Key Minerals in Photovoltaics

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Feb 4, 2010
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Rationale

- Solar PV growing fast – over 40%/yr
- Now 5-6 GW/yr
- Semiconductor (approximate, at 10% efficiency)
  - 10 km2 surface per GW
  - 10 m3 per GW
  - About 20 MT/GW (@ 2 gm/W, eventually, but more now as layers are not optimized for thinness)
- DOE 'Solar Vision' projects 10% PV by 2030 (220 GW in US, 1100 GW worldwide)

Key Technologies

- **Commercial and Competitive for Long-Term**
  - **Silicon**
  - **CdTe**
- Emerging and Promising
  - $CuInSe_2$ alloys with Ga and S
  - III-V multijunctions for concentrators (GaAs alloys with In, P; and Ge or GaAs substrates)
- Commercial but Less Competitive
  - Amorphous and thin film silicon
- Emerging and Less Certain of Success
  - Dye “Gratzel” cells
  - Plastic cells
- Bulk materials for supports and wiring
  - Copper
  - Fixed
  - One and Two-Axis Trackers

Major Materials

- Specialty
  - Commercial
    - Silicon
    - Silver
    - **Tellurium**
    - Cadmium
  - Emerging
    - **Indium**
    - **Selenium**
    - Molybdenum
    - **Gallium**
    - Germanium
    - Arsenic
    - Ruthenium
  - Many minor materials (Ni, P, Zn, Sn, S, N, H, more)
- Bulk
  - Steel
  - Aluminum
  - **Copper**
  - Adhesive
  - Insulating
  - Concrete
  - Plastic

Bottlenecks

- Risk and timing of investment
  - Unpredictability and rapid alteration of demand
  - “Silicon shortage”!
- Extraction
  - Is there enough?
  - Is it economically accessible in a timely manner?
- Refining
  - Is it technically feasible?
  - Is it economically favorable?
- Sources
  - Accessible for purchases or politically controlled?

Issue Materials

- Fundamental (amount, economics, competing uses)
  - Te
  - In
  - Ga
  - Se
  - Maybe
    - Ag
    - Cu
    - Mo
- Transitory (timing)
  - Refined materials
    - Si
    - Gases
    - Coated glass substrates
      - Transparent conductive oxides like tin oxide
    - Sputtering targets
    - Compounds
    - Other refined, processed sources

Issue Materials by Technology

- CdTe
  - Te
- CuInSe2-alloys
  - In
  - Ga
  - Se
- Silicon
  - Ag
- Bulk – Cu for wires

Approximate Amounts (2010)

	Thickness (microns), g/m2 (90% use)	g/W	Cost ($/g, $/W, $/m2; bulk, pure)	Competing Uses	Concern (mid- & long-term)
Te	3 um; 10-12 g	0.1 g/W (@ 110 W/m2)	$0.3/g, $0.03/W, $3.3/m2	Few and small	Price & Supply, and Intrinsic Availability
In	1-2 um; 2-4 g (In/Ga = 4)	0.02-0.04 g/W (@ 110 W/m2)	$0.5/g, $0.02/W, $1.5/m2	LCD (large and valuable)	Price & Supply, and Intrinsic Availability
Ga	1-2 um; 0.5-1 g (In/Ga =4)	0.005-0.01 g/W (@ 110 W/m2)	$0.5/g, $0.005/W, $0.4/m2	Few and small	Price & Supply, and Intrinsic Availability
Mo	1 um; 10 g	0.1 g/W (@ 110 W/m2)	$0.02/g, $0.002/W, $0.2/m2	Large	Price
Se	1-2 um; 3.5-7 g/m2	0.03-0.06 g/W (@ 110 W/m2)	$0.1/g, $0.005/W, $0.5/m2	Large and valuable	Price & Supply, and Intrinsic Availability
Ag	30 g/m2	0.2 g/W (@ 160 W/m2)	$0.5/g, 0.09/W, $15/m2	Large and valuable	Price
Cu				Large and valuable	Price

Approximate Future (2030) Amounts

	Thickness (microns), g/m2 (90% use)	g/W	Cost ($/g, $/W, $/m2; bulk, pure feedstock), 2010 prices	Competing Uses	How?
Te	2/3 um; 2 g	0.013 g/W (@ 150 W/m2)	$0.5/g, $0.007/W, $1/m2	Few and small	Thinner CdTe, Higher Efficiency
In	0.75 um; 1.5 g (In/Ga = 4)	0.01 g/W (@ 160 W/m2)	$1/g, $0.01/W, $1.5/m2	LCD (large and valuable)	Thinner CuInSe2 Alloy, Higher Efficiency
Ga for CIS	0.75 um; 0.4 g (In/Ga =4)	0.0025 g/W (@ 160 W/m2)	$1/g, $0.0025/W, $0.4/m2	Few and small	Thinner CuInSe2 Alloy, Higher Efficiency
Mo	0.5 um; 5 g	0.03 g/W (@ 160 W/m2)	$0.02/g, $0.0006/W, $0.1/m2	Large	Thinner Mo contact, Higher Efficiency
Se	0.75 um; 2.6 g/m2	0.016 g/W (@ 160 W/m2)	$0.2/g, $0.003/W, $0.5/m2	Large and valuable	Thinner CuInSe2 Alloy, Higher Efficiency
Ag	15 g/m2	0.07 g/W (@ 220 W/m2)	$1/g, 0.1/W, $15/m2	Large and valuable	Higher Efficiency
Cu				Large and valuable	

Material	MT/GW (2010)	MT/GW (2030)*
Te	100	13
In	30	9.4
Ga	8	2.3
Mo	100	30
Se	30	16
Ag	200	70

*From thinner layers and higher efficiencies

PV Scenarios

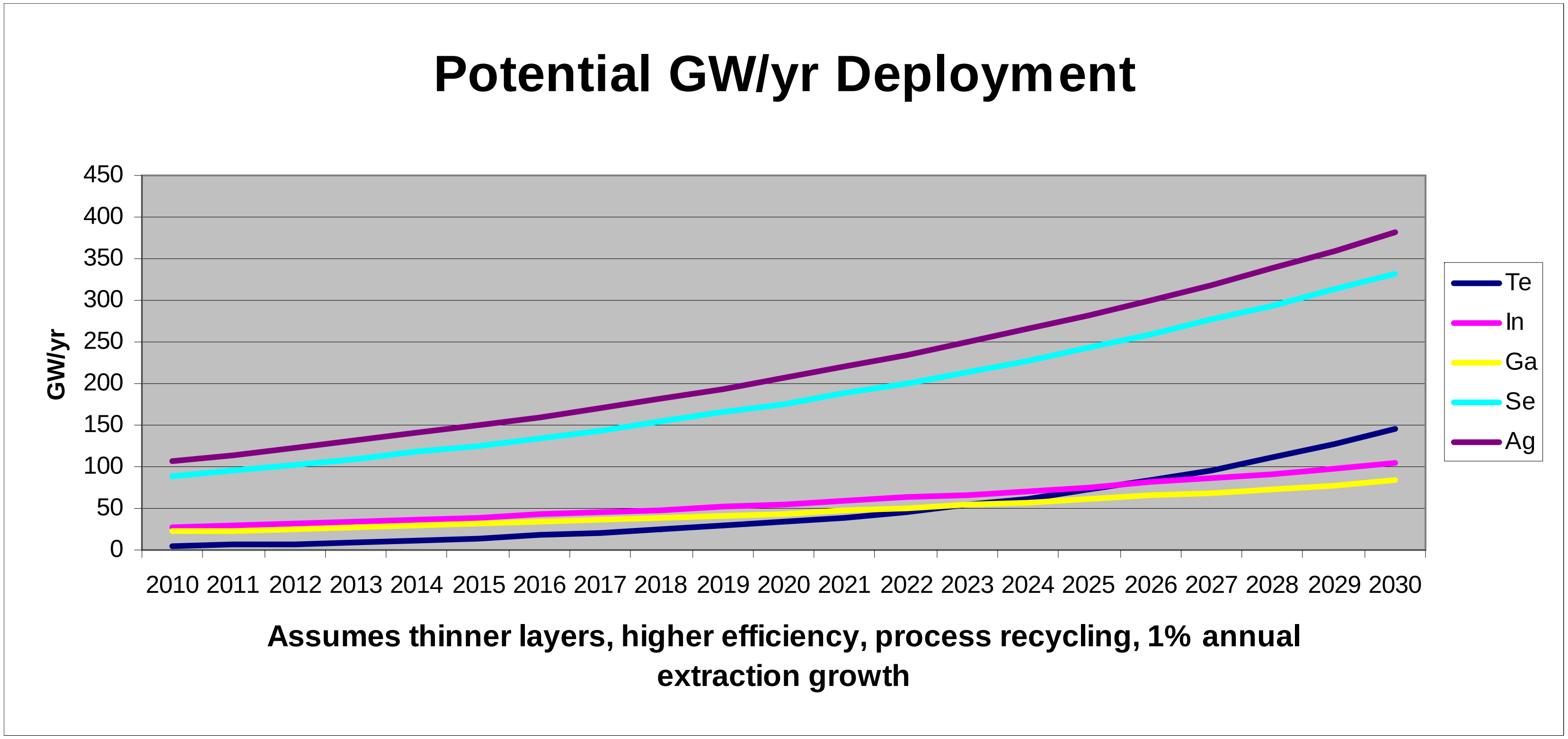
- Solar Vision 2030 (about 10% US electricity from *PV*, 20% from solar)
  - About 220 GW PV (US)
  - Implies about 1100 GW PV (worldwide)
  - Implies 160 GW/yr *annual* production in 2030 worldwide (16% annual growth rate)

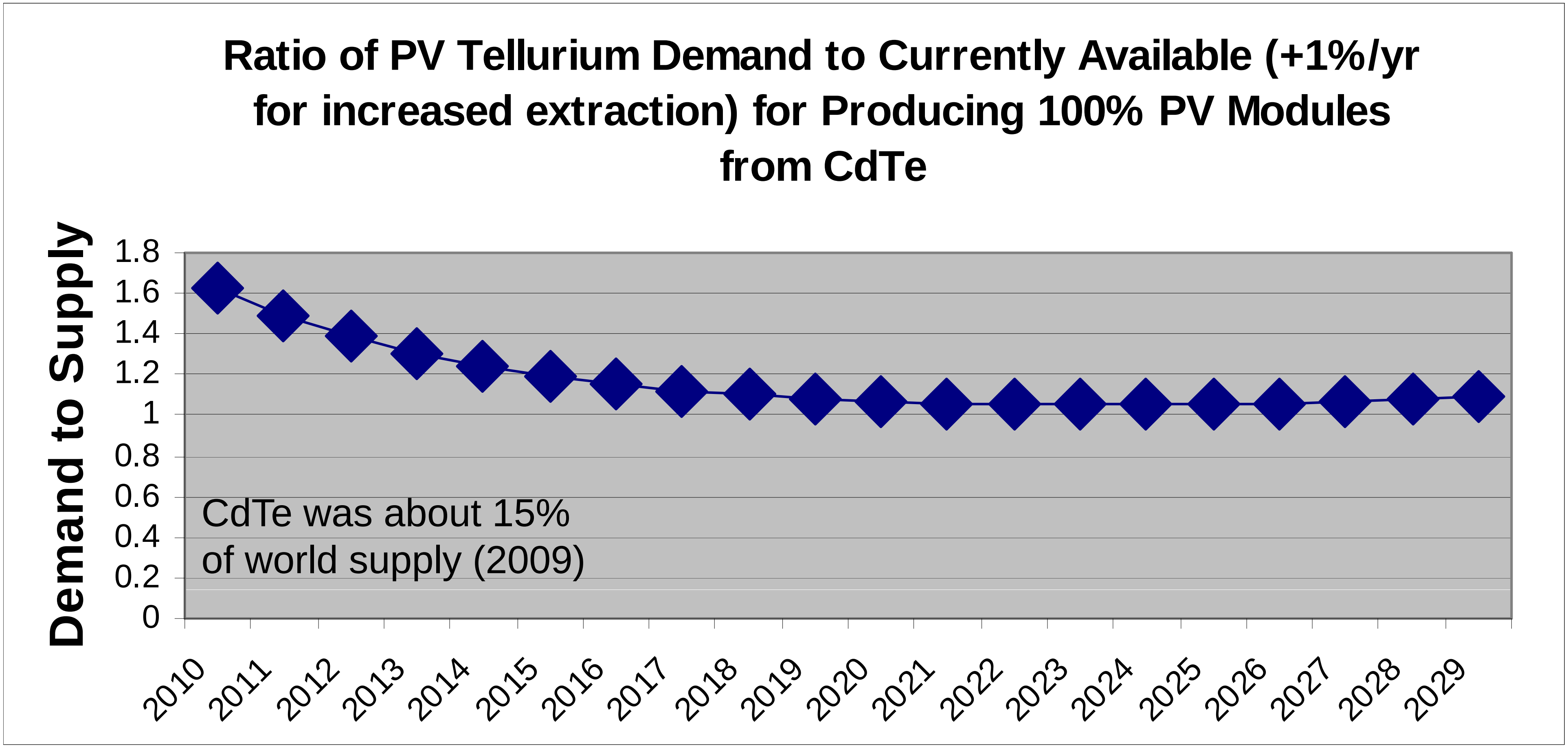
Material	MT/yr (2009)	Annual Amount 2030 (MT/yr) for 160 GW/yr (possible annual installations)
Te	120 MT (1.2 GW)	2080
In	3 (0.1 GW)	1500
Ga	0.8	370
Mo	10	4800
Se	3	2560
Ag	1200 (@ 6 GW)	11,200

Major Issues and Opportunities

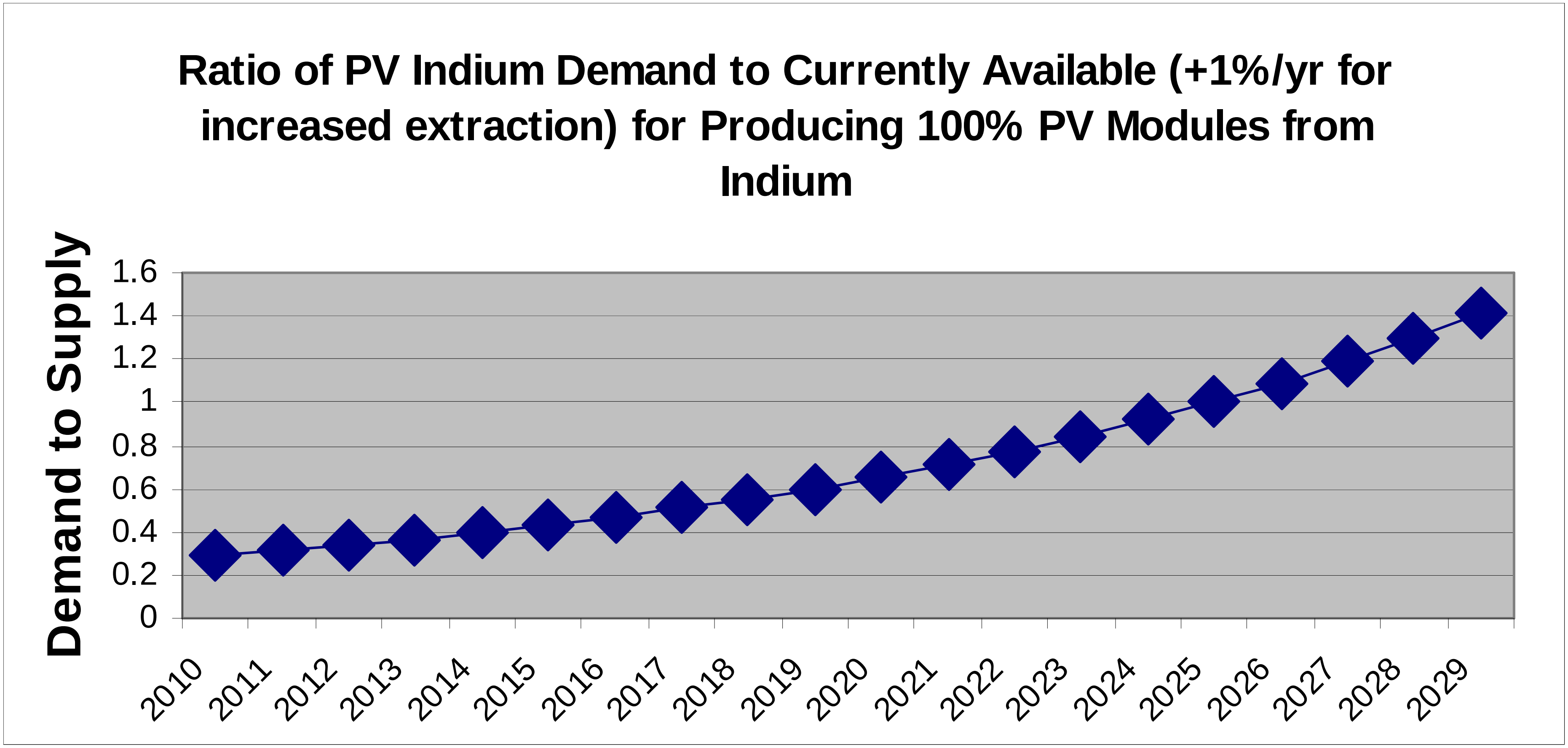
- Reductions in material intensity (g/W) for thinner layers, higher efficiencies
- Te
  - Dependence on Cu refining
  - Lack of refining from Au, Pb, Zn, other
  - Lack of Te-ore, e.g., bismuth telluride
  - Undersea Te on ridges
- In
  - Lack of concentrated ores
  - Serious competition with TCOs for flat panel displays, conductive pastes, and similar *high-value* electronics
- Ga – is it a special case due to high amount in crust?
  - About same as Pb

Gradual Improvement of GW/YR Potential

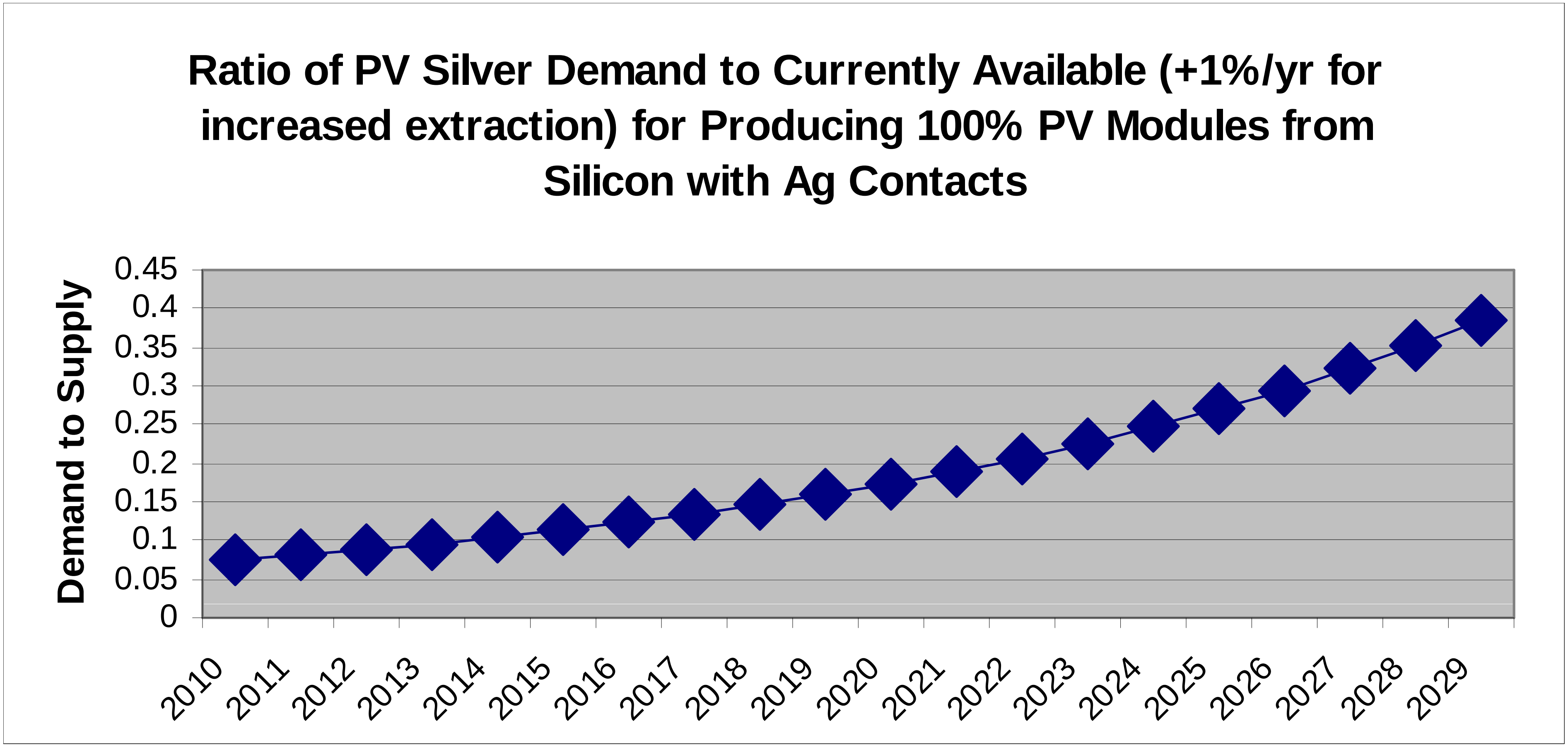




Assumes unrefined amounts above 500 MT/yr (2009) steadily added to reach full amount available (which is 1500 MT/yr in 2010, and 2000 MT 2030). This level of detail is explored for CdTe due to its importance (other slides do not include same detail about early evolution).



Ignores effect of significant competing uses of indium (e.g., flat panel displays)


Ratio of PV Silver Demand to Currently Available (+1%/yr for increased extraction) for Producing 100% PV Modules from Silicon with Ag Contacts
Demand to Supply
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029

Concluding Remarks

- Most important recent commercial PV technology, CdTe, must address all aspects of availability – supply increase and demand reduction
- Most important *emerging* commercial technology, CIGS, has In (and Ga) issues
- All PV technologies (even Si through Ag) have important involvement with mineral extraction and refining worldwide
  - Lack of US commitment to extraction and refining inside our borders is a concern for US manufacturing competitiveness in PV for these materials