# Long-term Estimates of Primary & Secondary Sources of Thin-film PV Materials -Recycling and Sustainability of PV-

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# 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

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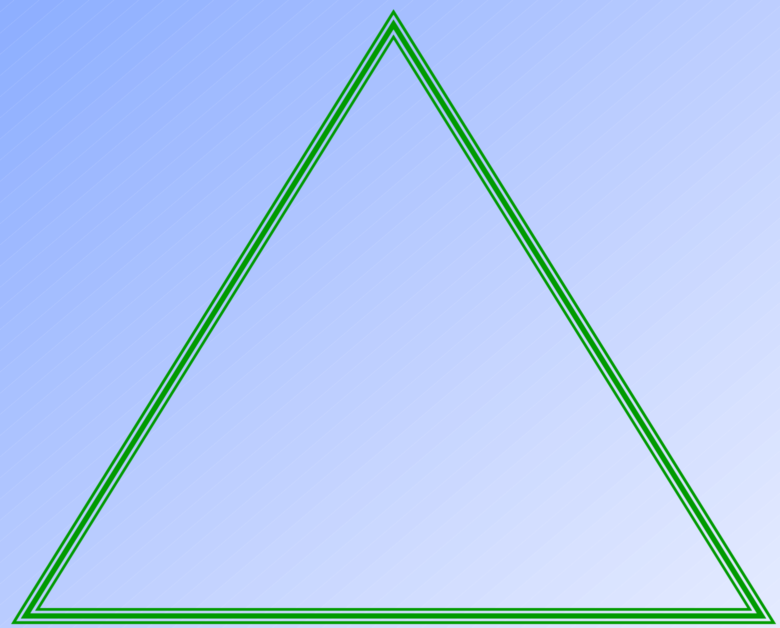
# The Triangle of Success

Affordability in a competitive world

**Low Cost**



**Resource Availability**

**Lowest Environmental Impact**

- In in CIGS
- Te in CdTe
- Ge in a-SiGe

***Material Constraints in Thin-Film PV***

# Presentation Outline

- Te, In & Ge needs in PV
- Te & In availability
  - Primary production
  - Recycling
- Projected PV Production Constraints due to material unavailability (2010-2100)
- Recycling technologies & cost

# Te, In & Ge  Needs in thin-film PV

| | | |
|---|---|---|
| | | 2008 |
| PV | Metal | Required (MT/GW) |
| CdTe | Te | **176** |
| CIGS | In | 83 |
| a-SiGe | Ge | 73 |

Fthenakis, *Renewable & Sustainable Energy Reviews*, 2009

# Te, In & Ge Needs in thin-film PV

| | | Current 2010 |
|---|---|---|
| PV | Metal | Required (MT/GW) |
| CdTe | Te | **106** |
| CIGS | In | 83 |
| a-SiGe | Ge | 73 |

| **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 |

# Te, In & Ge Supply & Needs in thin-film PV

| | | Current 2010 | **Expected 2020** |
|---|---|---|---|
| PV | Metal | Required (MT/GW) | **Required (MT/GW)** |
| CdTe | Te | 106 | **38-74** |
| CIGS | In | 83 | **11-20** |
| a-SiGe | Ge | 73 | **36-48** |

# 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 | 13 | 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

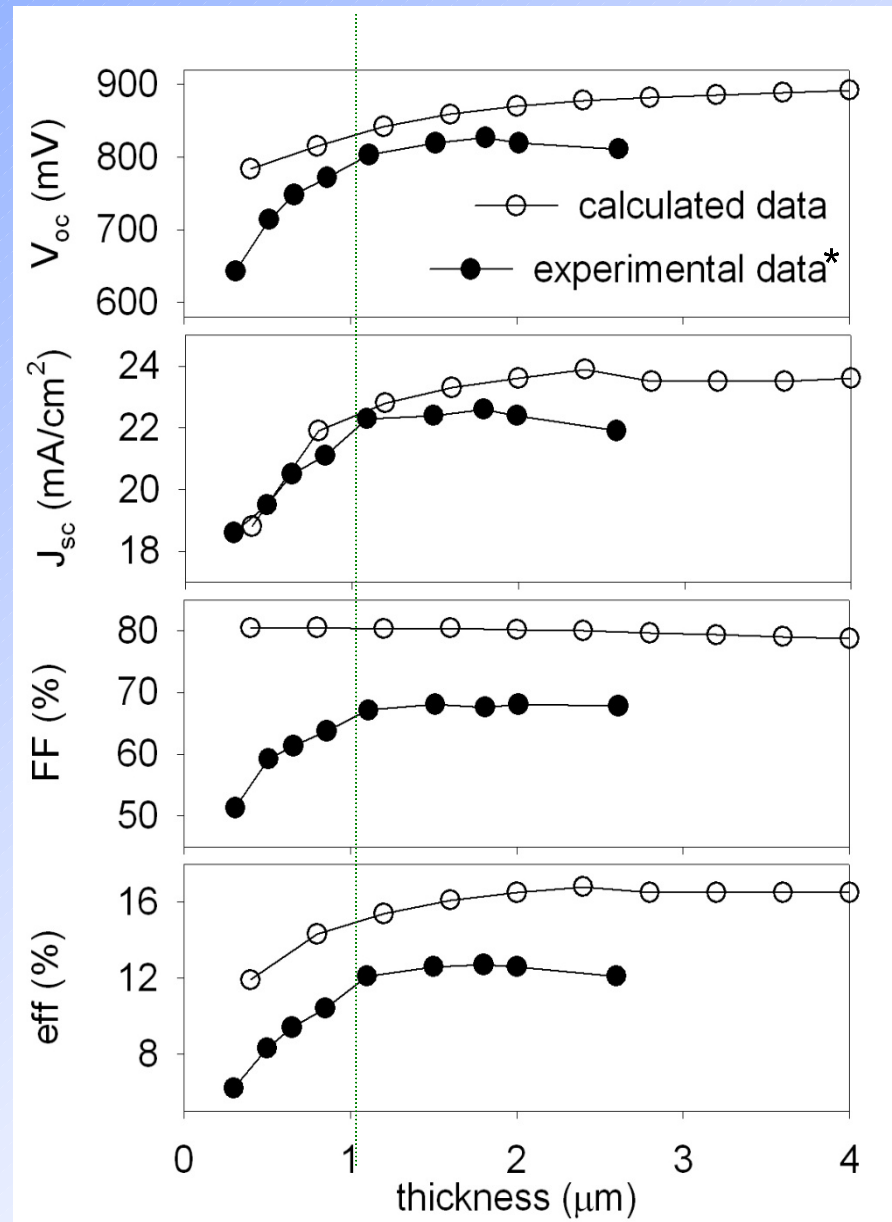
# Thin CdTe Cells can become Thinner

**Calculation:** Ray Hsiao, PhD thesis, Colorado State, 2010
**Experiment**: V.V. Plotnikov, et al, 35th PVSC, 2009.

Calculation uses 16% thick-CdTe baseline and assumes constant CdTe lifetime. Primary limitations to thin CdTe cells in the calculation:

1. Back-surface recombination
2. Incomplete absorption

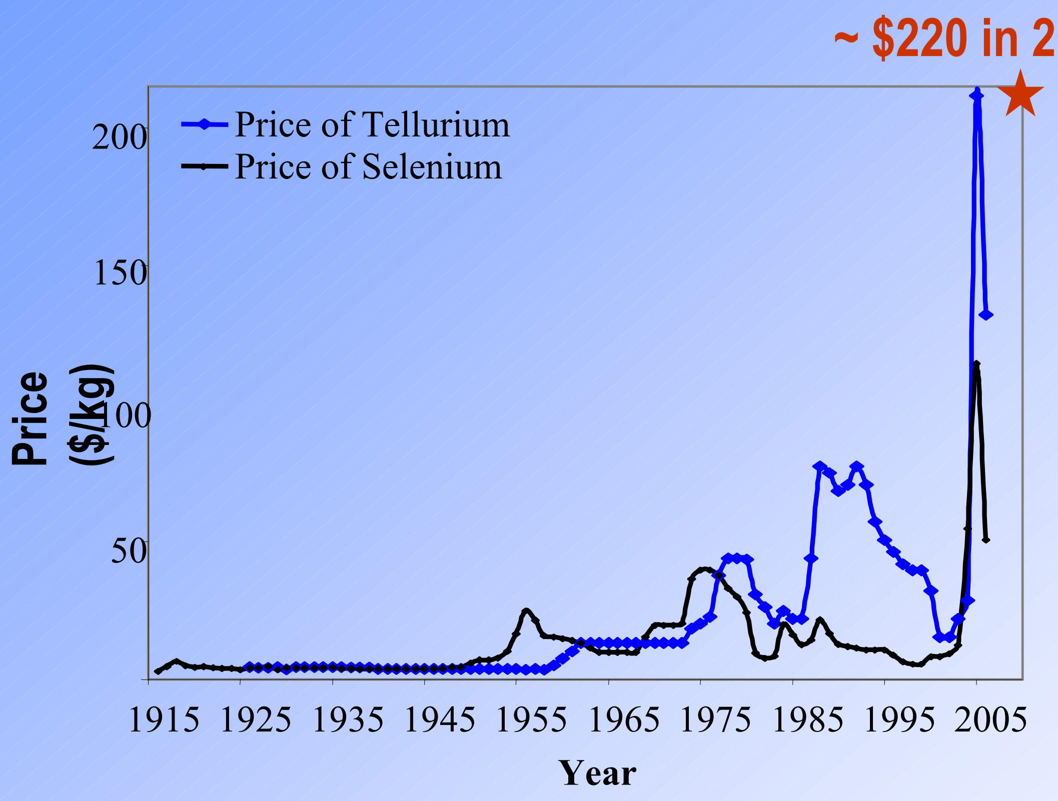
Note that fill-factor should increase slightly when thinner since there is less material for recombination. Seems to be the case experimentally down to one micron.




*Courtesy: Jim Sites, CSU*

# Tellurium Supply and Demand

**Prices of Te & Se**




*Source: USGS 2008*
*Ogebuoboh, 2007;*
*Fthenakis, update 2010*

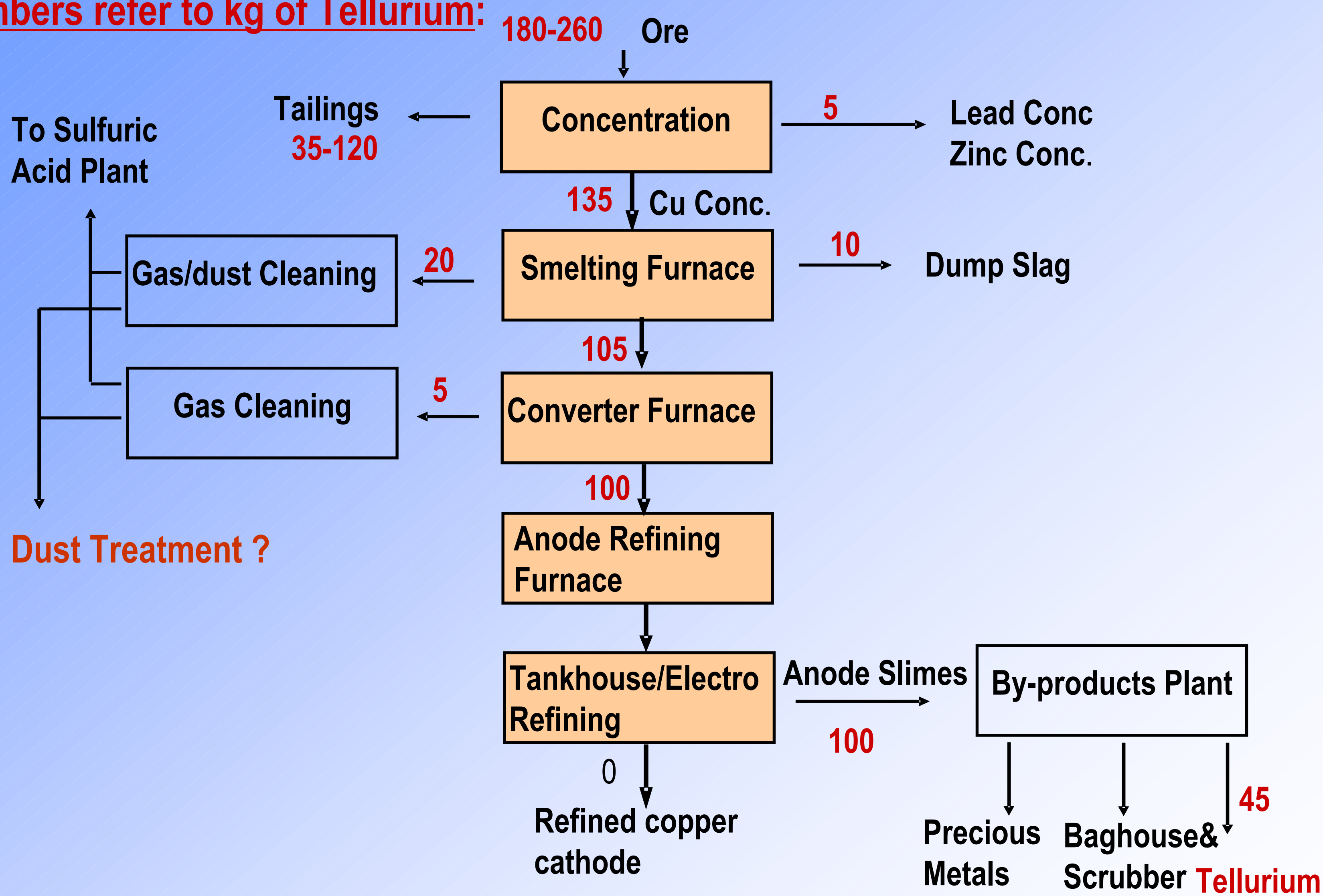
**2009 Te Consumption –550 MT**

| | Share (%) | Trend |
|---|---|---|
| Iron/Steel | 36 | ↔ |
| nonferrous | 7 | ↔ |
| PV, TE, IR | 33 | ↑ |
| Chemicals | 20 | ↔ |
| Other | 4 | ↔ |

# 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

# 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 |

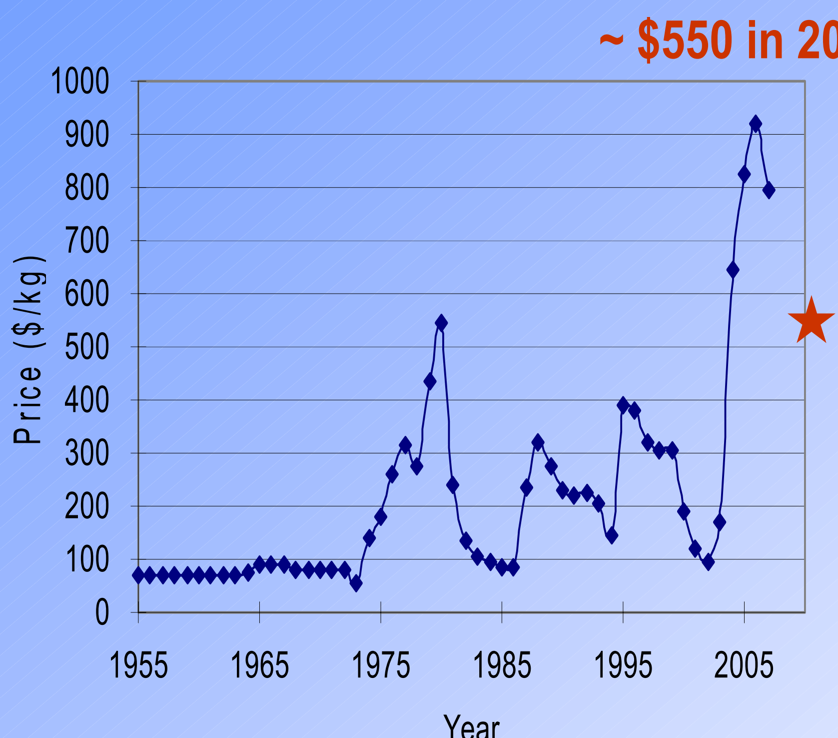
Main reason for lower Te than Se recovery rates

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

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

# Indium Supply and Demand

**Price of Indium**




**2007 Indium Consumption –580 MT**

| | Share (%) | Trend |
|---|---|---|
| Monitor | 33 | ↑ |
| TV | 24 | ↑ |
| Notebook | 15 | ↑ |
| Cell phone | 11 | ↑ |
| Other (PV) | 17 | ↑ |

*Source: USGS 2008*
*Ogebuoboh, 2007*

# Long-Term Projections

## Assumptions

- Te produced only as a by-product of Cu production from land-based sulfide ores:
  - *All the growth in Te production is assigned to PV*
- In and Ge are produced only as by-products of Zn production:
  - *Half the growth in Indium production is assigned to PV*

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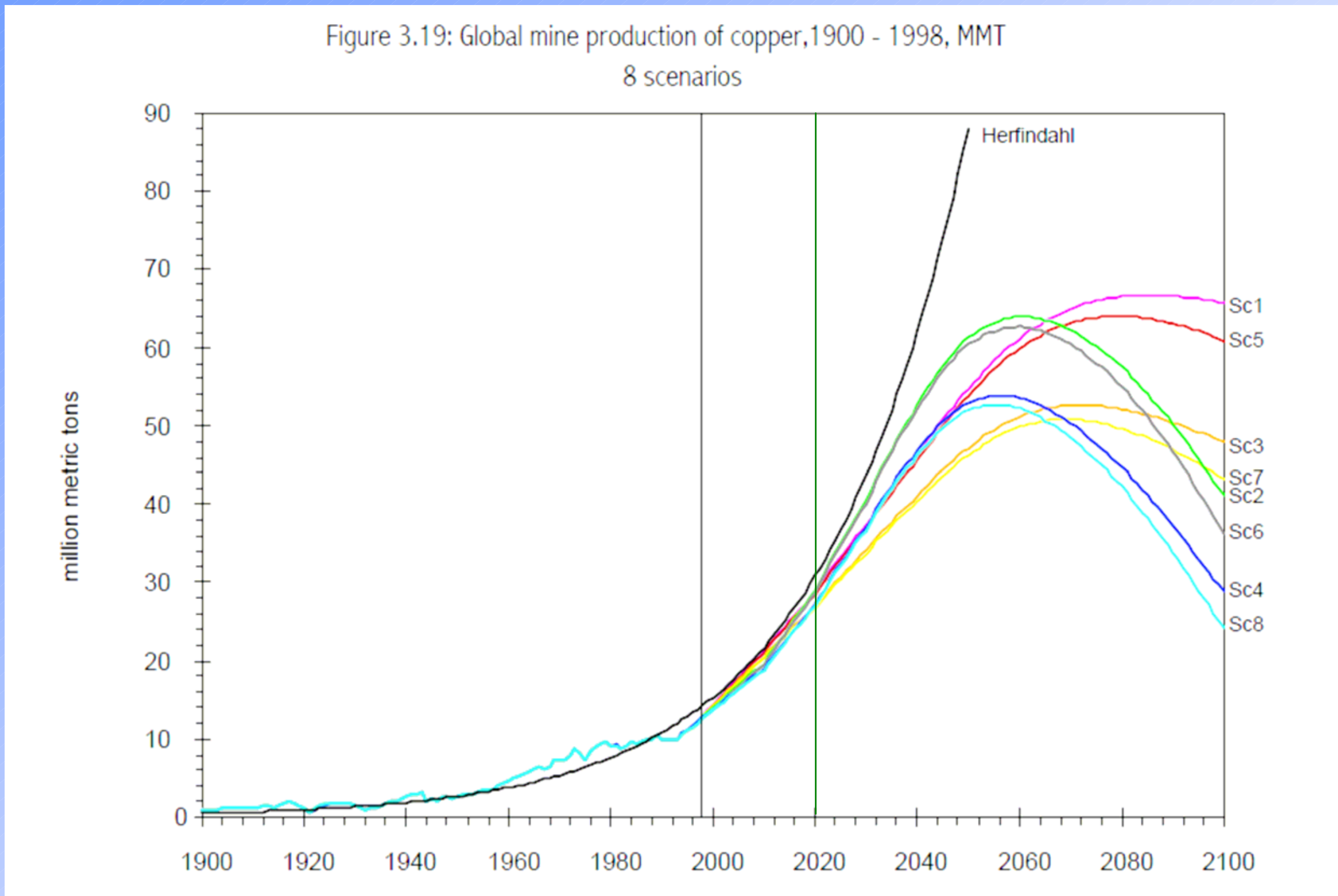
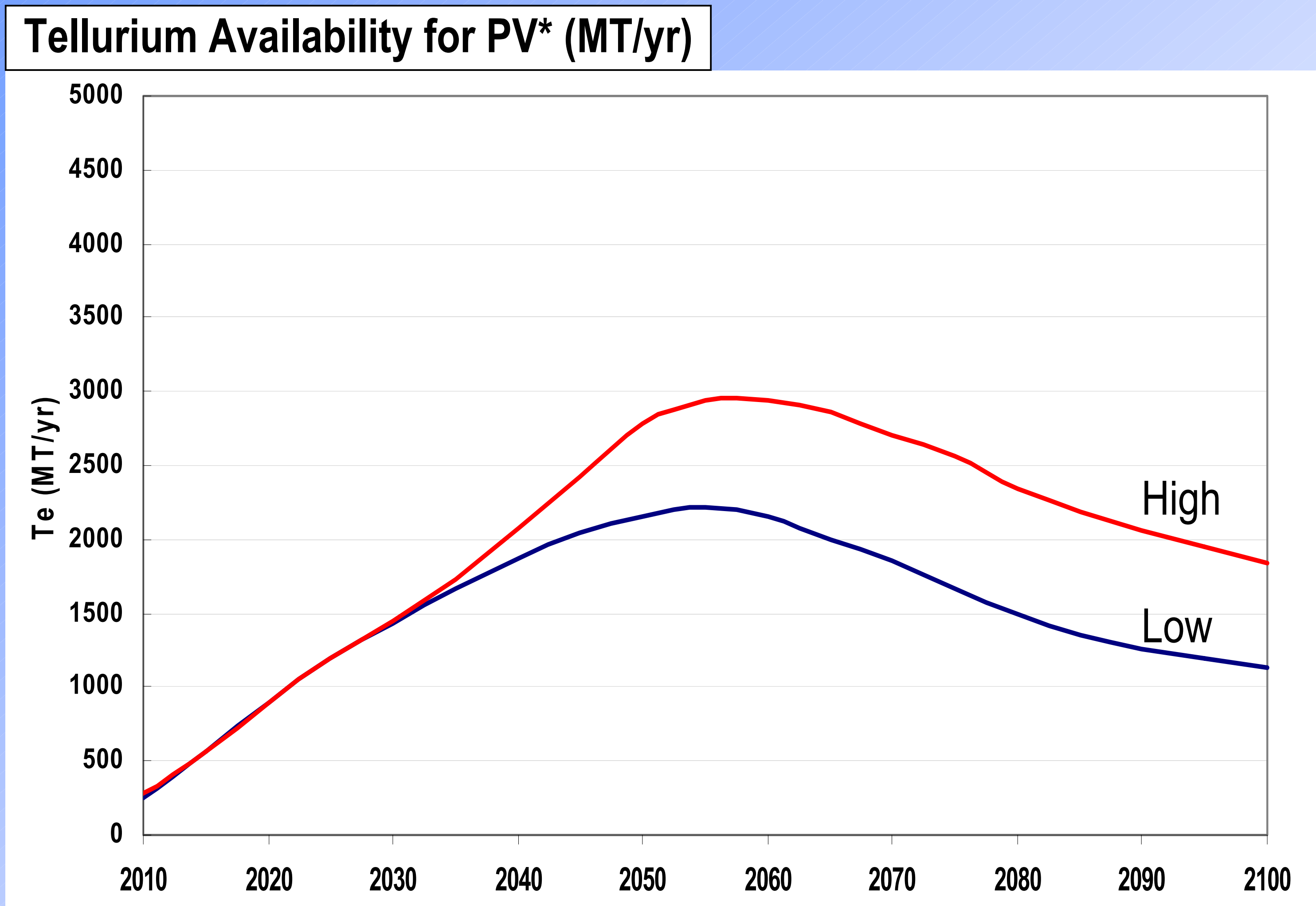
# Projection of Primary Cu Production
## (based on forecasted consumption*)




Ayres et al., 2002

* *economic and population growth assuming there are no (environmental) constraints in mining*

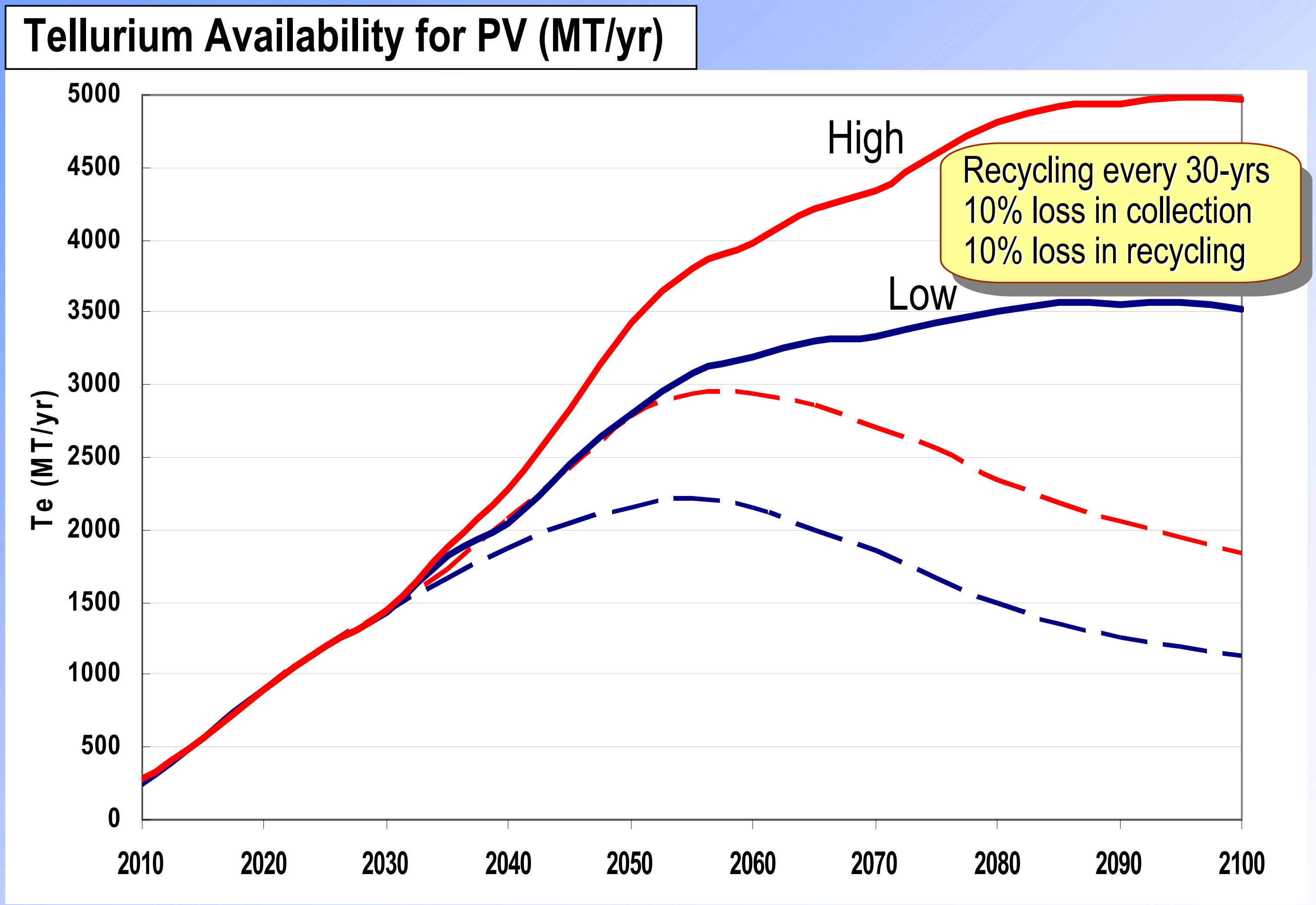
# Tellurium for PV* from Copper Smelters




•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



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Fthenakis, *Renewable & Sustainable Energy Reviews*, 2009

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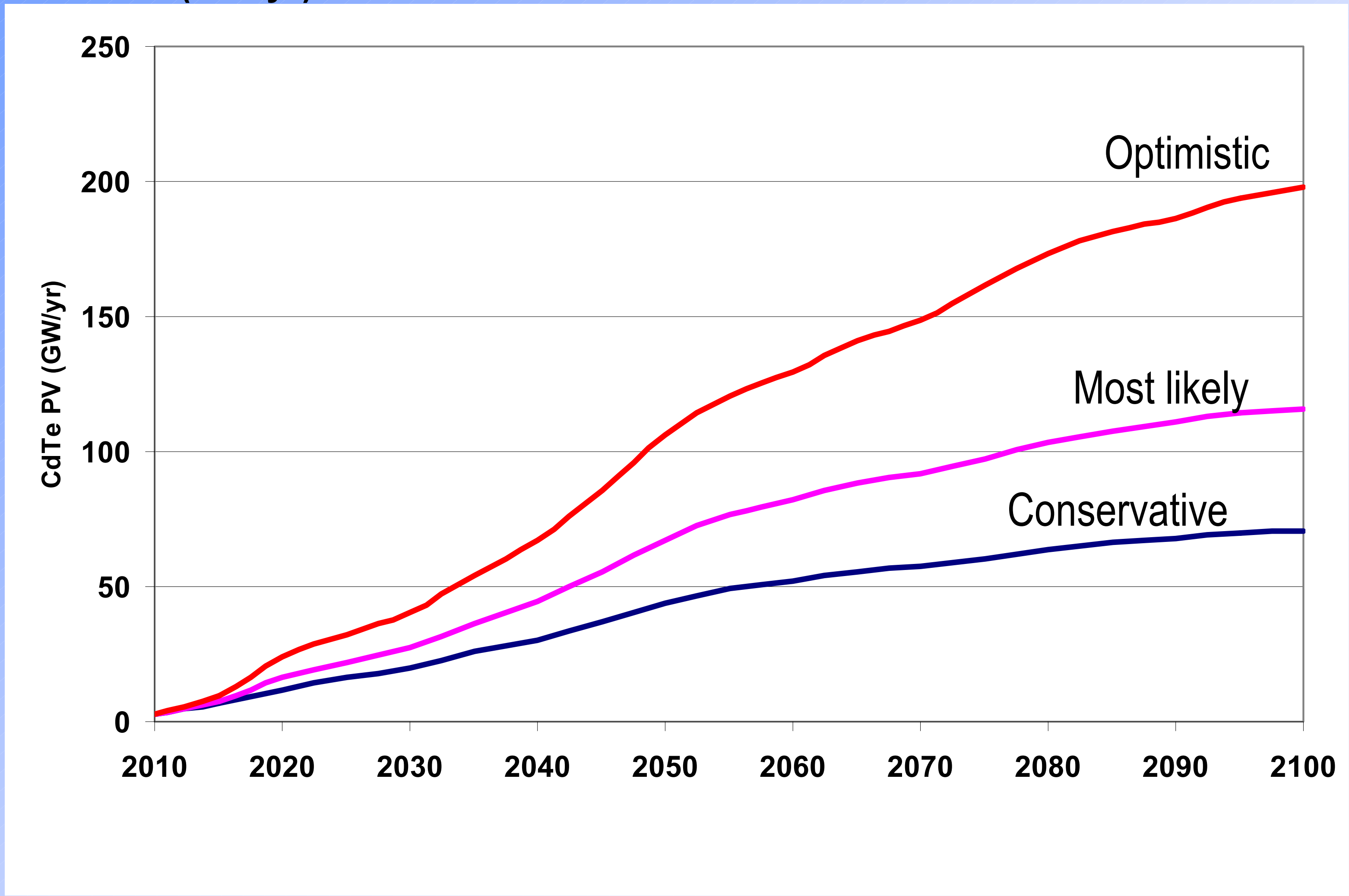
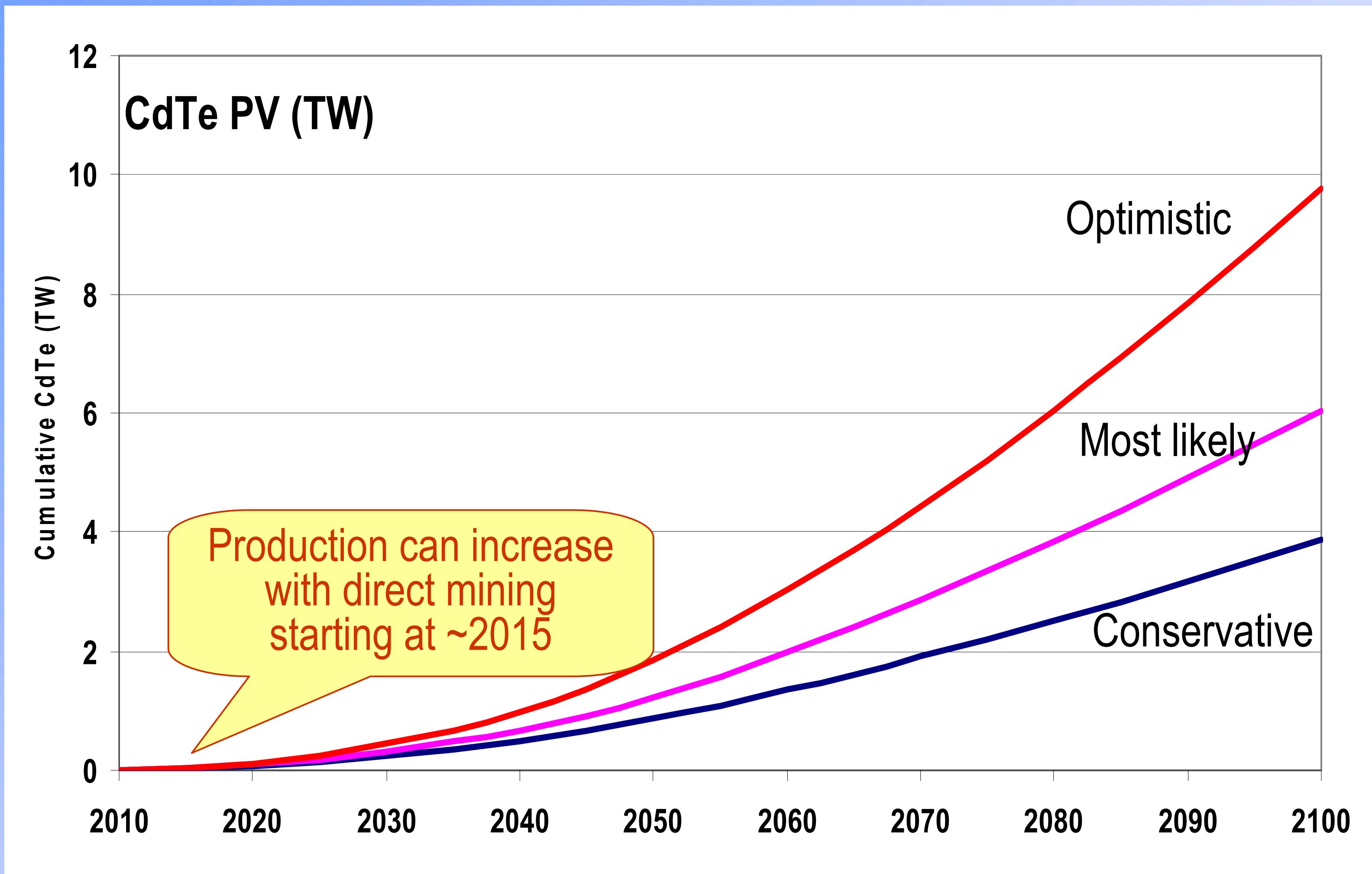
# CdTe PV Annual Production Constraints

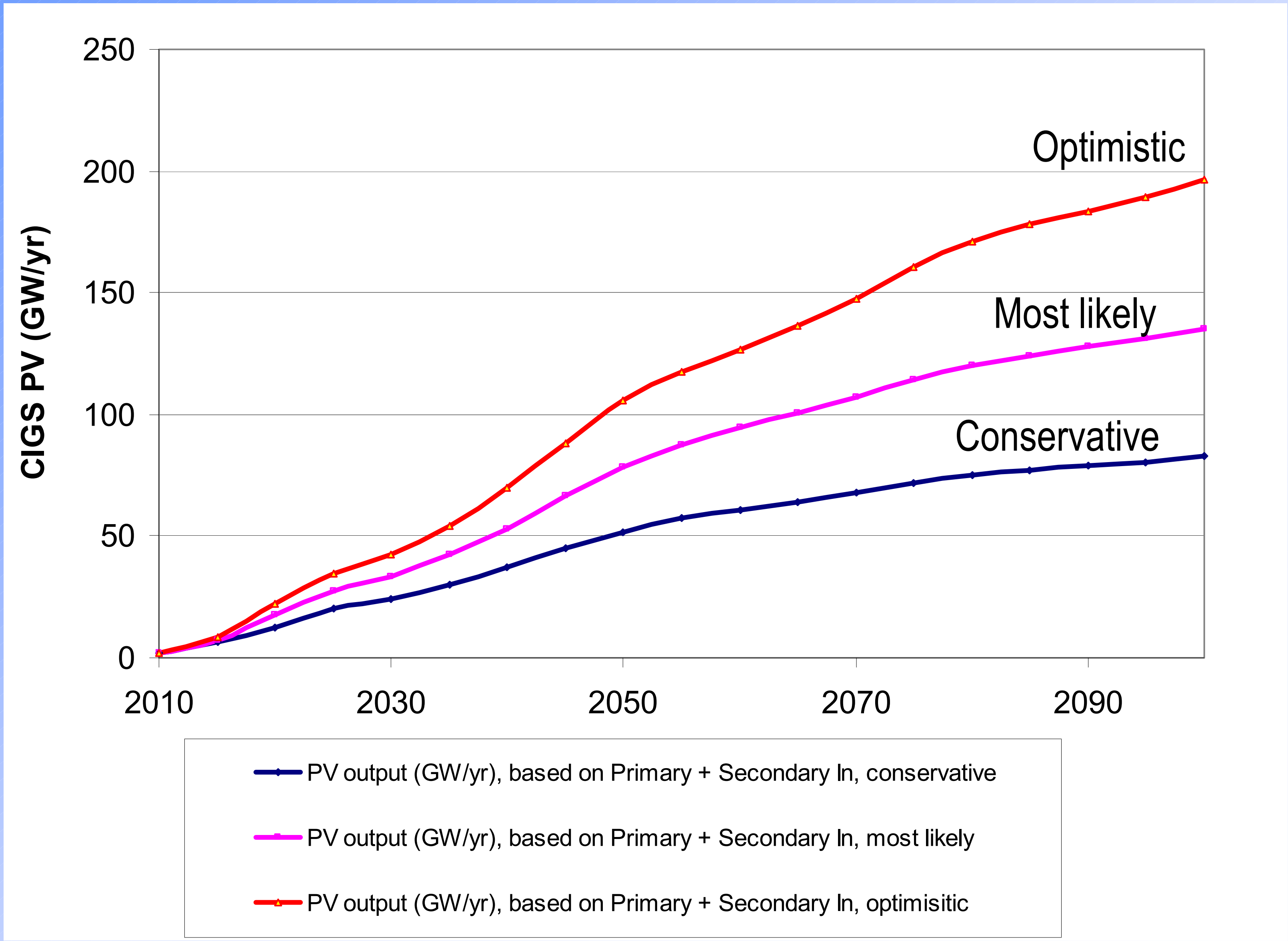
CdTe PV (GW/yr)



# Cumulative PV Production Constraints

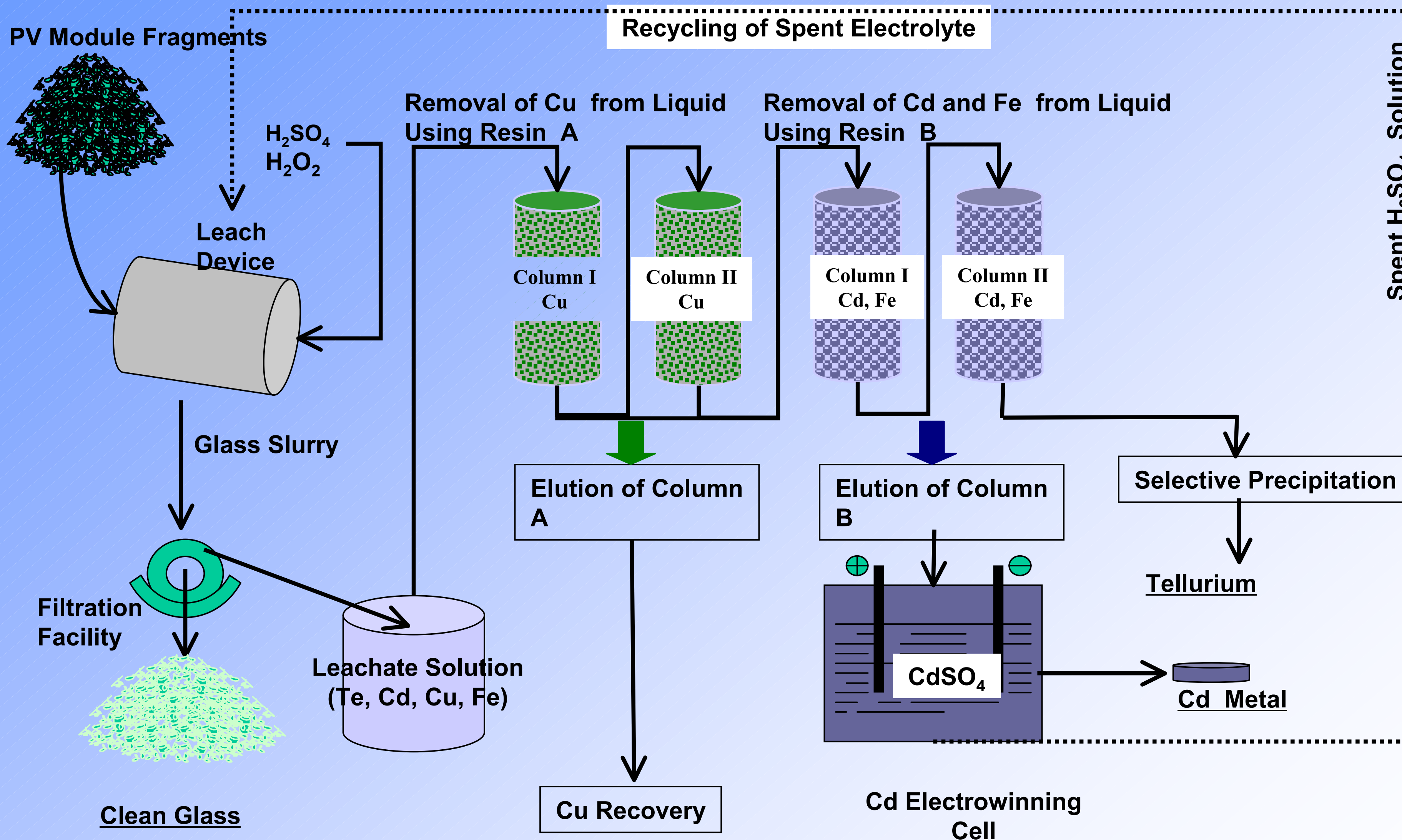


# CIGS Material-based Growth Constraints*




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

# Recycling R&D at BNL: CdTe and CIGS PV Modules



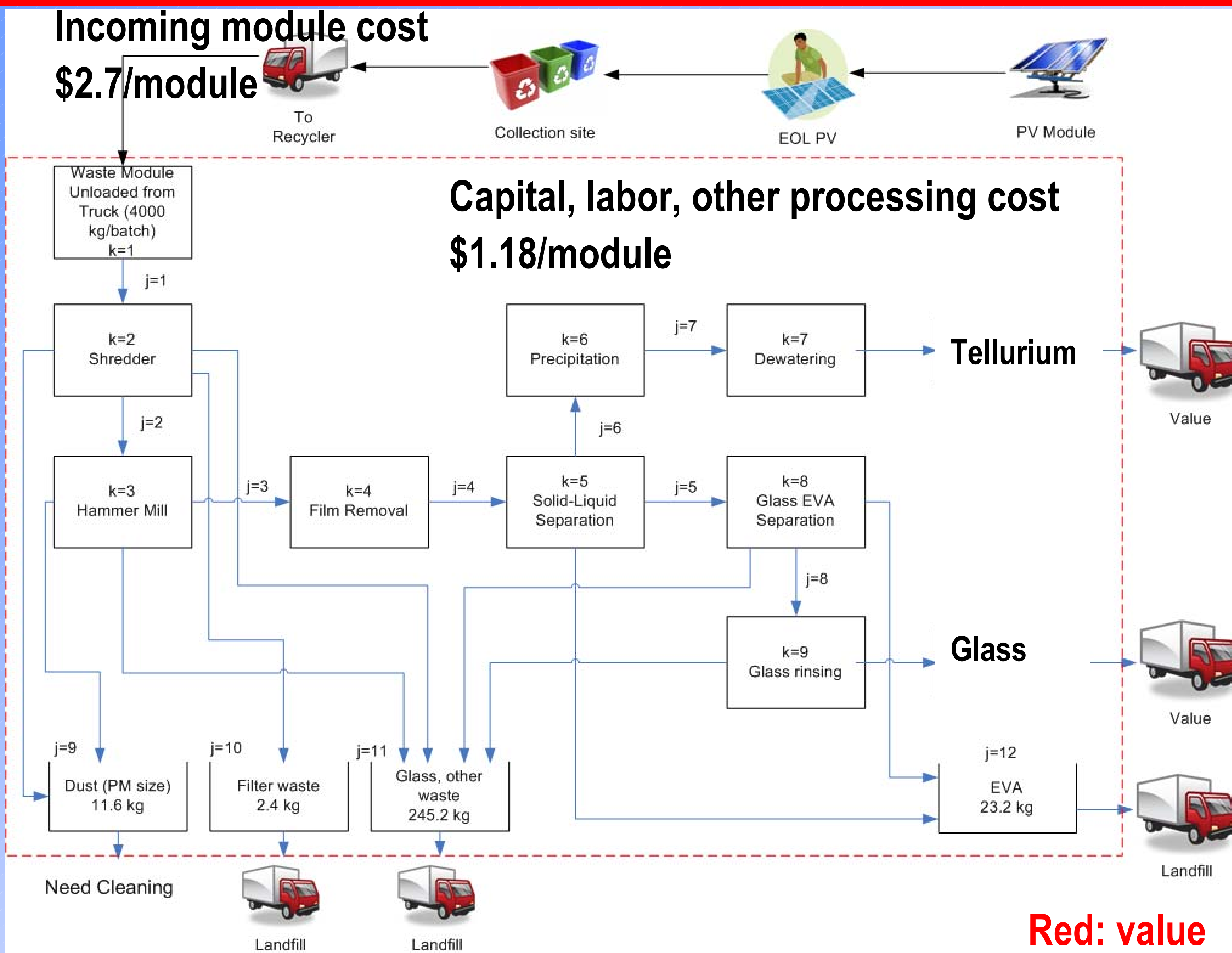


Fthenakis & Wang, Separating Te from Cd Waste, Patent No 7,731,920

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

# CdTe PV Recycling Cost Model




36 ¢ module

$0 if transported 1000 km

0.4 ¢ module

0.02 ¢ module

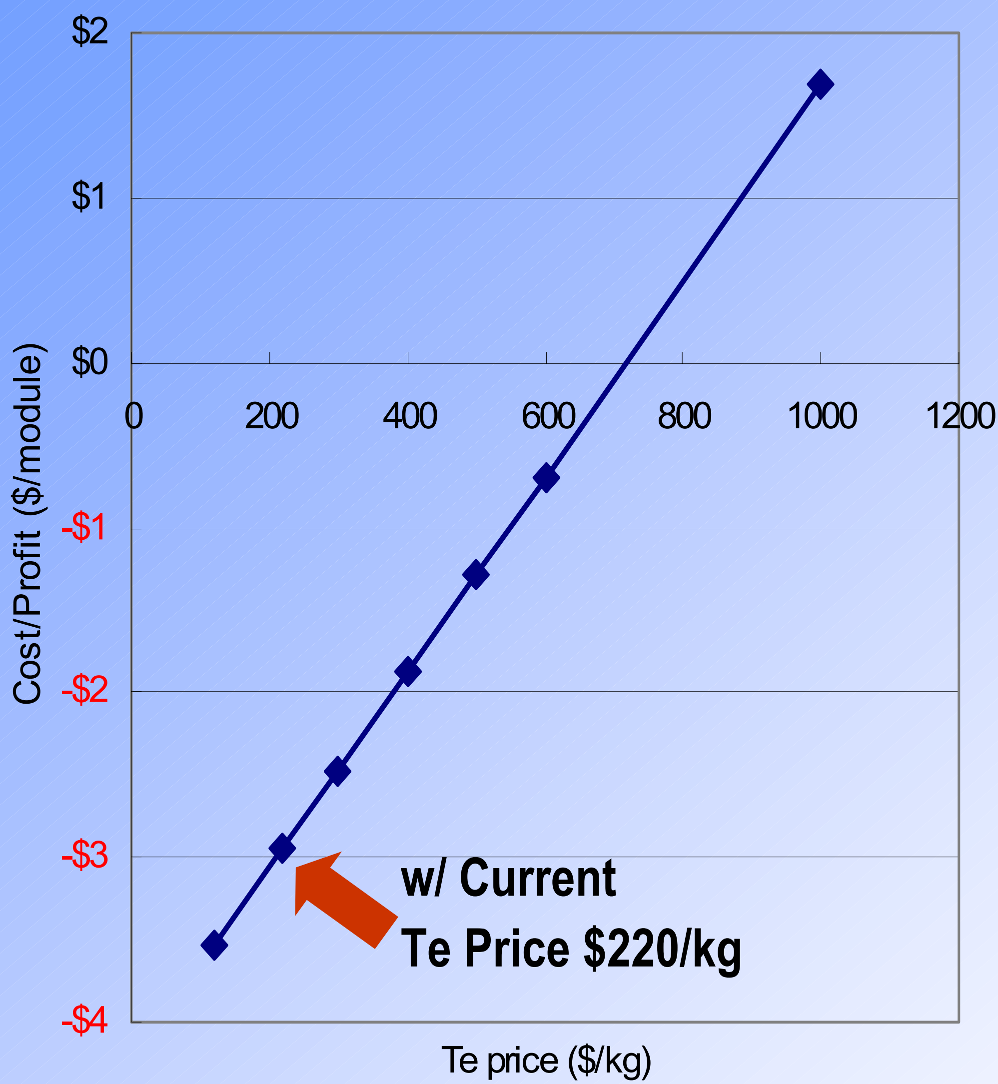
0.04 ¢ module

3.7 ¢/ module

Black: cost

*Choi and Fthenakis, in press*

# Price of Te vs. Total Cost/Profit ($/module)




| Te price ($/kg) | cost/profit ($/module) |
|---|---|
| 120 | -$3.54 |
| 220 | -$2.95 |
| 300 | -$2.47 |
| 400 | -$1.88 |
| 500 | -$1.29 |
| 600 | -$0.69 |
| 1000 | $1.68 |

- Total Cost/Profit breakeven point around Te price of $720/kg.
- Other costs are fixed

*Choi and Fthenakis, in press*

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# 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

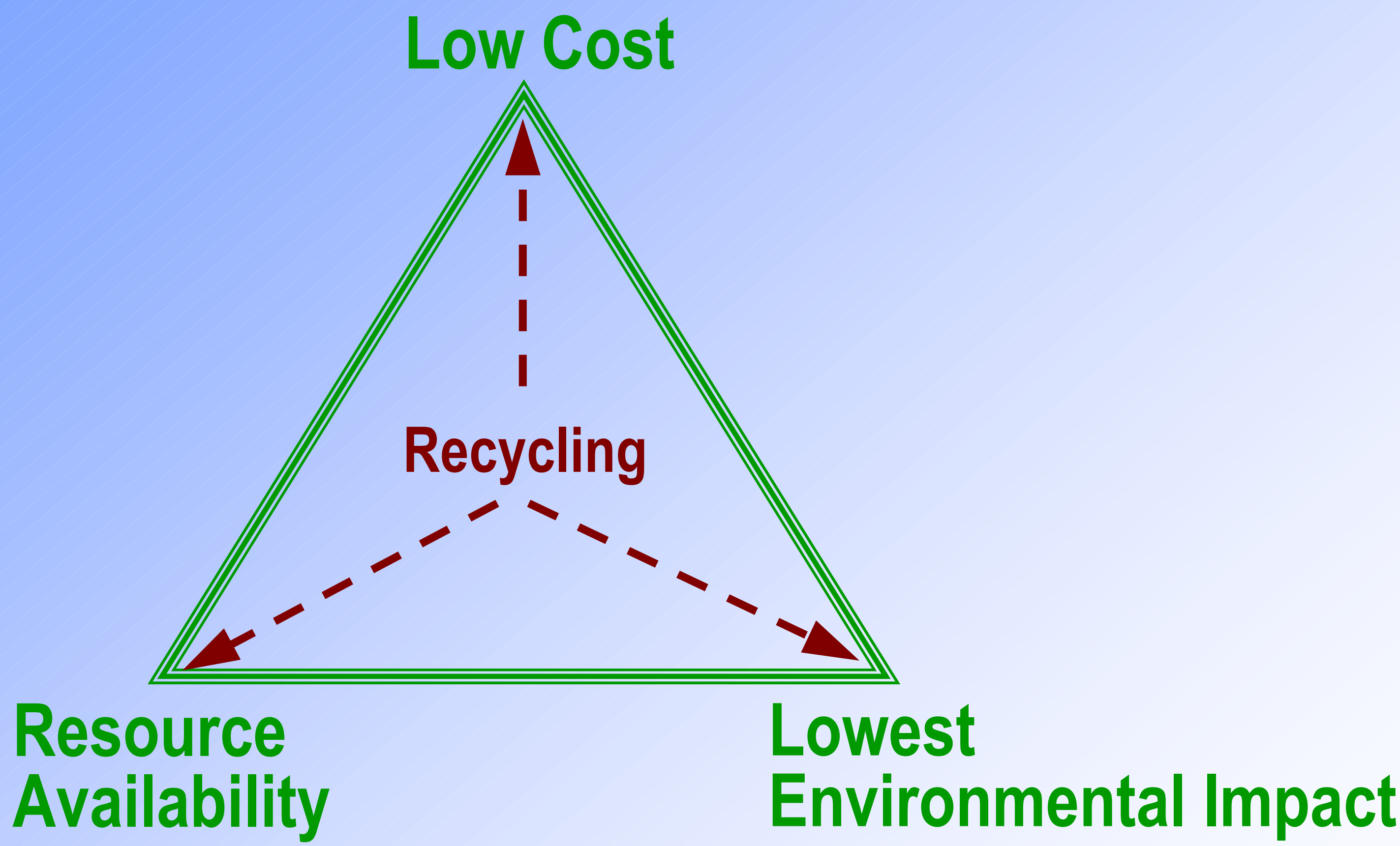
**Associated:**

- 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

# The Triangle of Success

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# Conclusion

- Recycling can double the availability of tellurium and Indium in the 2nd part of the century
- Thin-film PV can reach very high rates of growth without being impaired from material availability issues
- Recycling spent modules and developing thinner solar cells will become increasingly important in resolving cost, resource, and environmental constraints to large scales of sustainable growth

# Acknowledgment


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- Jim Sites –Colorado State U.
- Bill Stanbery -HelioVolt
- Marc Suys, 5NPlus
- Bolko von Roedern –NREL
- Ken Zweibel –George Washington U.



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