

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Earth & Environmental Engineering Department
Columbia University
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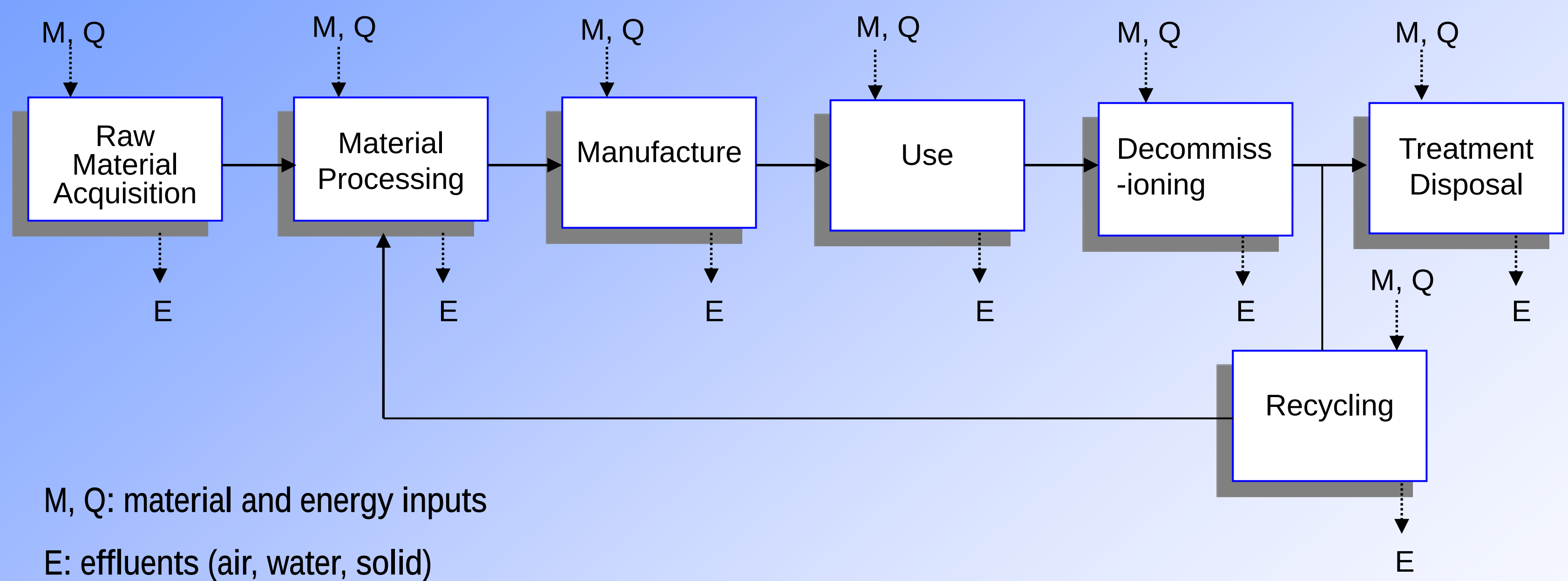
Brookhaven National Laboratory

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



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.

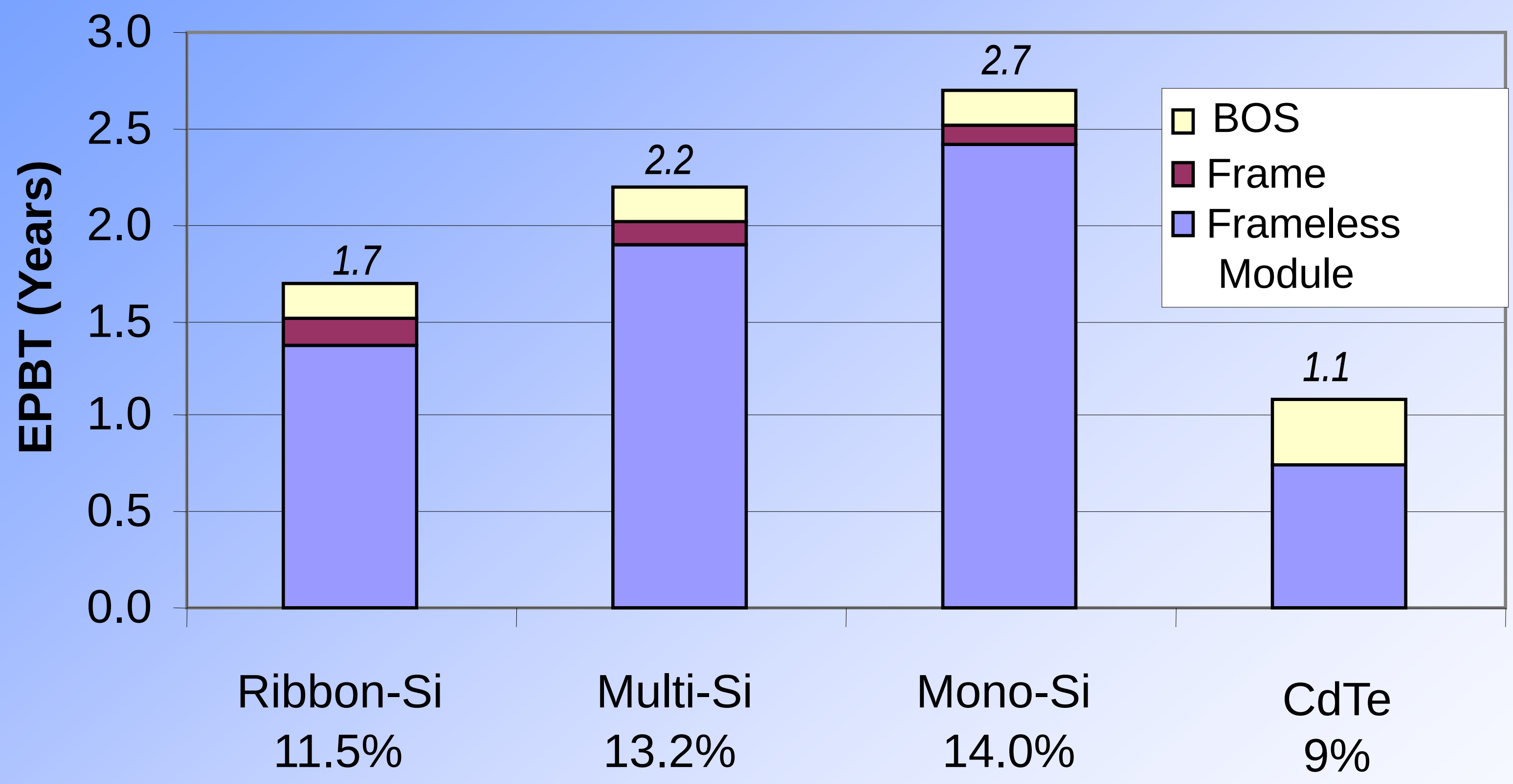
$$EPBT = (E_{mat}+E_{manuf}+E_{trans}+E_{inst}+E_{EOL}) / (E_{agen.} - E_{am})$$

where,

E_{mat} Primary energy demand to produce materials comprising PV system
E_{manuf} Primary energy demand to manufacture PV system
E_{trans} Primary energy demand to transport materials used during the life cycle
$E_{inst.}$ Primary energy demand to install the system
E_{EOL} Primary energy demand for end-of-life management
E_{agen} Annual electricity generation in primary energy
E_{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

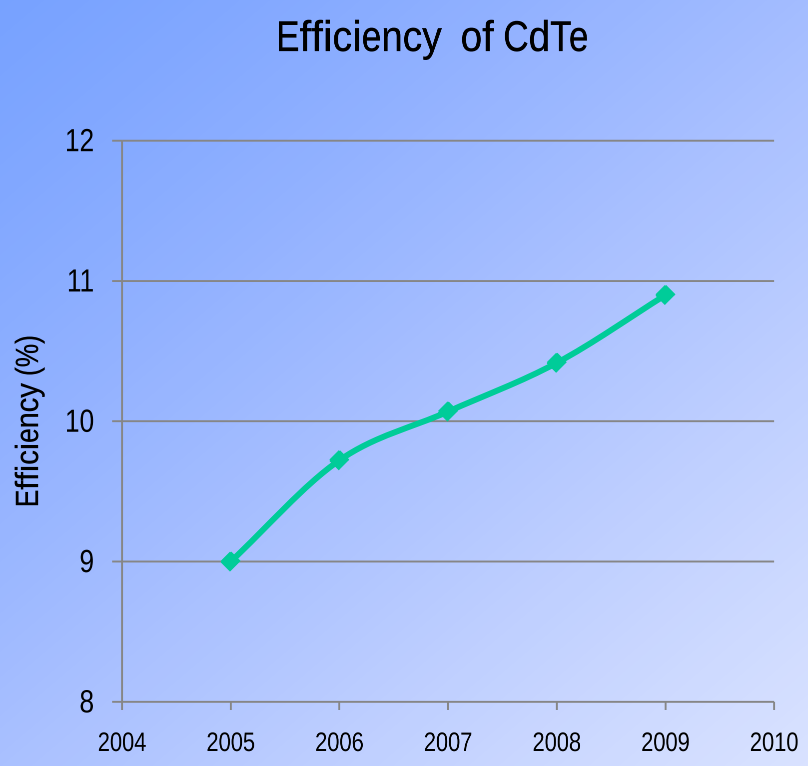
-Alsema & de Wild, *Material Research Society, Symposium vol. 895, 73, 2006*

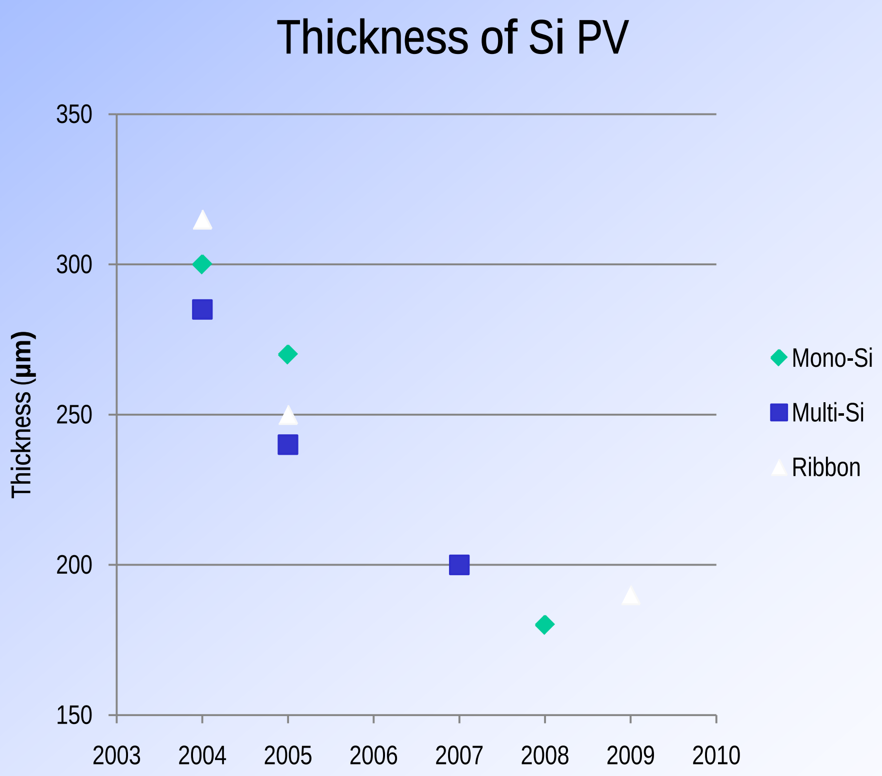
-deWild & Alsema, *Material Research Society, Symposium vol. 895, 59, 2006*

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

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

Progress in PV Technologies

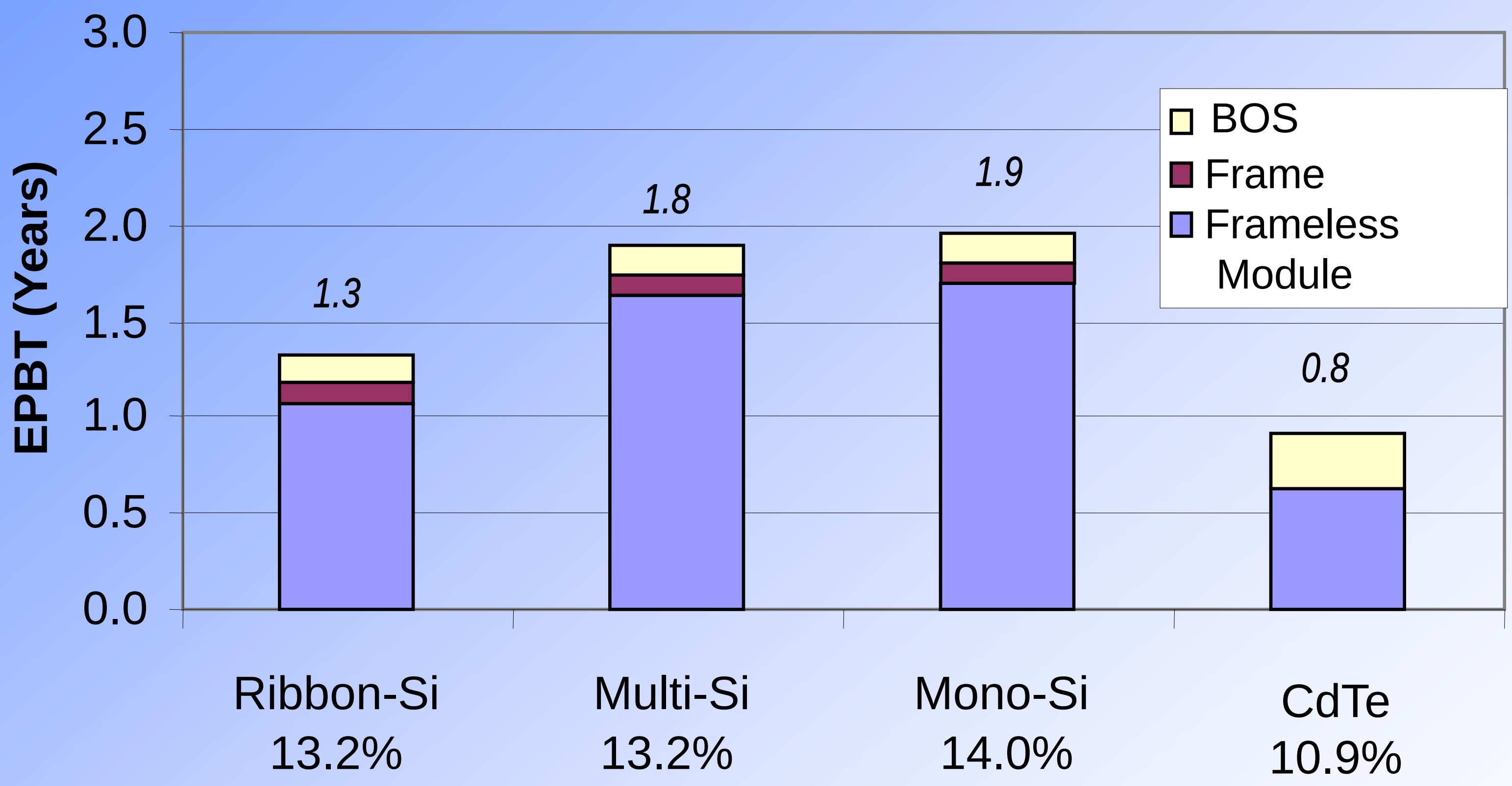




Sources: First Solar, de Wild-Scholten, ECN, 2009

Update of Energy Payback Times

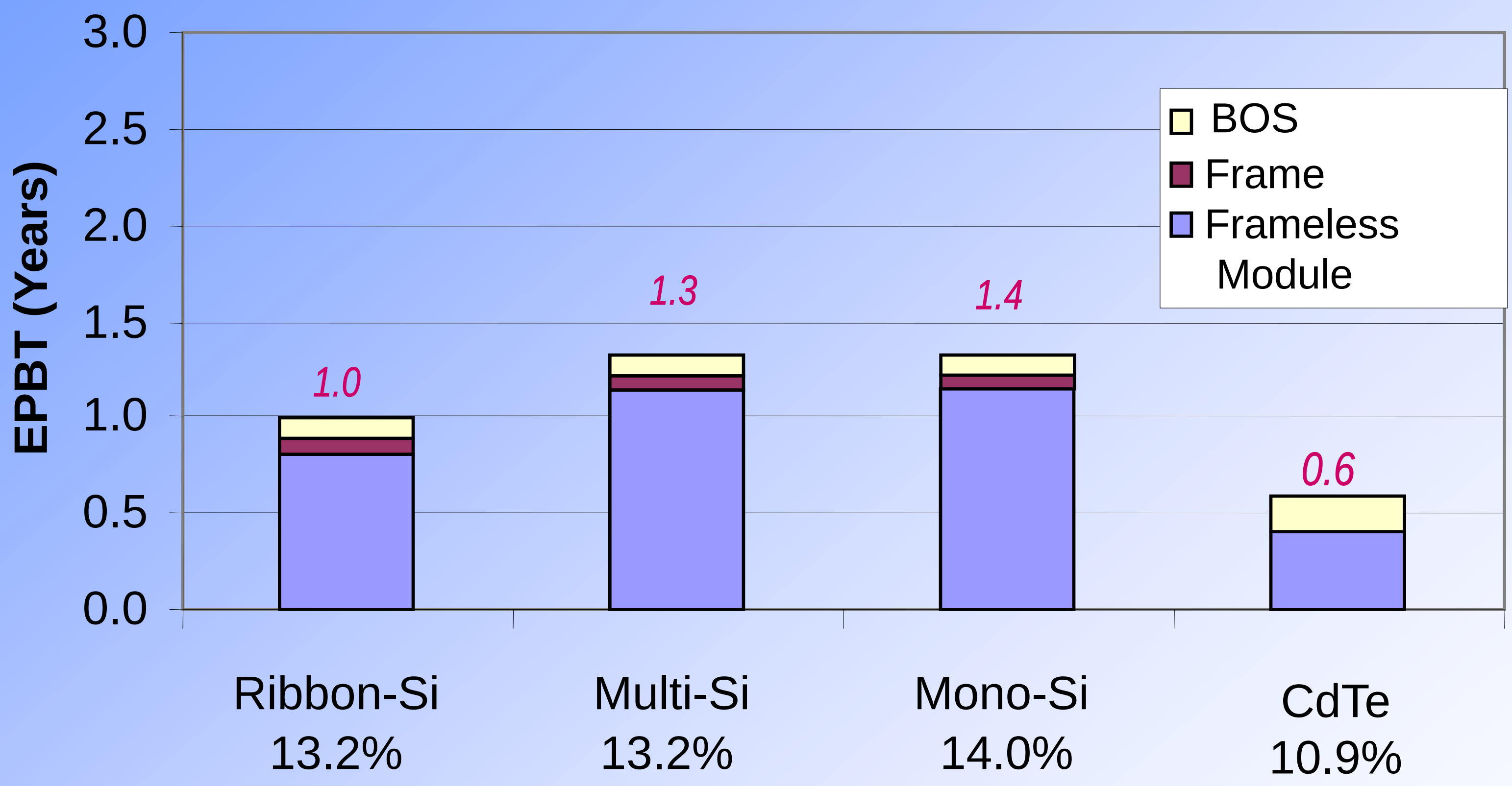
Insolation: 1700 kWh/m2-yr



deWild 2009, *EUPV, 2009*
Fthenakis et al., EUPV, 2009

Energy Payback Times in the US-SW

Insolation: 2300 kWh/m2-yr



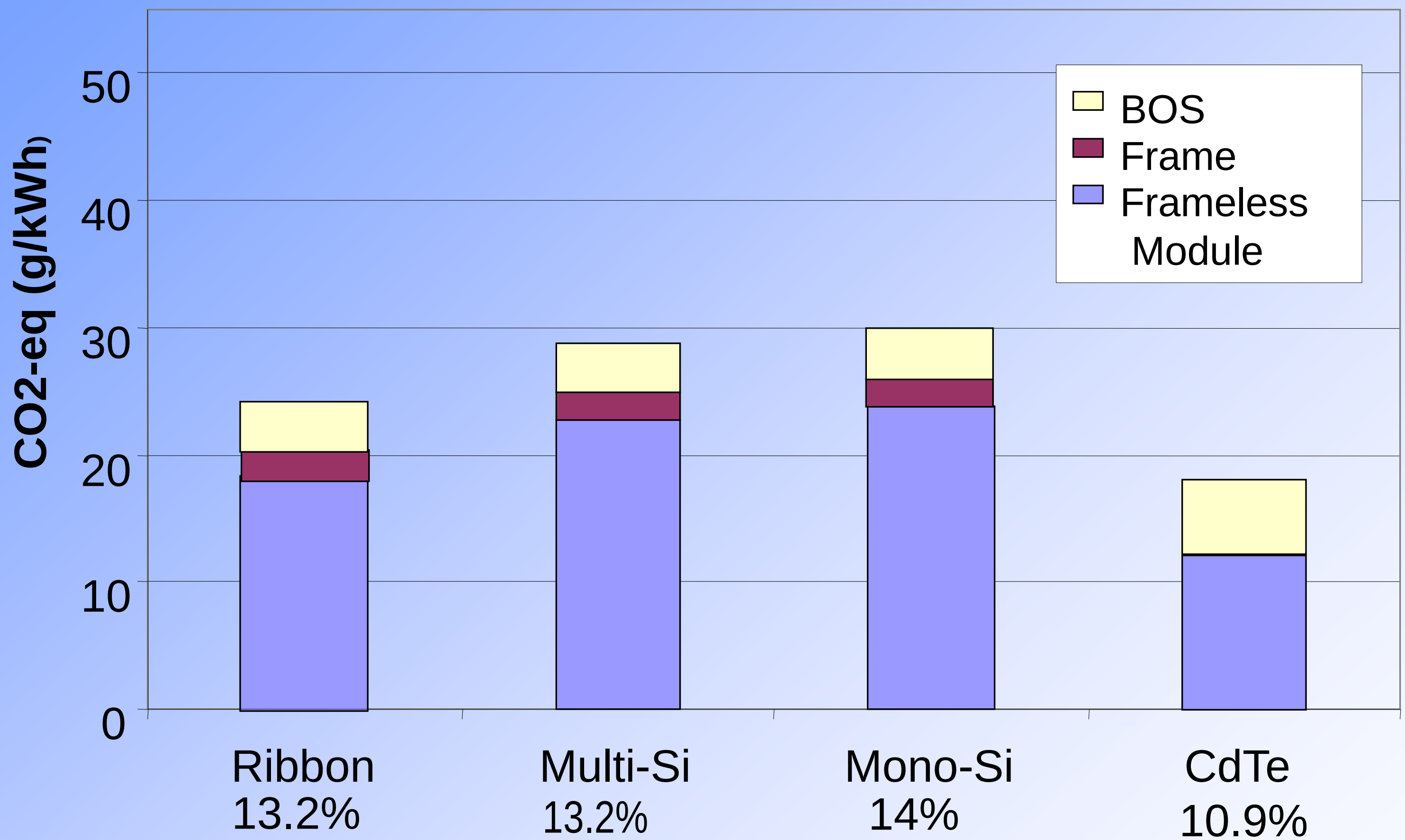
deWild 2009, *EUPV, 2009*

Fthenakis et al., EUPV, 2009

Greenhouse Gas (GHG) Emissions

Crystal Clear & BNL LCAs GHG Emissions –Europe

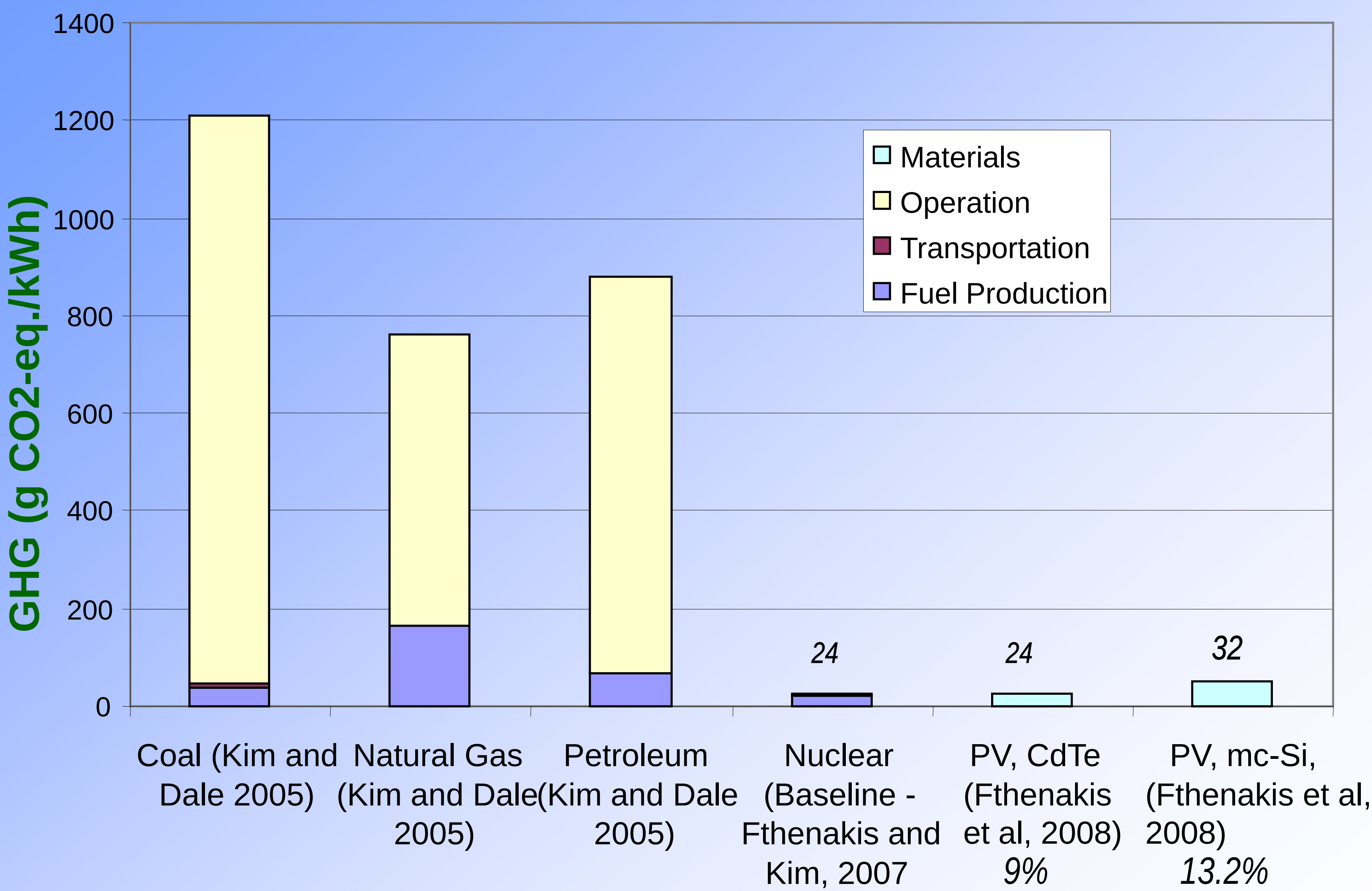
Insolation: 1700 kWh/m2-yr



deWild 2009, *EUPV, 2009*

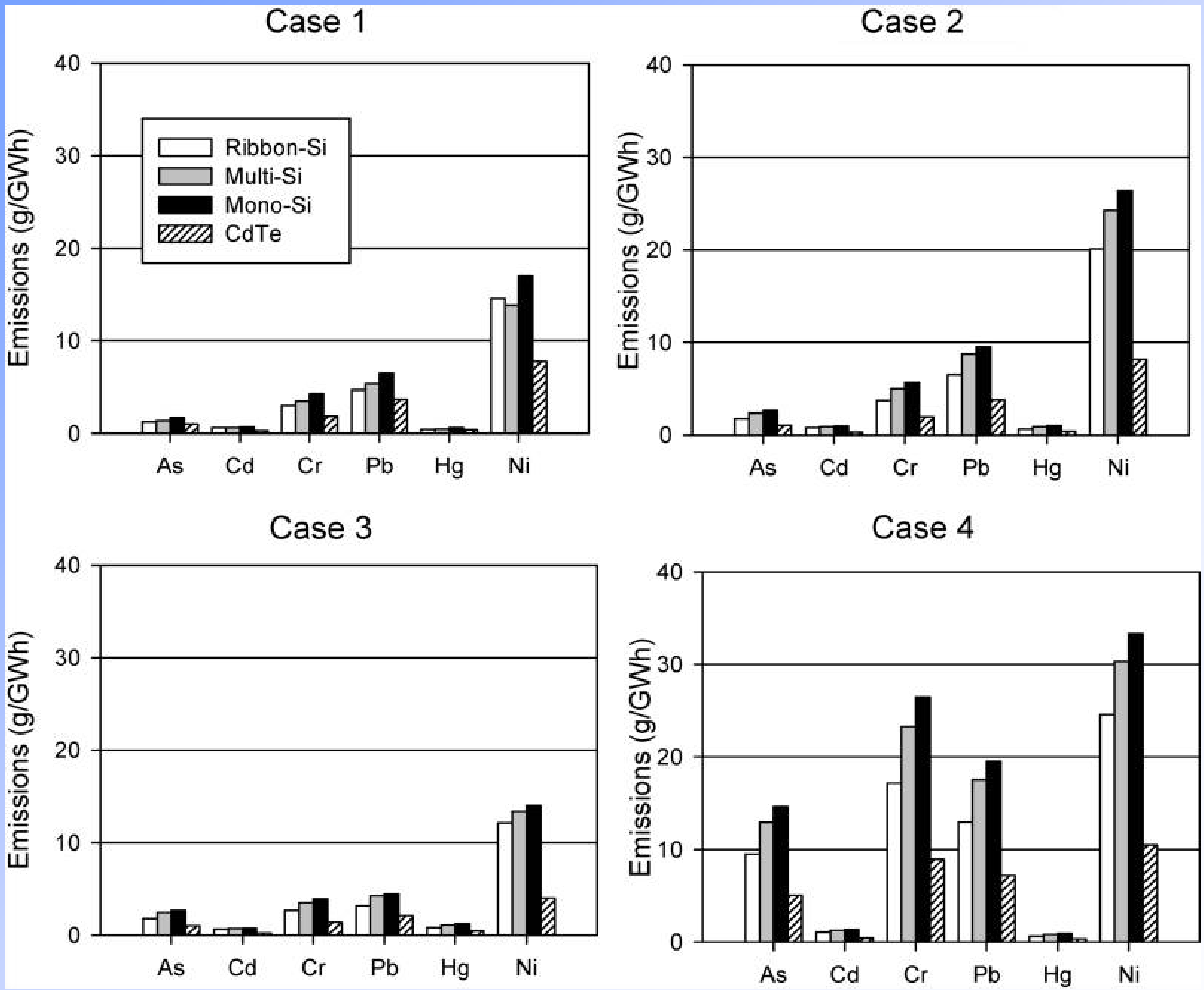
Fthenakis et al., EUPV, 2009

GHG Emissions from Life Cycle Energy of Electricity Production



California Energy Commission, *Nuclear Issues Workshop*, 2007
Fthenakis & Kim, *Energy Policy, 2007*

Heavy Metal Emissions in the Life-Cycle of PV



Fthenakis, Kim, Alsema. ES&T, 2009

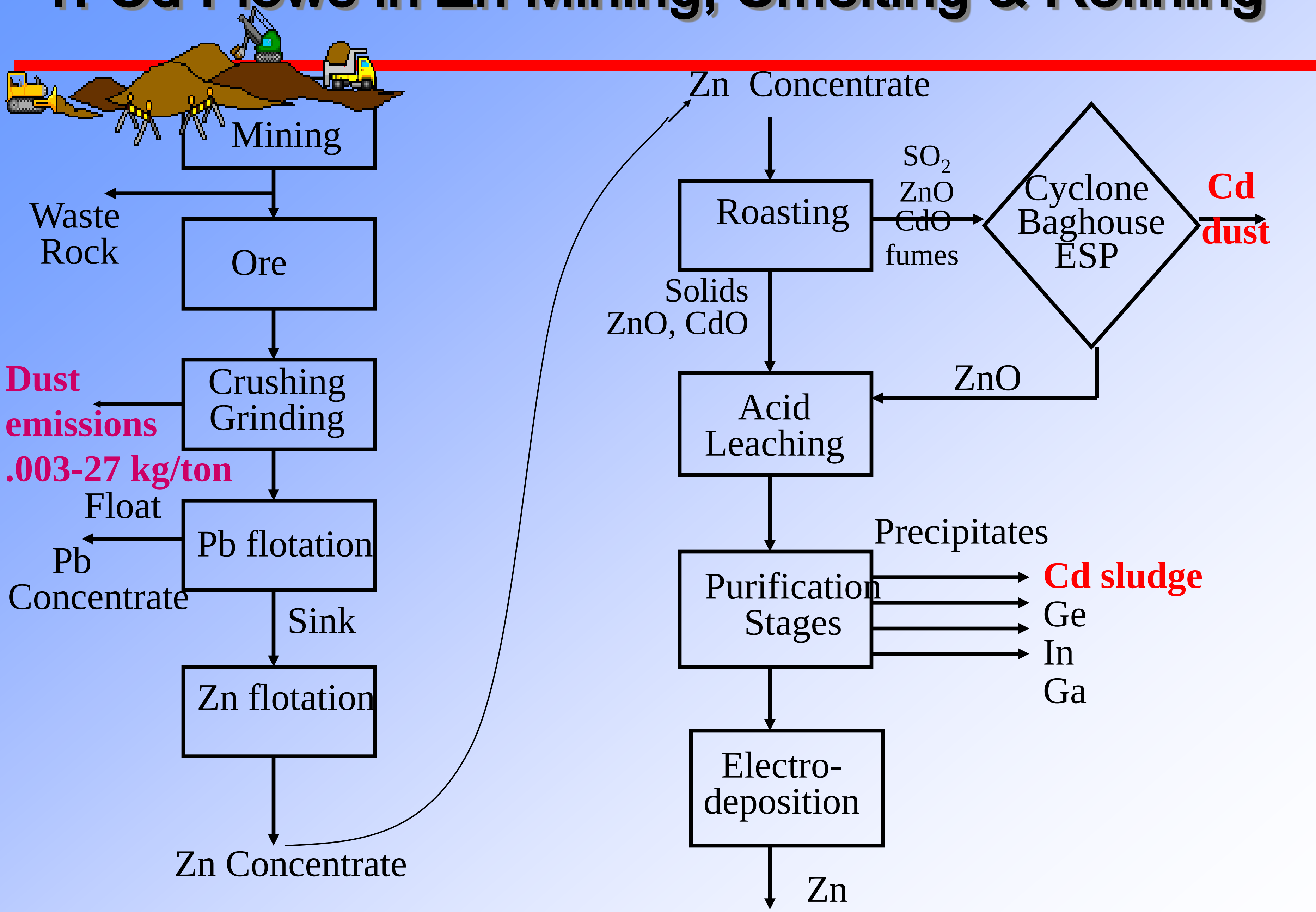
CdTe PV Life-Cycle Analysis (focus on Cd flows –air emissions)

Stages of the Life of CdTe PV:

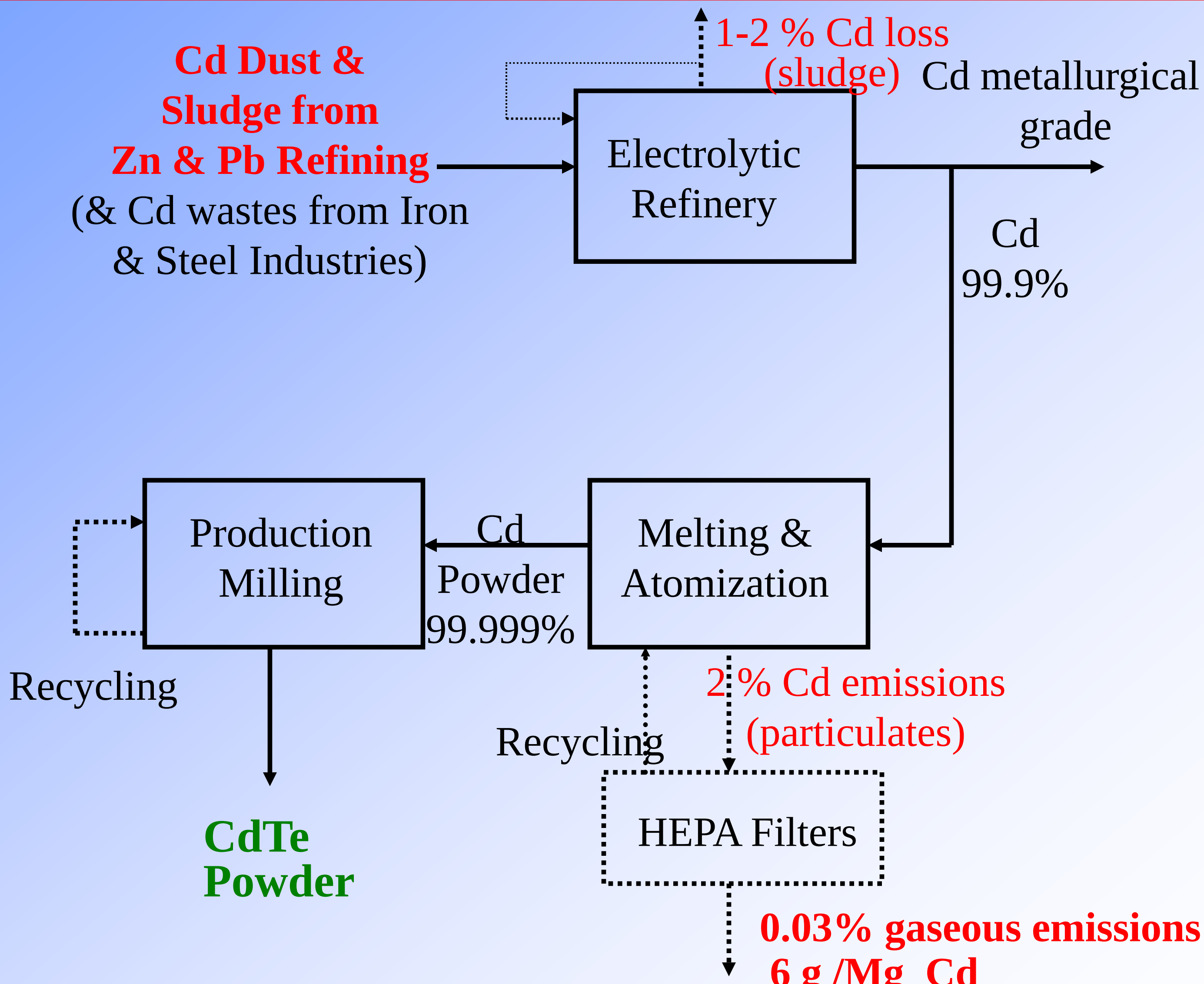
1. Mining/Smelting/Refining –Cd & Te production
2. Purification of Cd & Production of CdTe
3. Manufacture of CdTe PV modules
4. Use of CdTe PV modules
5. End-of-life of CdTe PV modules

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



2. Cd Flows from Cd Concentrates to CdTe



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**

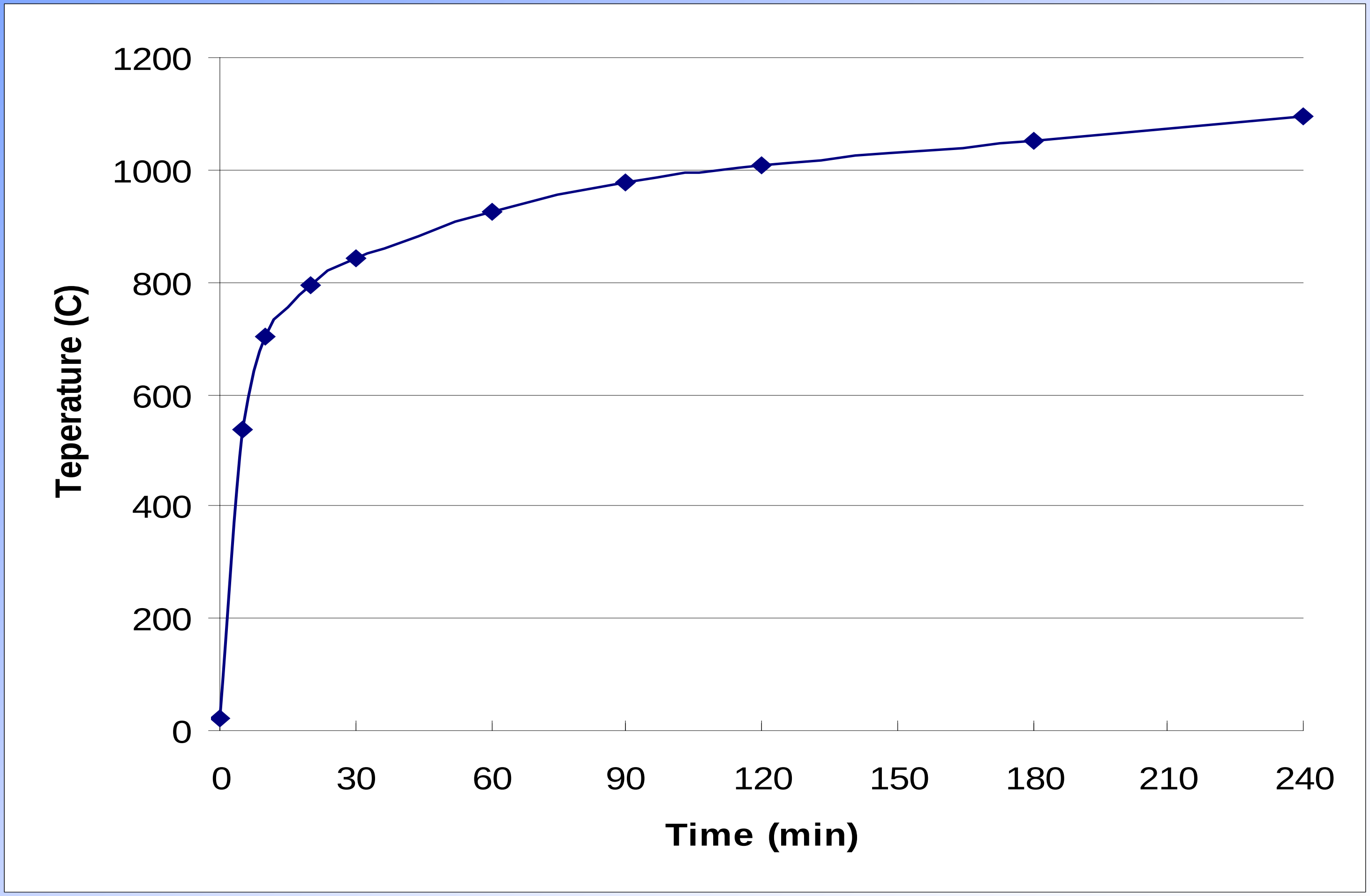
*"In a worst-case scenario for CdTe modules the leached Cd concentration in the collected water is estimated to be no higher than the German drinking water concentration. No critical increase of the natural element concentration is observed after leaching into the soil for 1 year" (*Steinberger, *PiP,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

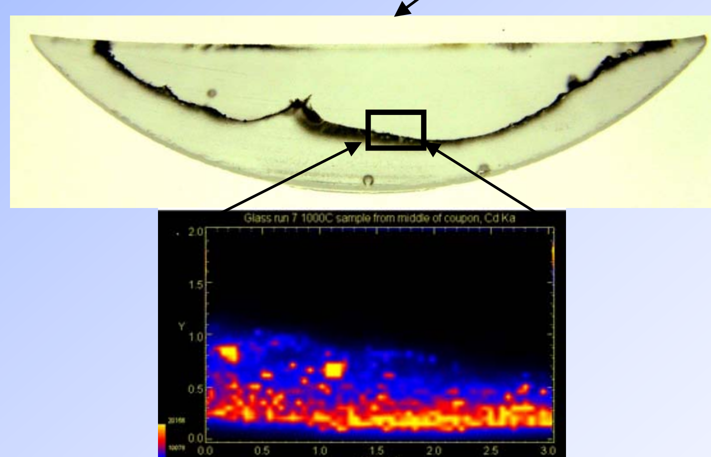


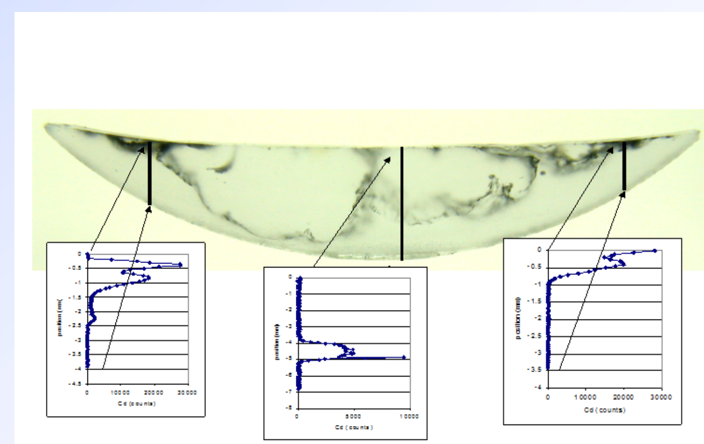
CdTe PV Fire-Simulation Tests: XRF Analysis

Heat

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

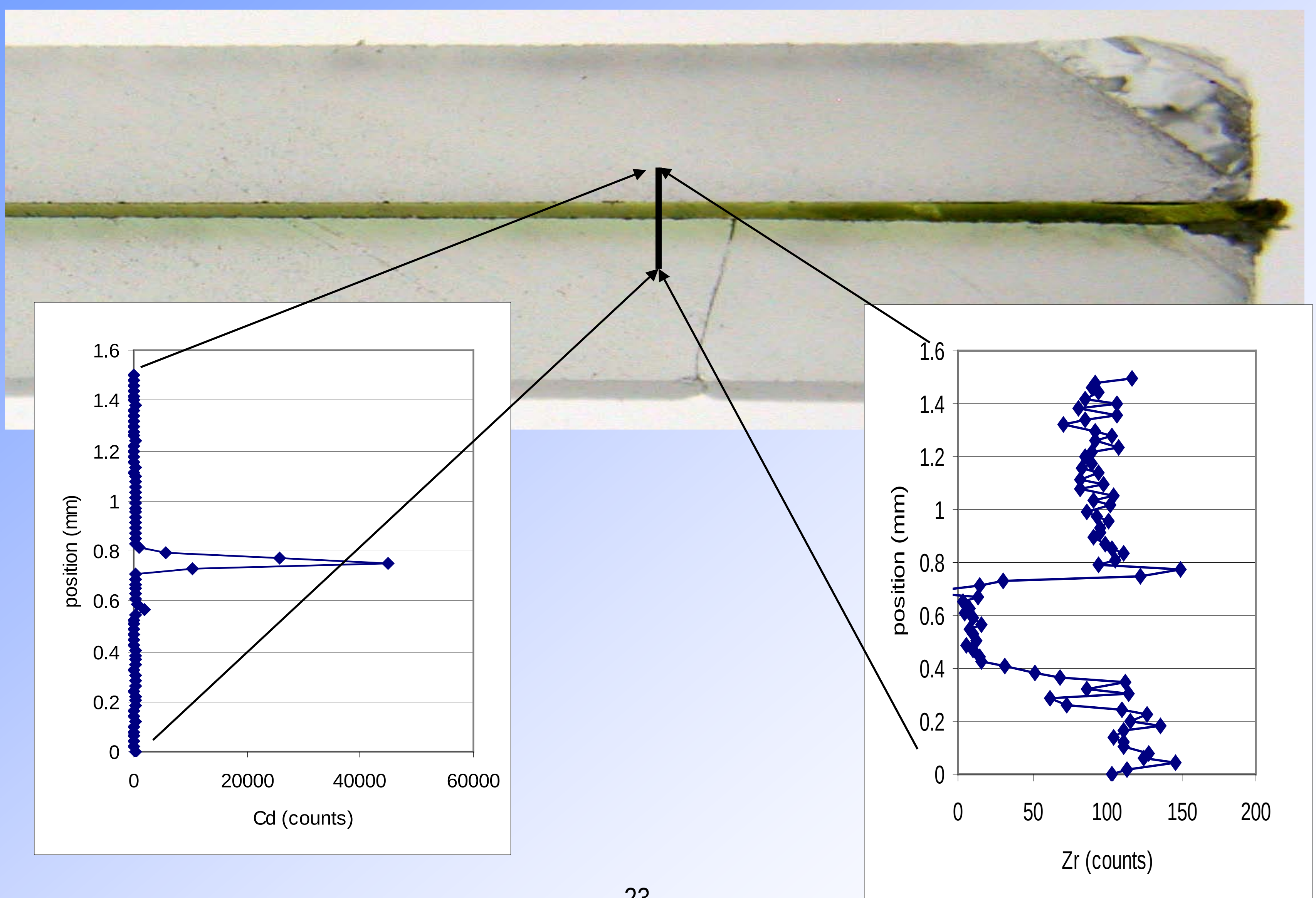
XRF-micro-probing –
Cd Distribution in PV Glass
1000 °C, right end of sample





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

XRF-micro-probing -Cd & Zr Distribution in PV Glass Unheated Sample -Vertical Cross Section



Atmospheric Cd Emissions from the Life-Cycle of CdTe PV Modules –Reference Case

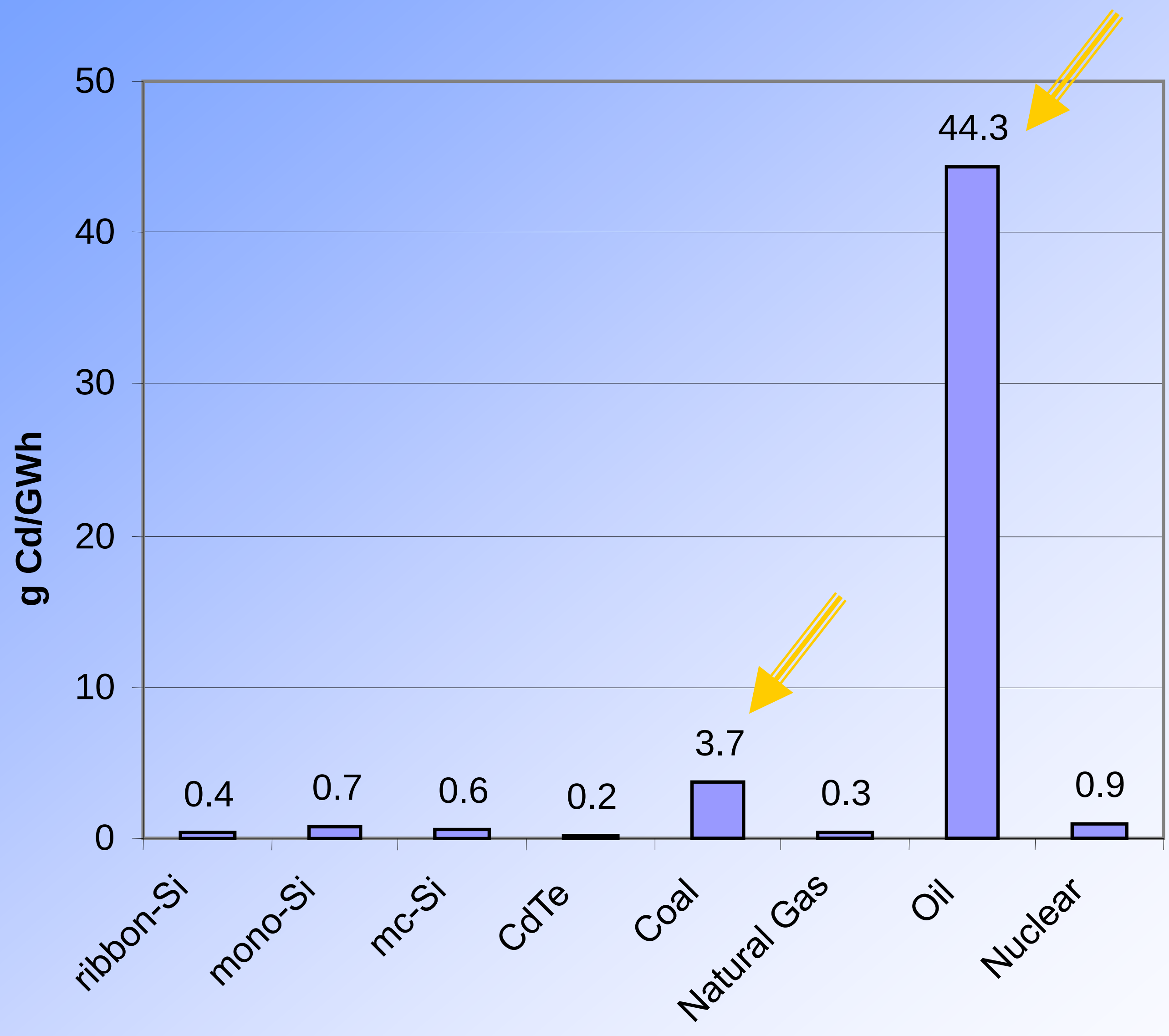
Process	(g Cd/ton Cd*)	(%)	(mg Cd/GWh)
1. Mining of Zn ores	2.7	0.58	0.02
2. Zn Smelting/Refining	40	0.58	0.30
3. Cd purification	6	100	7.79
4. CdTe Production	6	100	7.79
5. CdTe PV Manufacturing	0.4*	100	0.52*
6. CdTe PV Operation	0.05	100	0.06
7. CdTe PV Recycling	0.1*	100	0.13*
TOTAL EMISSIONS			16.55

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

* 2009 updates

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

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

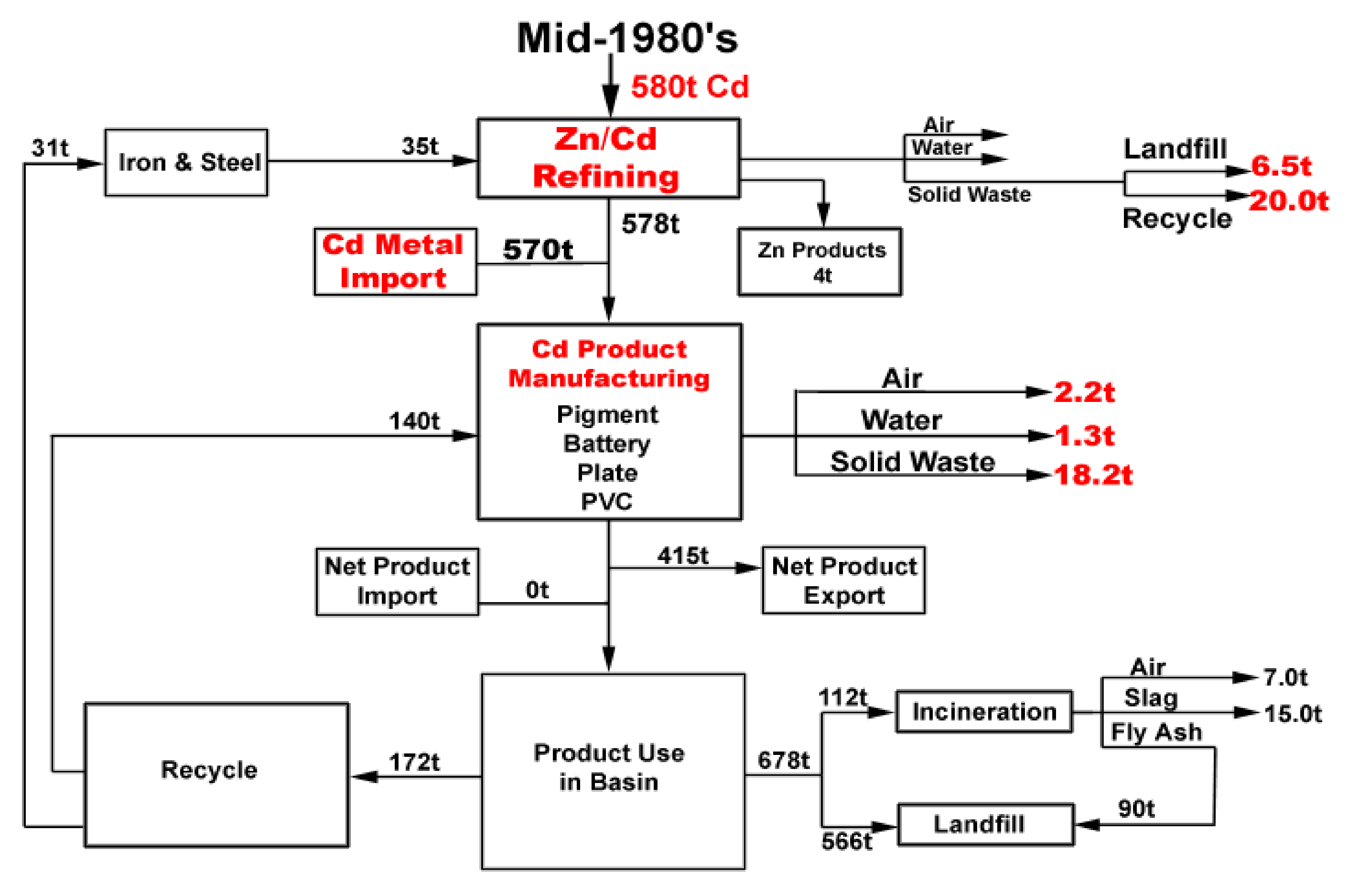
A Holistic View of Cd Use in PV

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)

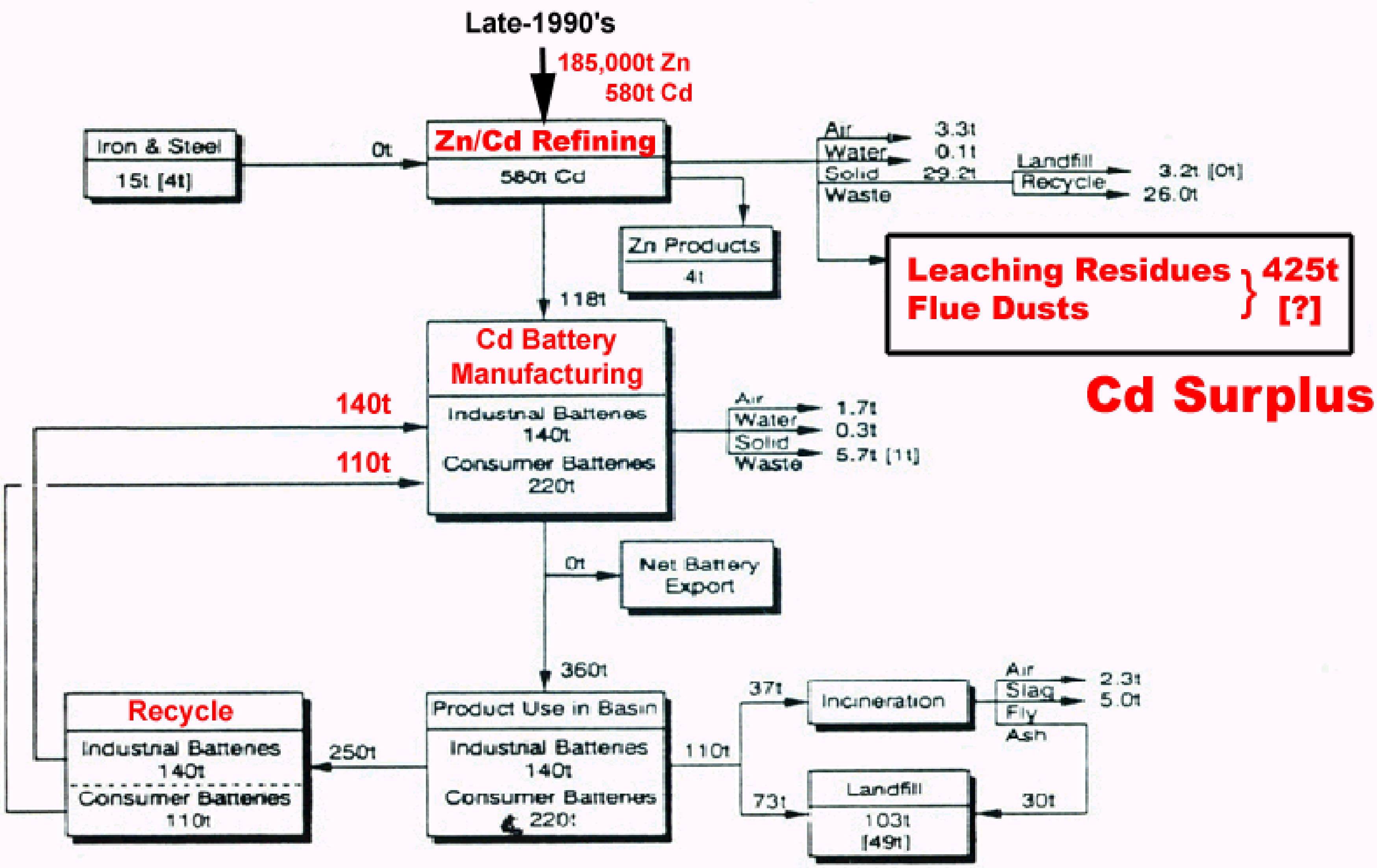
- Liewellyn T. Cadmium , **Bureau of Mines** Information Circular 1994, US Department of the Interior.
- Plachy J., **U.S. Geological Survey Minerals Yearbook**—2001, Cadmium—Chapter 17.
- Stigliani W, Anderberg S. Chapter 7. In: Ayres R, Simonis U, editors. **Industrial metabolism.** Tokyo, Japan: The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

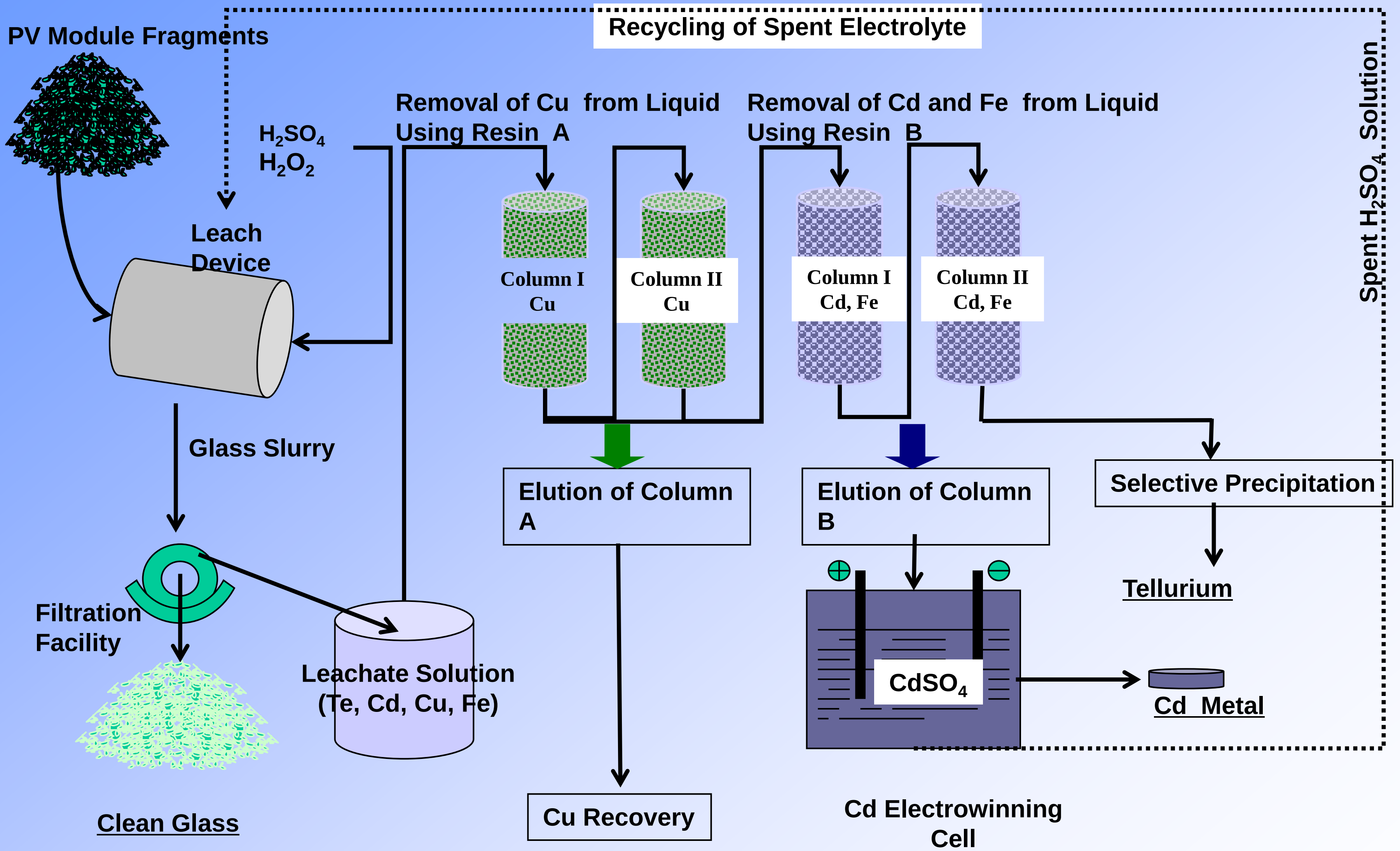
A Holistic View: Notes

- 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



Cd-Te Separation Patent

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: Research and Applications, 14:363-371, 2006.

First Solar Module Recycling Process

Courtesy: First Solar

The PV CYCLE Voluntary Initiative

ASSOCIATION PV CYCLE

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