Environmental Aspects of Thin Film Module Production and Product Lifetime

Vasilis Fthenakis

PV Environmental Research Center

Brookhaven National Laboratory

and

Center for Life Cycle Analysis

Columbia University

Invited Plenary Presentation at the 25th European Photovoltaic Solar Energy Conference, Valencia, September 9, 2010

email: vmf@bnl.gov

web: www.pv.bnl.gov

www.clca.columbia.edu

BROOKHAVEN NATIONAL LABORATORY

PV Sustainability Criteria

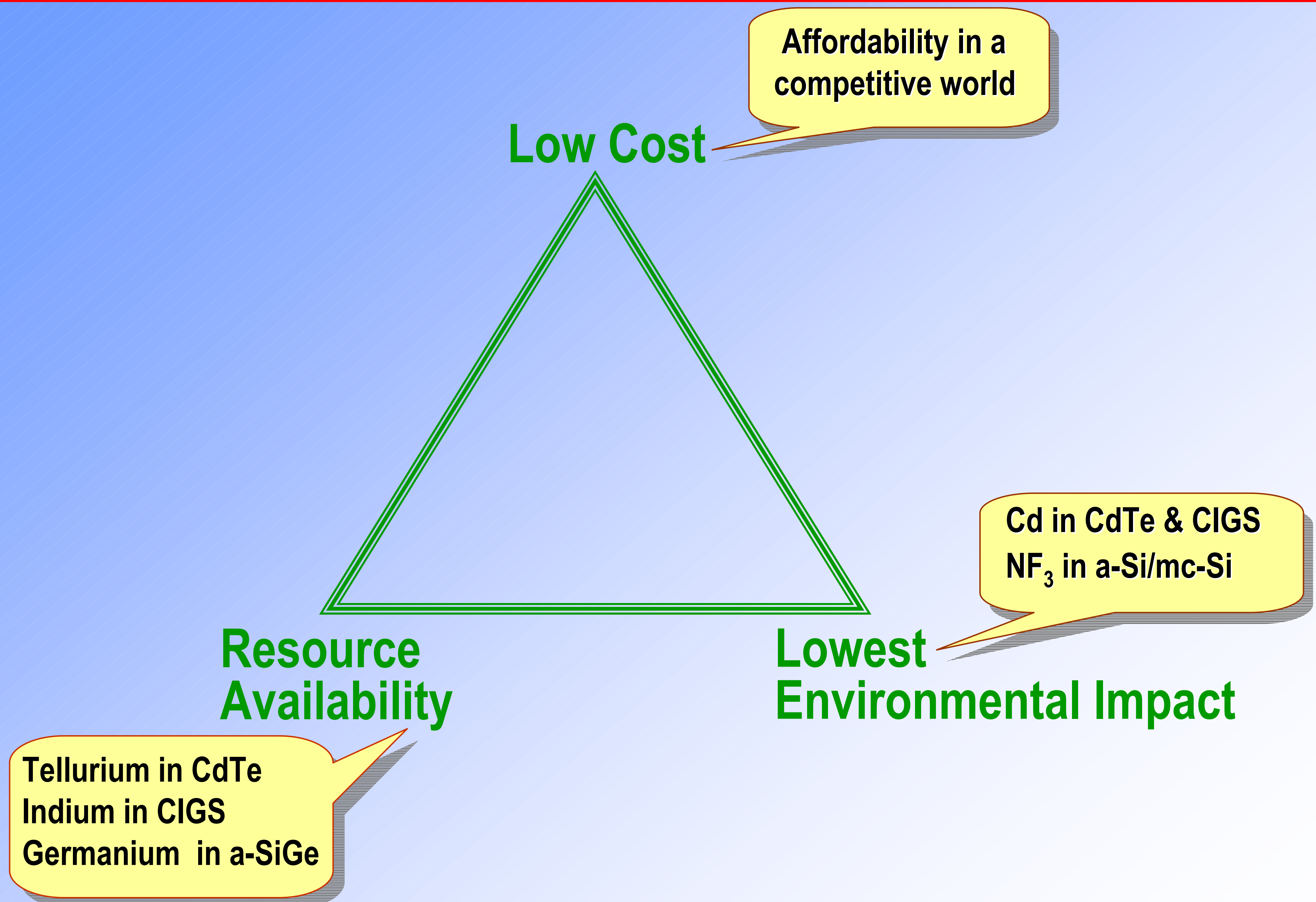
- Photovoltaics are required to meet the need for abundant electricity generation at competitive costs, whilst conserving resources for future generations, and having environmental impacts lower than those of alternative future energy-options

Sustainability Metrics:

- Low Cost
- Resource Availability
- Minimum Environmental Impact

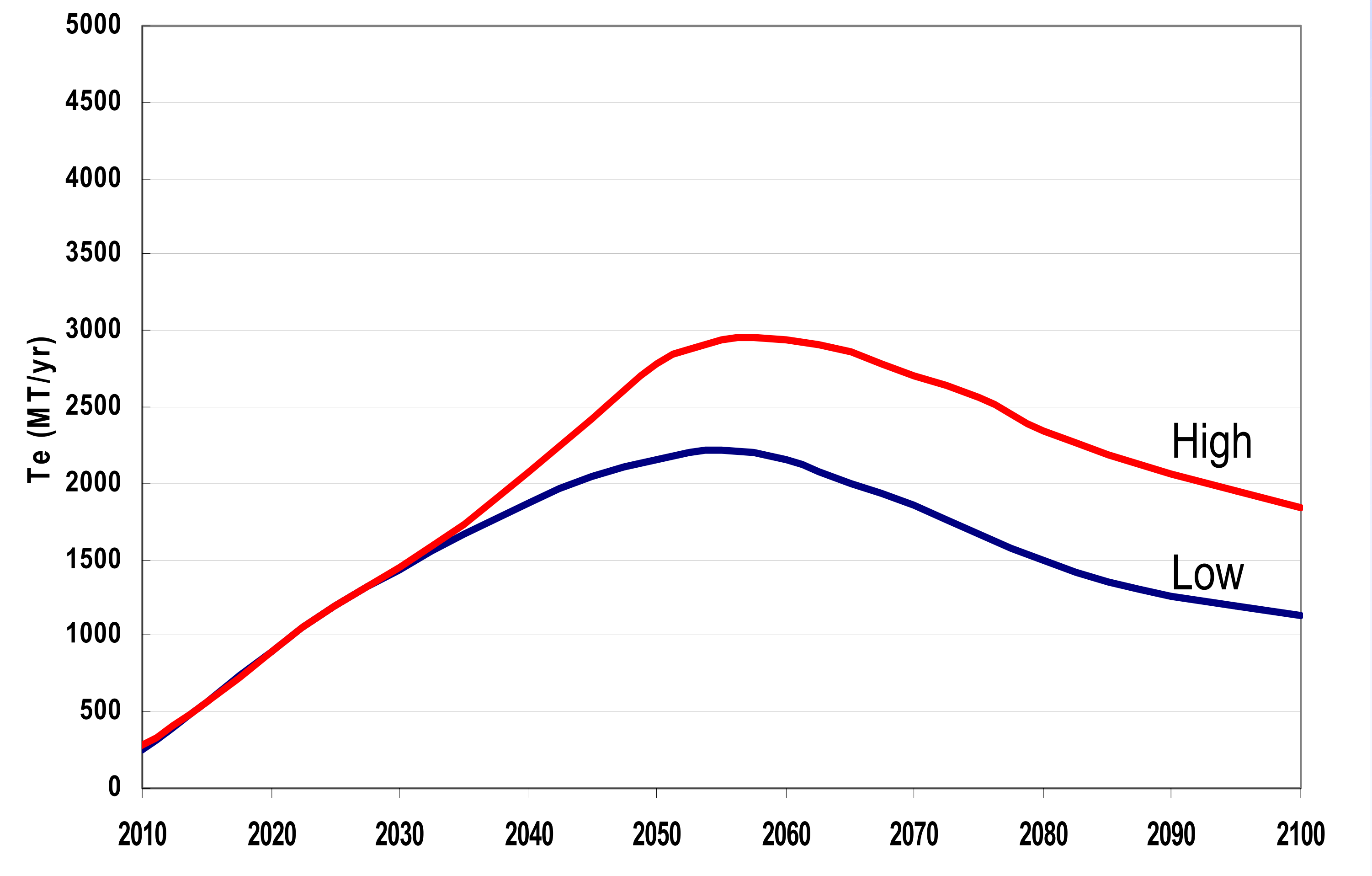
BROOKHAVEN NATIONAL LABORATORY

Thin-Film PV -The Triangle of Success



Tellurium for PV* from Copper Smelters

Tellurium Availability for PV* (MT/yr)

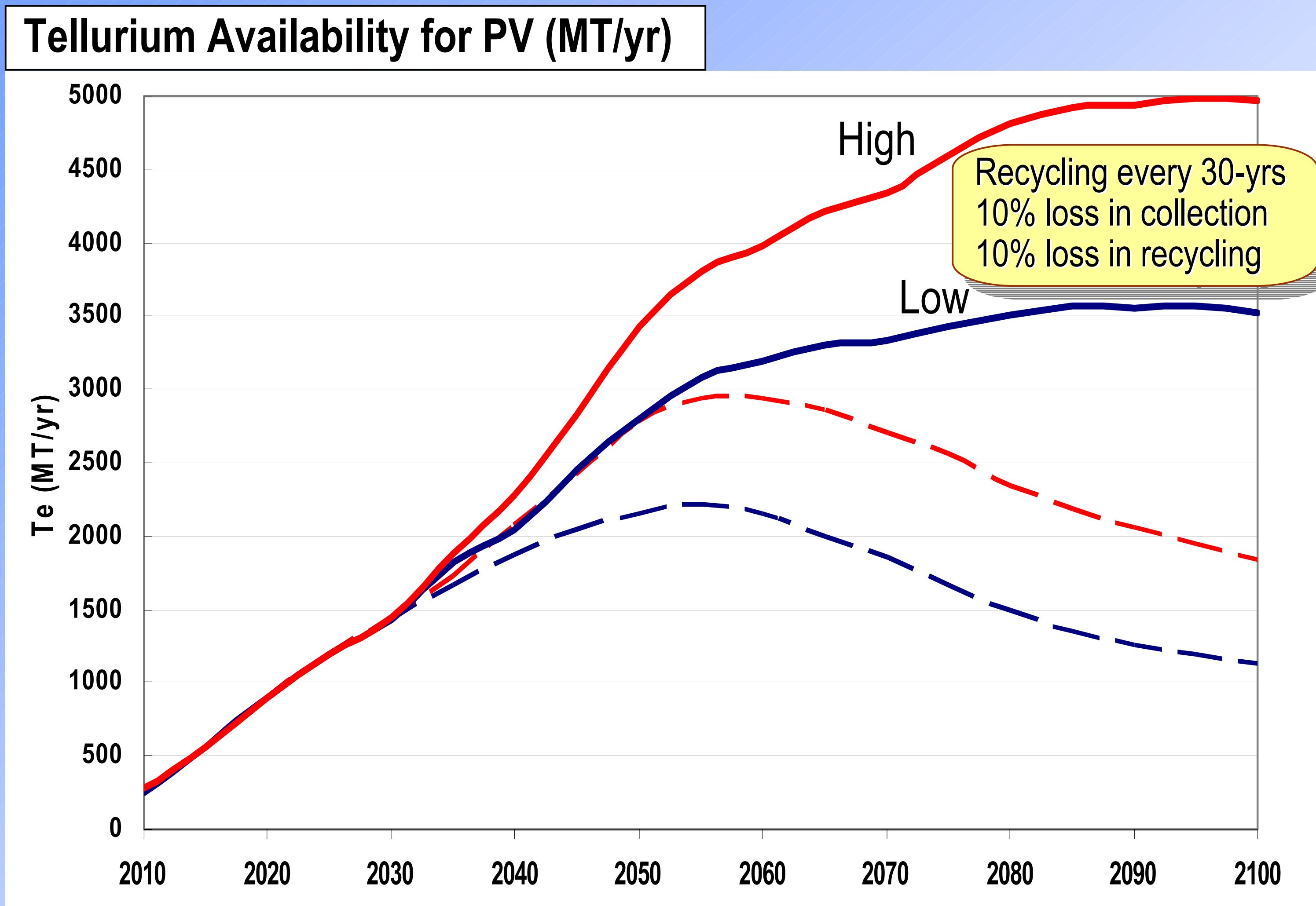


•Global Efficiency of Extracting Te from anode slimes increases to 80% by 2030 (low scenario); 90% by 2040 (high scenario)

* 322 MT/yr Te demand for other uses has been subtracted

Fthenakis, *Renewable & Sustainable Energy Reviews*, 2009

Te Availability for PV:
Primary + Recycled



Assumptions for Thin-Film PV Growth

PV Type	Efficiency (%)			
	2008	2020		
		Conservative	Most likely	Optimistic
CdTe	**10.8**	**12.3**	**13.2**	**14**
CIGS	**11.2**	**14**	**15.9**	**16.3**
a-Si-Ge	**6.7**	**9**	**9.7**	**10**

Fthenakis, *Renewable & Sustainable Energy Reviews*, 2009
Update 2010

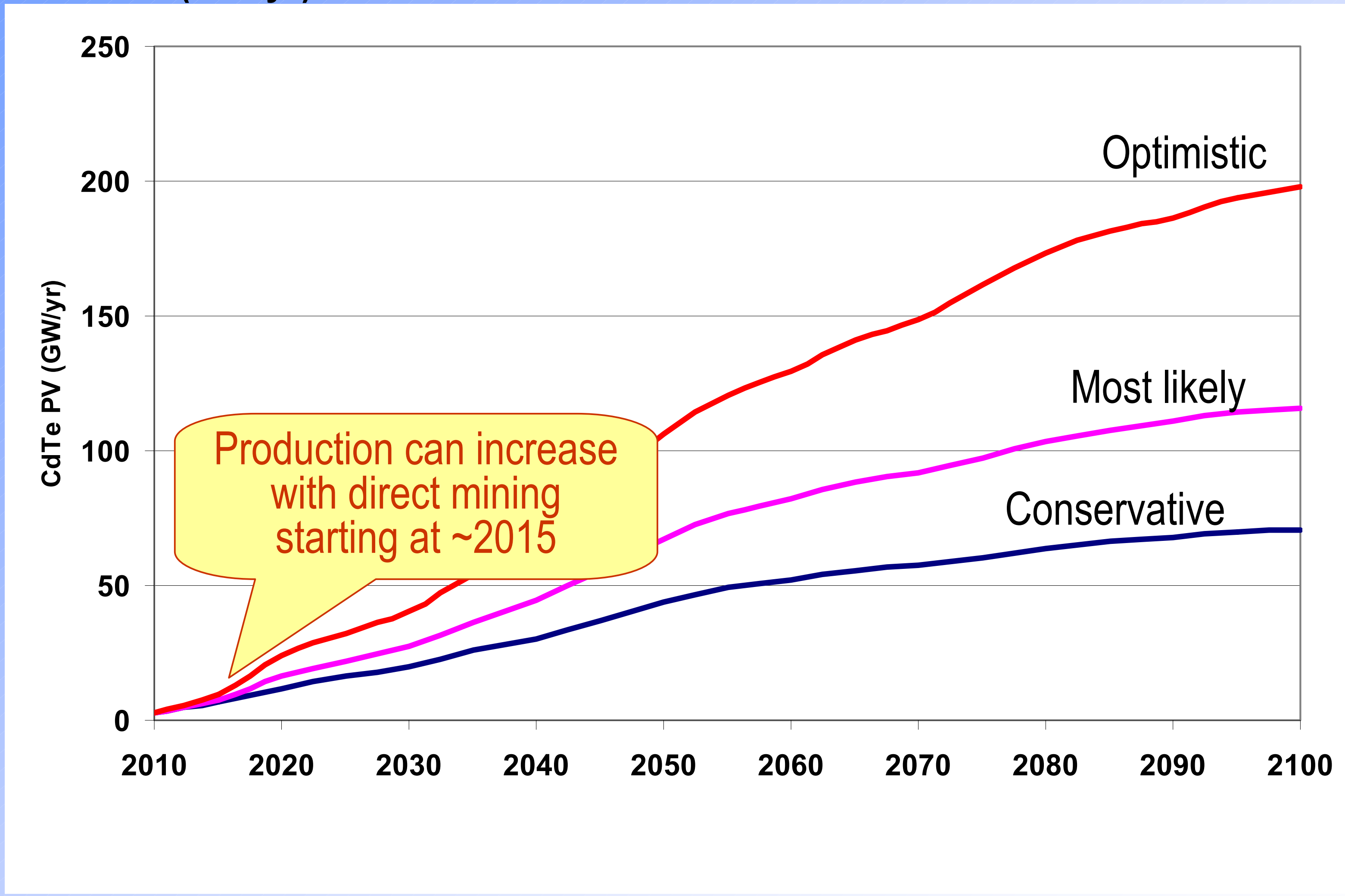
Assumptions for Thin-Film PV Growth

PV Type	Efficiency (%)				Layer Thickness (μm)			
	2008	2020			2008	2020		
		Conservative	Most likely	Optimistic		Conservative	Most likely	Optimistic
CdTe	10.8	12.3	13.2	14	3.3	2.5	1.5	1.
CIGS	11.2	14	15.9	16.3	1.6	1.2	1.	0.8
a-Si-Ge	6.7	9	9.7	10	1.2	1.2	1.1	1.

Fthenakis, *Renewable & Sustainable Energy Reviews*, 2009

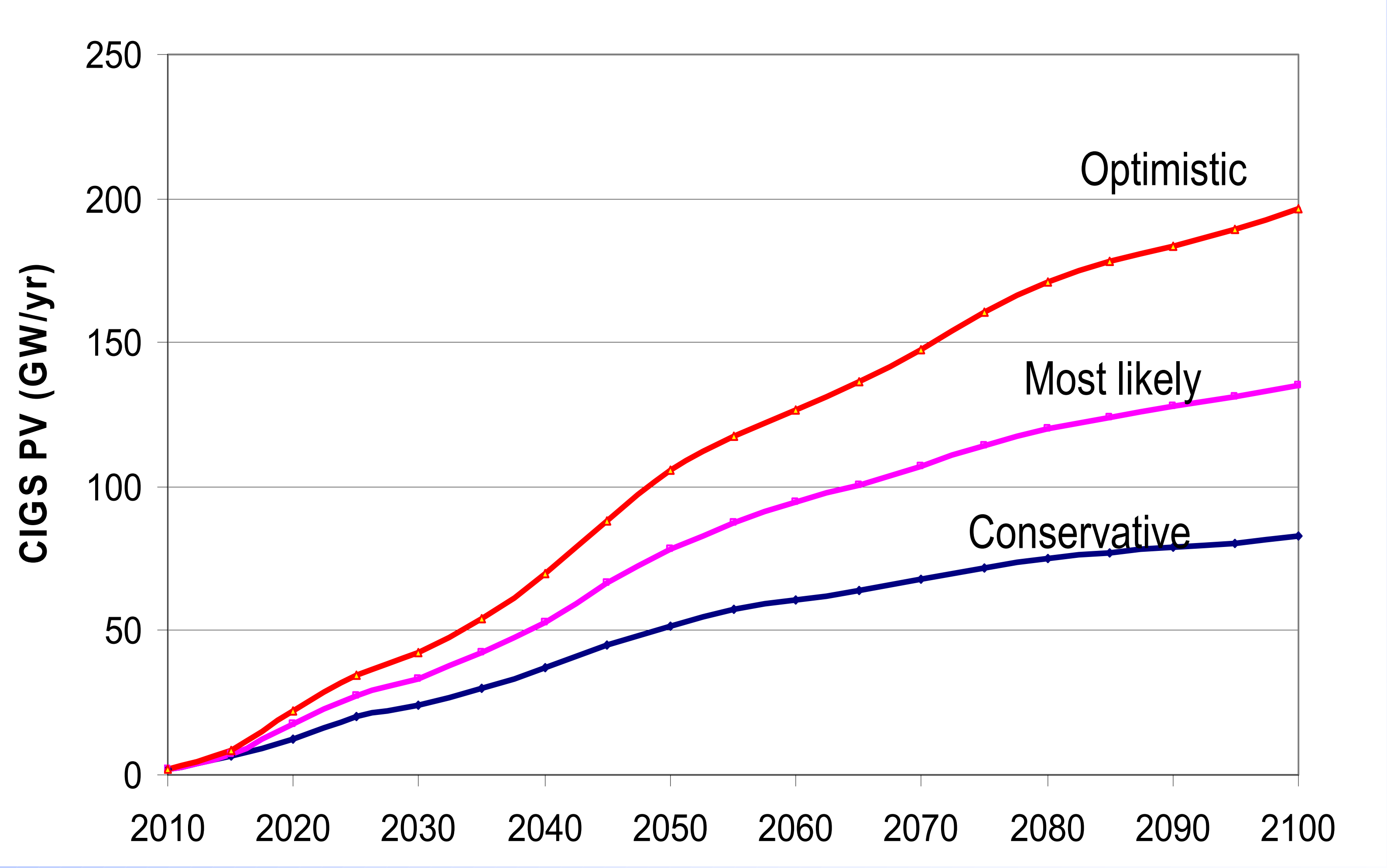
CdTe PV Annual Production Constraints

CdTe PV (GW/yr)



CIGS Material-based Growth Constraints*

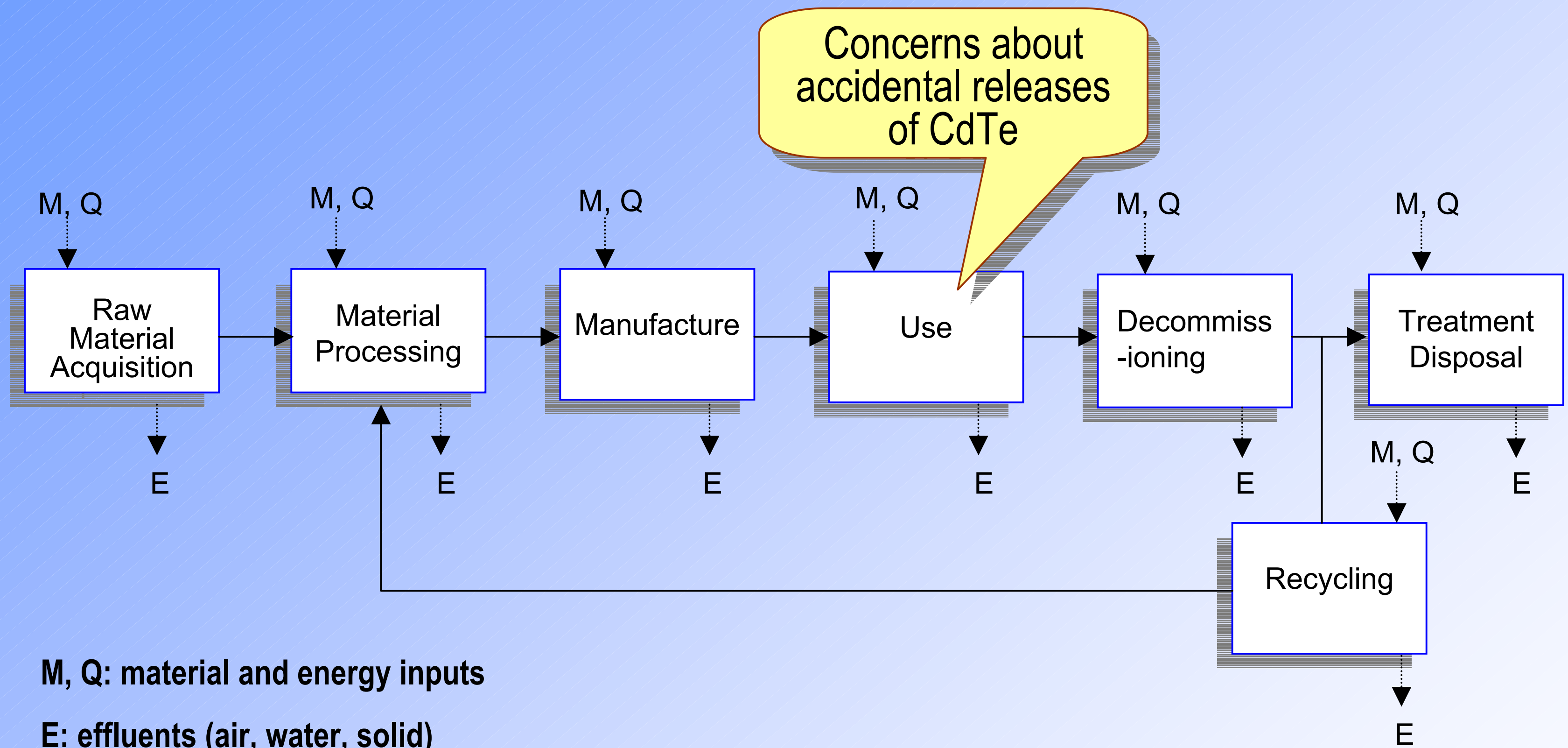
CIGS PV (GW/yr)



Fthenakis, *IEEE PVSC*, June 23, 2010

* 1/2 of In production growth is allocated to PV

Life Cycle Environmental Impacts



M, Q: material and energy inputs

E: effluents (air, water, solid)

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*:*

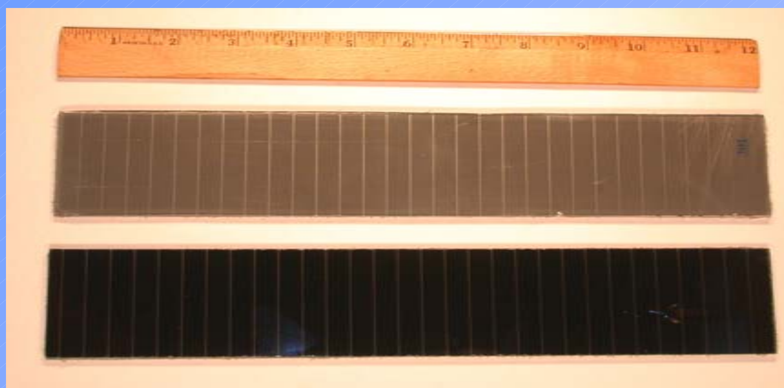
BNL, US-DOE, 2004

EC-JRC, 2004

German Ministry of the Environment, (BMU), 2005

French Ministry of Ecology, Energy, 2009

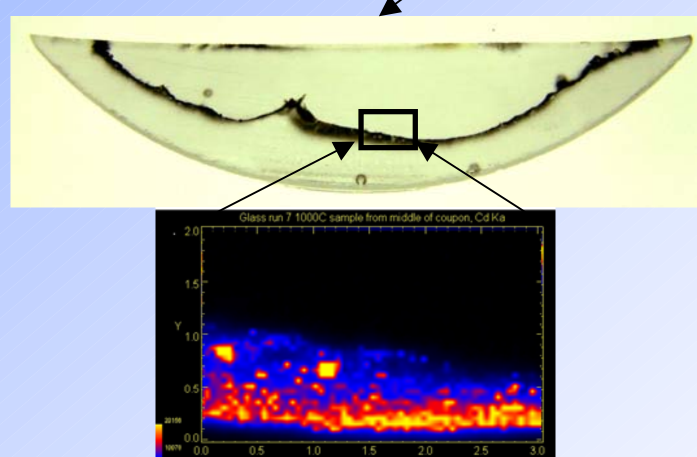
CdTe PV Fire-Simulation Tests: XRF Analysis

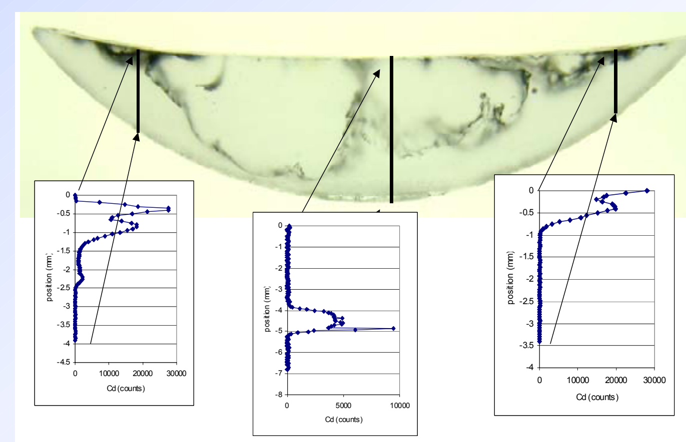


Heat

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*

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)

Uncontrolled dumping of CdTe-modules will result in greater environmental risks compared with disposal in approved landfill sites

CdTe PV Product Life –Accidental Releases

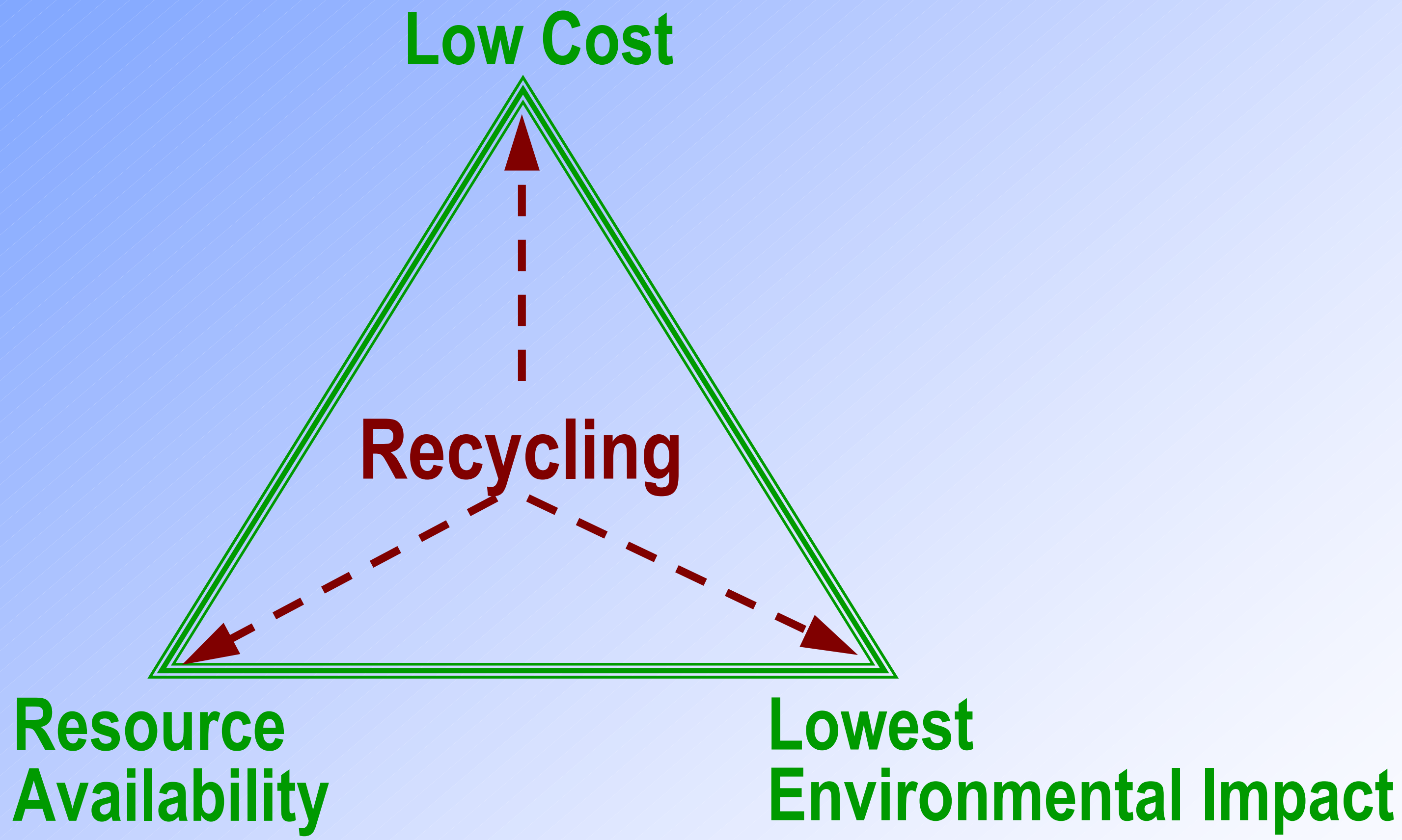
- **Leaching from shuttered modules**
  - *10 mm fragments -Rain-worst-case scenario- " leached Cd concentration in the collected water is no higher than the German drinking water concentration."*
    (Steinberger, Frauhoffer Institute Solid State Technology, Progress in Photovoltaics, 1998)
  - *< 4 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

The Triangle of Success



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

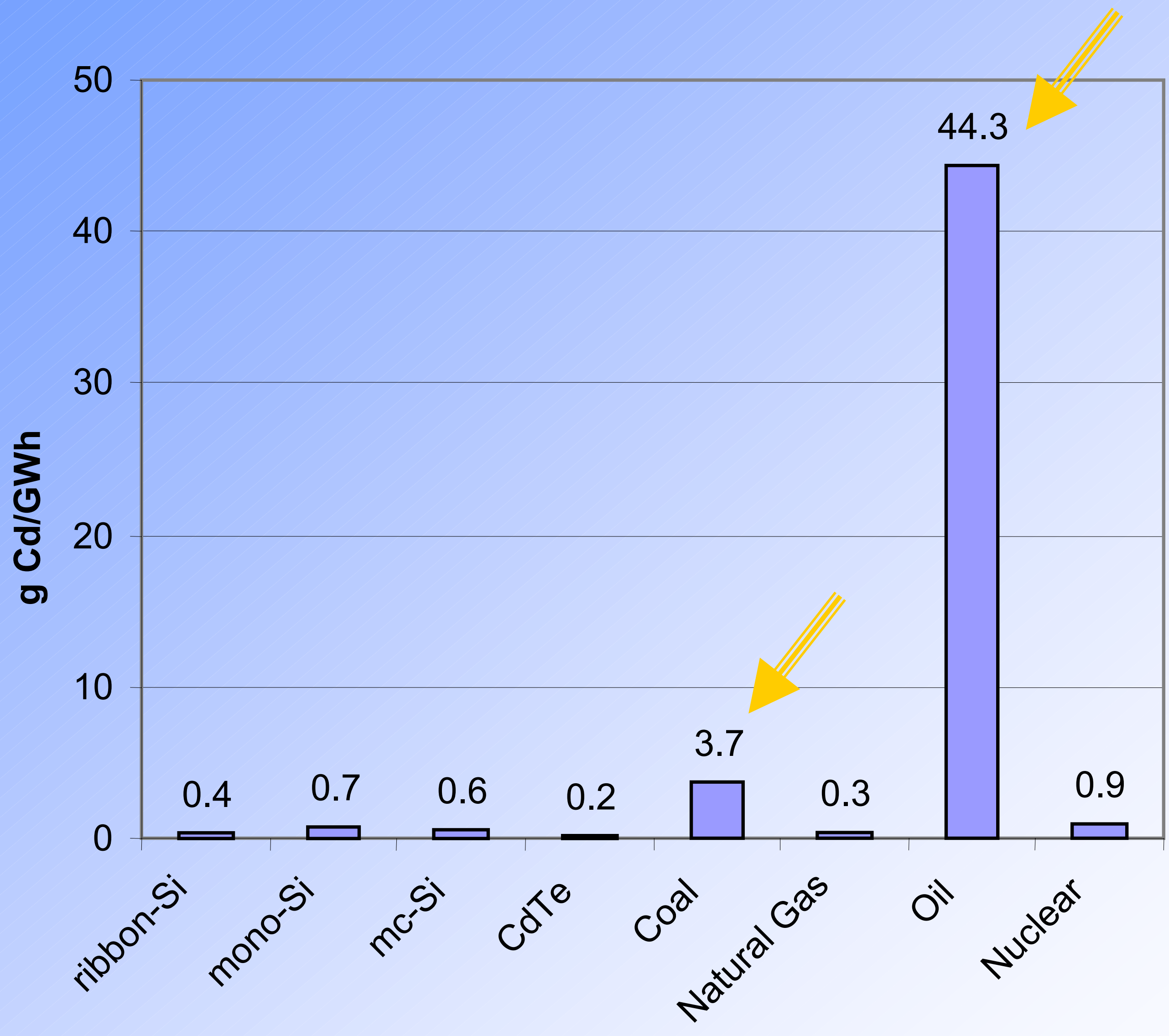
Process	(g Cd/ton Cd*)	(%)	(mg Cd/GWh)
1. Mining of Zn ores	2.7	0.58	0.02
2. Zn Smelting/Refining	40	0.58	0.30
3. Cd purification	6	100	7.79
4. CdTe Production	6	100	7.79
5. CdTe PV Manufacturing	0.4*	100	0.52*
6. CdTe PV Operation	0.05	100	0.06
7. CdTe PV Recycling	0.1*	100	0.13*
TOTAL EMISSIONS			16.55

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

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

* 2009 updates

Total Life-Cycle Cd Atmospheric Emissions



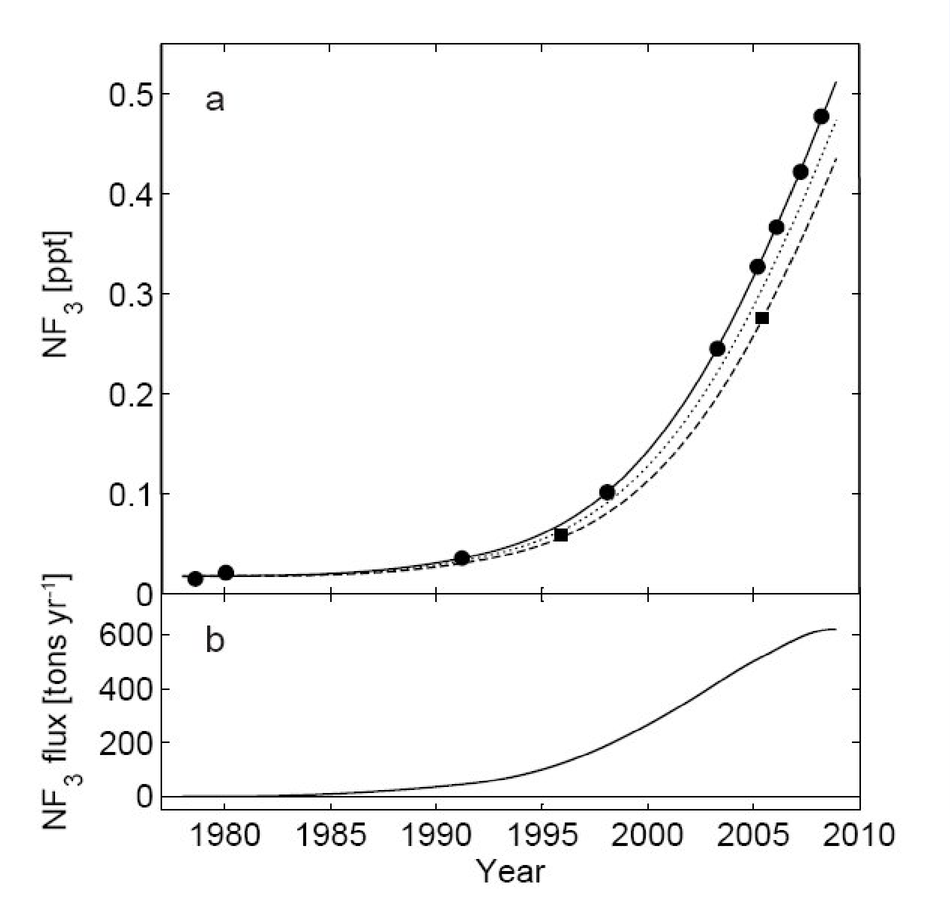
Fthenakis and Kim, *Thin-Solid Films*, 515(15), 5961, 2007
Fthenakis, Kim & Alsema, Environ. Sci. Technol, 42, 2168, 2008

GHGs Used in PV Module Manufacturing

Substance	Source
CF4	c-Si surface etching
C2F6	c-Si reactor cleaning
SF6	a-Si/nc-Si reactor cleaning
NF3	a-Si/nc-Si reactor cleaning

PV: climate killer? The NF3 story

Photon Magazine, December 2008



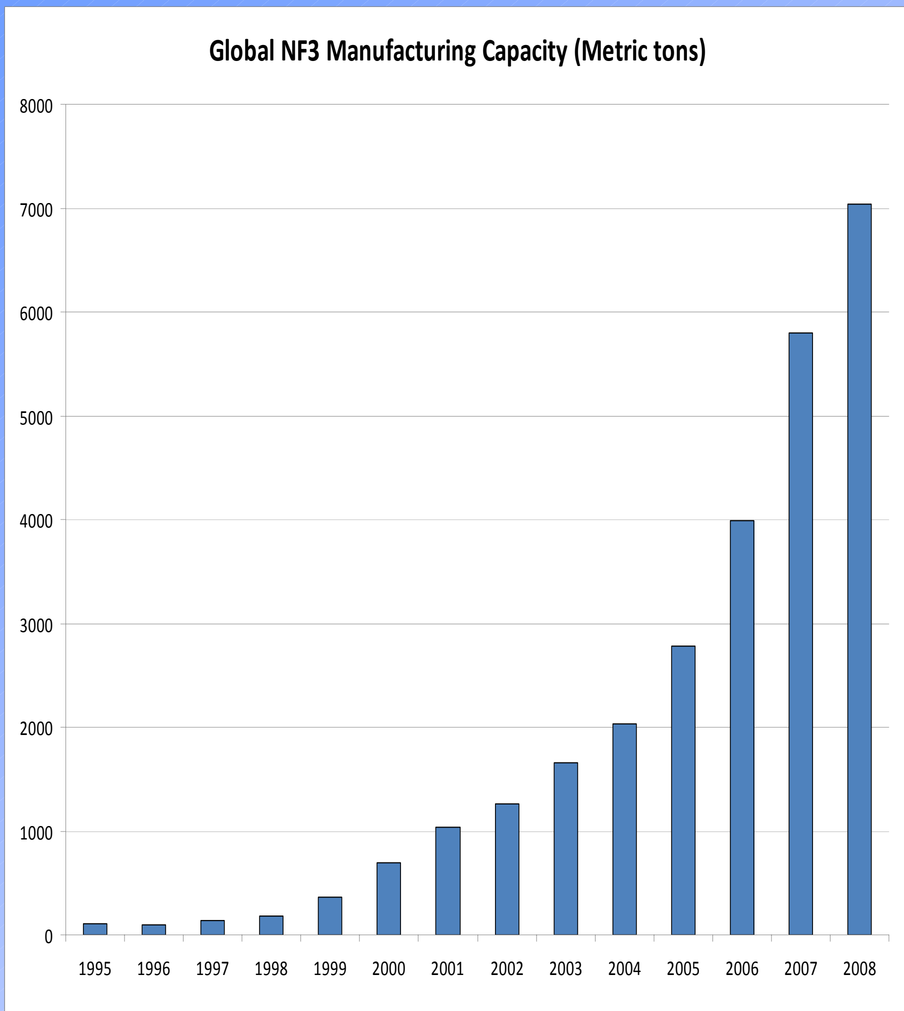
Weiss et al (2008), **Nitrogen trifluoride in the global atmosphere**, *Geophysical Research Letters*, 2008

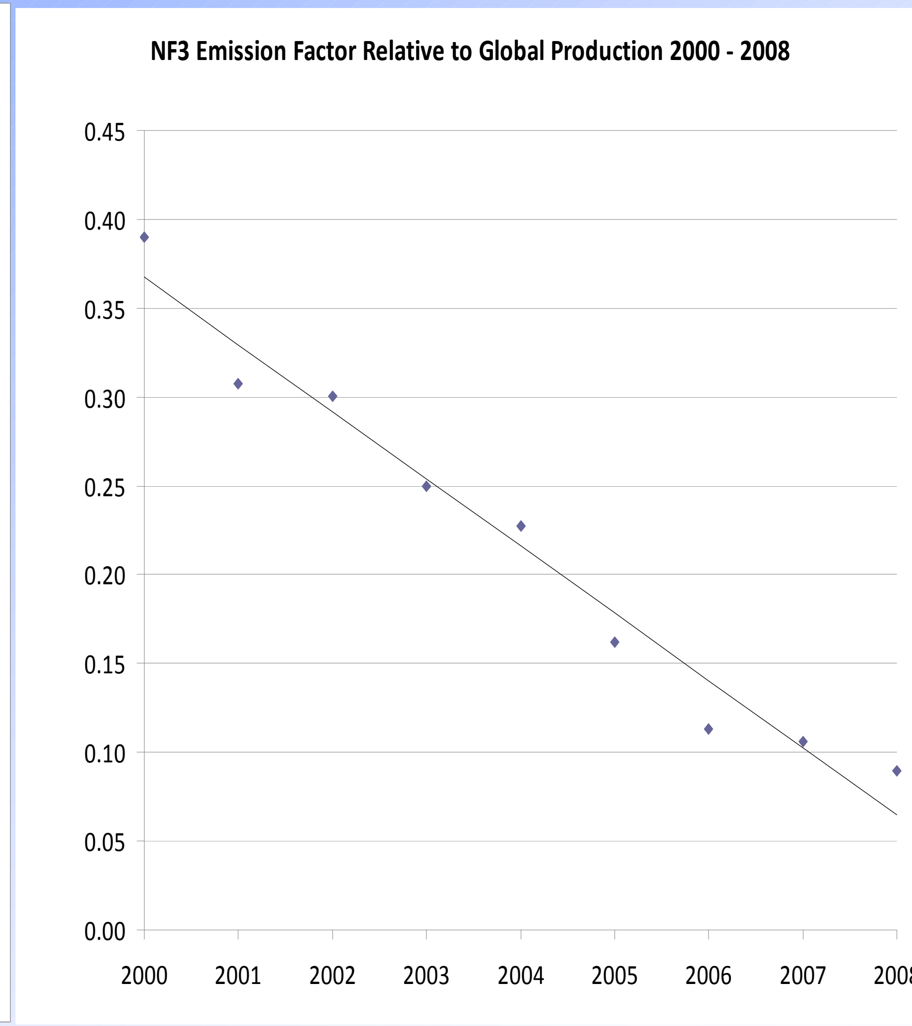
NF_3 Emissions in a-Si/nc-Si PV Life-Cycles

- Analysis based on detailed data from
  - Air Products –**NF_3 Production**
  - Applied Materials –**NF_3 Use in PV**

- Qualitative information from
  - Kanto Denka - **NF_3 Production**
  - Oerlikon –**NF_3 Use in PV**

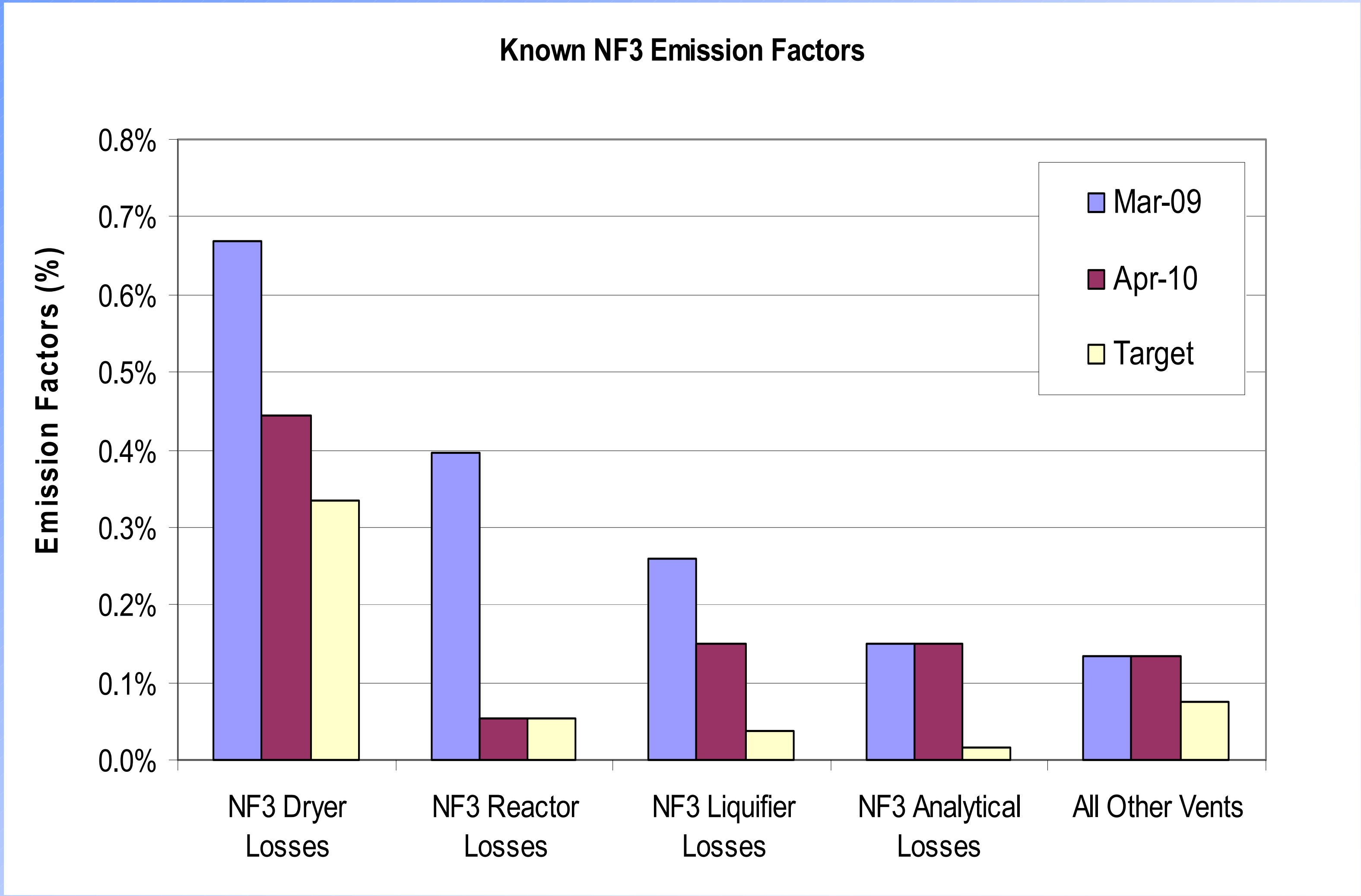
Trends in NF_3 Production and Emission Factors





Source: R. Ridgeway, Air Products

Emission Trends in NF3 Manufacturing



Source: R. Ridgeway, Air Products

NF3 Emission Measurements in Typical a-Si and tandem Si PV Fabs

Factory	Source	avg NF3 Conc (ppm)	DRE (%)	Emission Factor (%)
A	Applied Materials	1.0	99.98	0.02
B	Applied Materials	8.5	99.90	0.1
C	Applied Materials	27.5	99.75	0.25
D	Third Party	2.0	99.98	0.02
E	Third Party	8.6	99.90	0.1
F	Third Party	11.0	99.87	0.13
Average			99.89	0.11

For average U.S. insolation (1800 kWh/m^2/y) NF_3 life-cycle emissions add 2 - 7 g/kWh of $CO_{2\text{-eq}}$

BROOKHAVEN NATIONAL LABORATORY

Conclusion

- Thin-film PV can reach very high rates of growth without being impaired from material availability issues.
- Recycling spent modules will become increasingly important in resolving cost, resource, and environmental constraints to large scales of sustainable growth.
- The controlled use of NF_3 in the a-Si/nc-Si PV industry will not alter the environmental benefits of PV replacing fossil fuels if best practices are adopted globally.

Email: VMF@BNL.GOV

www.pv.bnl.gov

BROOKHAVEN NATIONAL LABORATORY

Acknowledgment

- Support from US-DOE, Solar Technologies Program
- Jeff Britt - Global Solar
- Jun Ki Choi, Huyng Chul Kim – BNL
- Daniel Clark, Mehran Moalem –Applied Materials
- Al Compaan –U. Toledo
- Xunming Deng –Xunlight
- Subhendu Guha - Uni-Solar
- D.R. Nagaraj - Cytec
- Funsho Ojebuoboh, Alex Heard, Dave Eaglesham, Tim Mays, Lisa Krueger -First Solar
- Robert Ridgeway –Air Products
- Jim Sites –Colorado State U.
- Bill Stanbery -HelioVolt
- Marc Suys, 5NPlus
- Bolko von Roedern –NREL
- Ken Zweibel –George Washington U.

email: VMF@BNL.GOV
web: www.pv.bnl.gov

BROOKHAVEN NATIONAL LABORATORY