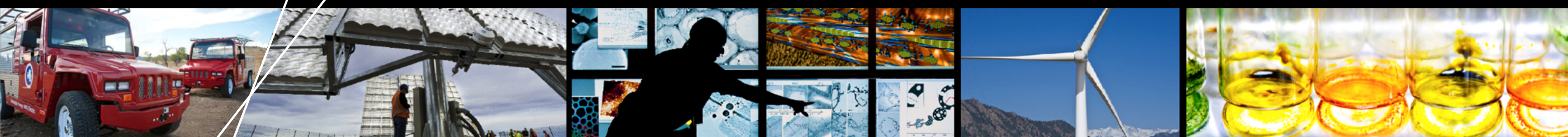
Supply Chain Dynamics of Tellurium (Te), Indium (In), and Gallium (Ga) Within the Context of PV Module Manufacturing Costs



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NREL/PR-6A20-57138

SEMI 2012 Strategic Materials Conference

October 23, 2012

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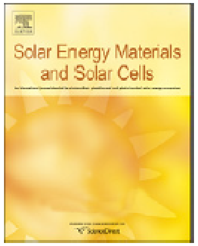

Perspectives on the pathways for cadmium telluride photovoltaic module manufacturers to address expected increases in the price for tellurium

Michael Woodhouse [a,*], Alan Goodrich [a,*], Robert Margolis [a], Ted James [a], Ramesh Dhere [c], Tim Gessert [c], Teresa Barnes [c], Roderick Eggert [b], David Albin [c,*]

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[b] *Colorado School of Mines, United States*
[c] *The National Renewable Energy Laboratory, National Center for Photovoltaics, 1617 Cole Blvd, Golden, CO 80401, United States*

Supply-Chain Dynamics of Tellurium, Indium, and Gallium Within the Context of PV Module Manufacturing Costs

Michael Woodhouse[1], Alan Goodrich[1], Robert Margolis[1], Ted L James[1], Martin Lokanc[2], and Roderick Eggert[2]

Publication accepted by the *Journal of Photovoltaics*.

What is the material intensity (I, in metric tonnes per GW) for using an element within a layer in a PV module?

$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

Where:

d = Layer thickness (in μm)

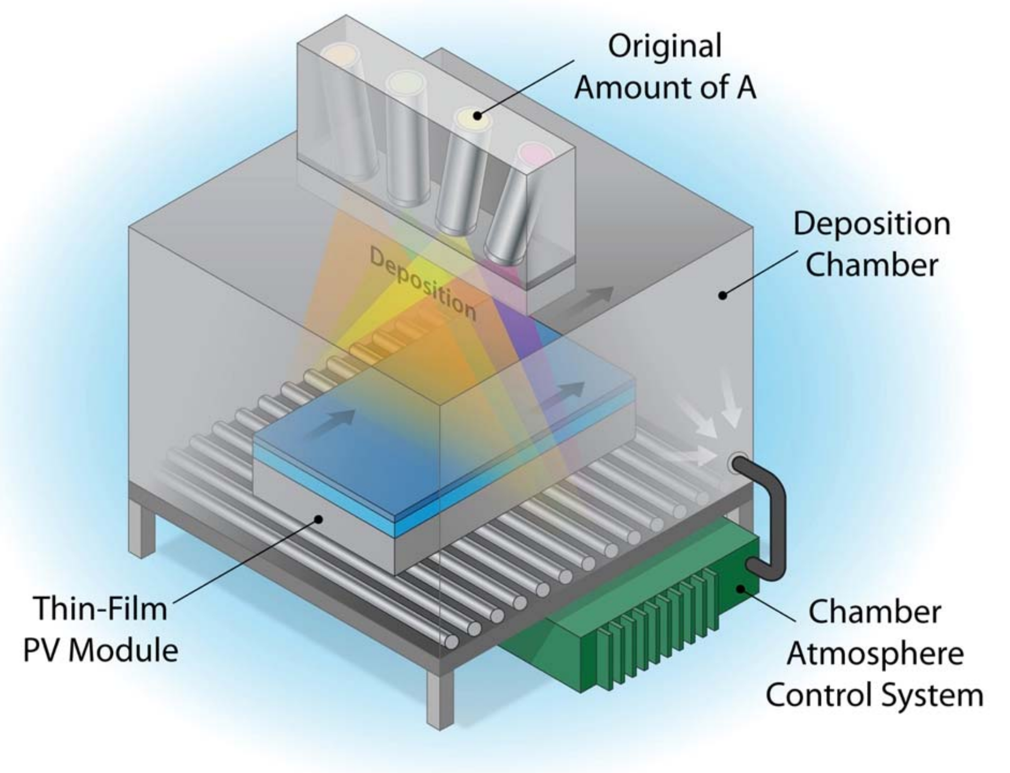
ρ = Layer density (in $g \cdot cm^{-3}$)

X_A = The mass fraction of element A within the layer

η = The area-based module power rating (in W/m^2)

U_A = The utilization of element A in manufacturing, representing the fraction of the original amount of A that is actually captured within the completed module

R_A = The recovery fraction of element A in manufacturing, representing the initial amount of A that can be reused after the appropriate deposition on the module and after the appropriate recovery steps.



The sensitivity of PV module manufacturing costs to the price for the element's precursor

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

P_A = Price of the element at a standard grade of purity (\$/ kg)

T = Tolling charge to refine the element to 'solar grade' and to meld it into its appropriate precursor for manufacturing (\$/ kg)

X_Y = Weight percentage of A in the precursor compound (0.53 for CdTe, 1 for In and Ga in CIGS and HVPE GaAs, 0.61 for $Ga(CH_3)_3$)

R_A = Net recovery fraction of A from the manufacturing line, after the appropriate deposition and recovery processes

RV_A = Recovery value of A (\$/ kg).

Tellurium in Single-Junction Polycrystalline CdTe

BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY FOR TELLURIUM IN CdTe. 2012 BASELINE.								
Element A of interest	d	ρ ($g \cdot cm^{-3}$)	X_A	η ($W \cdot m^{-2}$)	U_A / R_A	**I_A (MT/ GW)**	P_A & T	**C_{A+T}**
Te in CdTe	2.5 µm [1, 2]	5.85 [3]	0.53	128 [4]	0.70 [5] / 0.20 [5]	**69**	P_{Te} ≈ $150/ kg [6] T_{CdTe} ≈ $110/ kg [7]	**$0.034/ W**

Estimated 2011 Material Supply Base for Tellurium

Primary annual production from Cu byproduct recovery

500 - 600 MT [8]

Notes and References:

The element prices shown are rough estimates from a relevant industry collaborator. The exact pricing terms for any material supply contract, and the duration of delivery, are highly guarded and need to be considered on a case-by-case basis.

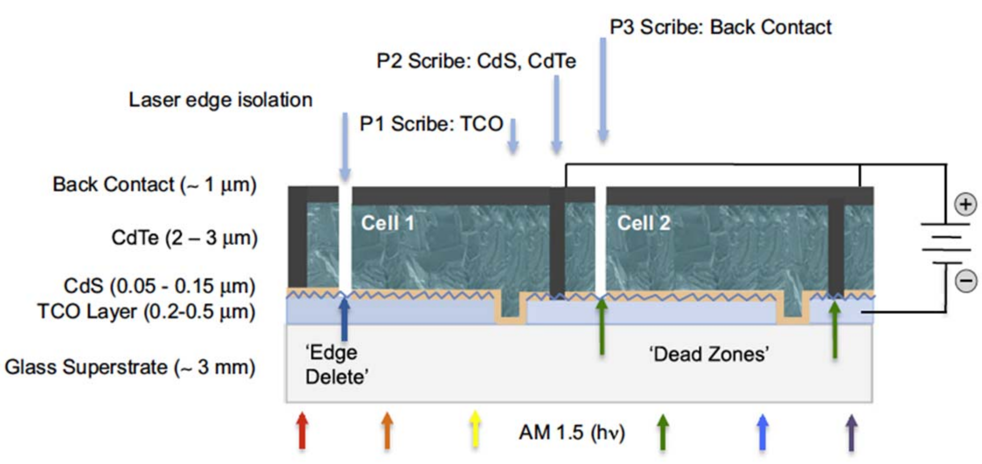
$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

Material constraint if relying upon byproduct recovery at present efficiencies

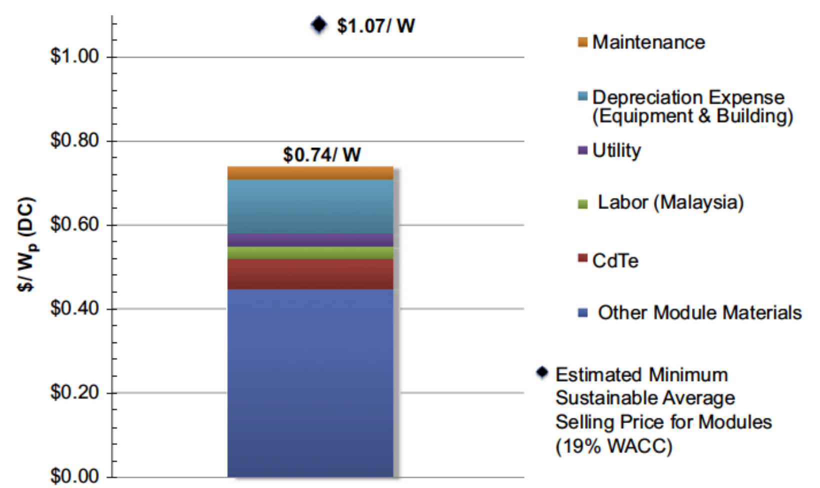
≈ 600/ 69

9 GW



Cost Model Results for CdTe Module Manufacturing

η = 11.7%, 2.5µm CdTe, Malaysian Production Location



Indium in $Cu[In_{(1-x)}Ga_x]_ySe_2$, or 'CIGS'

BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY FOR INDIUM IN CIGS. 2012 BASELINE.								
Element A of interest	d	ρ ($g \cdot cm^{-3}$)	X_A	η ($W \cdot m^{-2}$)	U_A / R_A	**I_A (MT/ GW)**	P_A & T	**C_{A+T}**
In in CIGS	2.0 µm [9]	5.75 [10]	≈ 0.22[1] [9, 11]	157 [4, 12]	0.55[2] / 0.25	**23**	P_{In} ≈ \$520/ kg [13] T_{In} ≈ \$100/ kg[3]	**\$0.018/ W**

Estimated 2011 Material Supply Base for Indium

Primary annual production from Zn byproduct recovery

$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

550 - 650 MT [20, 21]

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

Notes and References:

The element prices shown are rough estimates from a relevant industry collaborator. The exact pricing terms for any material supply contract, and the duration of delivery, are highly guarded and need to be considered on a case-by-case basis.

[1] Representative weight percentage, calculated from the CIGS stoichiometry within the given references.

[2] For sputtering, the target material utilization for a rotary target is around 75%, while the material utilization of a planar target is around 30%. The net fraction of material that is then captured within the module is then the product of this material utilization and the transfer efficiency. The value shown here is the product of these two for a rotary target, and is also a representative collection fraction for the co-evaporation approach to CIGS module manufacturing.

[3] This will very much depend upon the chosen form factor, and rotatable targets are generally more expensive than planar targets. The remaining material on a spent sputtering or evaporation target can usually be resold—in consultation with a CIGS manufacturing firm we assume here that the remaining material on a used rotary target could be resold with a typical reclamation value of around 25% of the original value.

Indium in $Cu[In_{(1-x)}Ga_x]_ySe_2$, or 'CIGS'

BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY FOR INDIUM IN CIGS. 2012 BASELINE.								
Element A of interest	d	ρ ($g \cdot cm^{-3}$)	X_A	η ($W \cdot m^{-2}$)	U_A / R_A	I_A (MT/ GW)	P_A & T	C_{A+T}
In in CIGS	2.0 µm [9]	5.75 [10]	≈ 0.22[1] [9, 11]	157 [4, 12]	0.55[2] / 0.25	**23**	P_{In} ≈ $520/ kg [13] T_{In} ≈ $100/ kg[3]	**$0.018/ W**

Estimated 2011 Material Supply Base for Indium

Primary annual production from Zn byproduct recovery

$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

550 - 650 MT [20, 21]

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

Notes and References:

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material on a spent sputtering or evaporation target can usually be
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Material constraint if relying upon byproduct recovery at present efficiencies
≈ 650/ 23

28 GW

Gallium in $Cu[In_{(1-x)}Ga_x]_ySe_2$, or 'CIGS'

BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY AND COST FOR GALLIUM IN CIGS. 2012 BASELINE.								
Element A of interest	d	ρ ($g \cdot cm^{-3}$)	X_A	η ($W \cdot m^{-2}$)	U_A / R_A	I_A (MT/ GW)	P_A & T	C_{A+T}
In in CIGS	2.0 μm [9]	5.75 [10]	≈ 0.07[1] [9, 11]	157 [4, 12]	0.55[2] / 0.25[4]	**7.5**	P_{Ga} ≈ $400/ kg [14] T_{In} ≈ $100/ kg[3]	**$0.005/ W**

Estimated 2011 Material Supply Base for Gallium

Primary annual production from Bauxite (Al) byproduct recovery

$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

250 – 300 MT [22, 23]

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

Notes and References:

The element prices shown are rough estimates from a relevant industry collaborator. The exact pricing terms for any material supply contract, and the duration of delivery, are highly guarded and need to be considered on a case-by-case basis.

[1] Representative weight percentage, calculated from the CIGS stoichiometry within the given references.

[2] For sputtering, the target material utilization for a rotary target is around 80%, while the material utilization of a planar target is around 30%. The net fraction of material that is then captured within the module is then the product of this material utilization and the transfer efficiency. The value shown here is the product of these two for a rotary target, and is also a representative collection fraction for the co-evaporation approach to CIGS module manufacturing.

[3] This will very much depend upon the chosen form factor, and rotatable targets are generally more expensive than planar targets. The remaining material on a spent sputtering or evaporation target can usually be resold—in consultation with a CIGS manufacturing firm we assume here that the remaining material on a used rotary target could be resold with a typical reclamation value of around 25% of the original value.

[4] This may be deposited from a Cu-Ga composite target if sputtering.

Gallium in $Cu[In_{(1-x)}Ga_x]_ySe_2$, or 'CIGS'

BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY AND COST FOR GALLIUM IN CIGS. 2012 BASELINE.								
Element A of interest	d	ρ ($g \cdot cm^{-3}$)	X_A	η ($W \cdot m^{-2}$)	U_A / R_A	**I_A (MT/ GW)**	P_A & T	**C_{A+T}**
In in CIGS	2.0 µm [9]	5.75 [10]	≈ 0.07[1] [9, 11]	157 [4, 12]	0.55[2] / 0.25[4]	**7.5**	P_{Ga} ≈ \$400/ kg [14] T_{In} ≈ \$100/ kg[3]	**\$0.005/ W**

Estimated 2011 Material Supply Base for Gallium

Primary annual production from Bauxite (Al) byproduct recovery

$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

250 – 300 MT [22, 23]

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

Notes and References:

The element prices shown are rough estimates from a relevant industry collaborator. Th
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[4] This may be deposited from a Cu-Ga composite target if sputtering.

Material constraint if relying upon byproduct recovery at present efficiencies
≈ 300/ 7.5

40 GW

Gallium in Single-Junction GaAs

BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY AND COST CONTRIBUTIONS FOR GALLIUM IN SINGLE-JUNCTION GaAs. 2012 BASELINE.								
Element A of interest	d	ρ $(g \cdot cm^{-3})$	X_A	η $(W \cdot m^{-2})$	U_A / R_A	**I_A (MT/ GW)**	P_A & T	**C_{A+T}**
Ga in Single-Junction GaAs (MOCVD)	2.5 µm [15-17]	5.32 [18]	0.48	235 [19]	0.30 / 0.00[5]	**91**	P_{Ga} ≈ $400/ kg [14] T_{TMG} ≈ $2100/ kg[6]	**$0.373/ W**
Ga in Single-Junction GaAs (HVPE)	2.5 µm	5.32 [18]	0.48	235[7]	0.30 / 0.00[5]	**91**	P_{Ga} ≈ $400/ kg [14] T_{Ga} ≈ $100/ kg	**$0.046/ W**

Estimated 2011 Material Supply Base for Gallium

Primary annual production from Bauxite (Al) byproduct recovery

$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

250 – 300 MT [22, 23]

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

Notes and References:

The champion module efficiencies shown in this table are taken from Table II in reference [19]. The efficiencies are independently-verified, but not all of the modules represented are produced and sold at GW–or even MW—levels of scale.

The element prices shown are rough estimates. The exact pricing terms for any material supply contract, and the duration of delivery, are highly guarded and need to be considered on a case-by-case basis.

[5] It is our understanding that Ga is not currently recovered from the MOCVD and HVPE processes for depositing GaAs, but this is more than likely due to the fact that these are currently just research-level investigations.

[6] Estimated price of around $2500/ kg for large volume purchasing contracts of $Ga(CH_3)_3$, provided by a relevant major supplier.

[7] This module efficiency has not been demonstrated and is used for illustrative purposes only. An HVPE GaAs cell efficiency greater than 20% has been reported in reference [24].

Gallium in Single-Junction GaAs

BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY AND COST CONTRIBUTIONS FOR GALLIUM IN SINGLE-JUNCTION GaAs. 2012 BASELINE.								
Element A of interest	d	ρ $(g \cdot cm^{-3})$	X_A	η $(W \cdot m^{-2})$	U_A / R_A	**I_A (MT/ GW)**	P_A & T	**C_{A+T}**
Ga in Single-Junction GaAs (MOCVD)	2.5 μm [15-17]	5.32 [18]	0.48	235 [19]	0.30 / 0.00[5]	**91**	P_{Ga} ≈ $400/ kg [14] T_{TMG} ≈ $2100/ kg[6]	**$0.373/ W**
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Estimated 2011 Material Supply Base for Gallium

Primary annual production from Bauxite (Al) byproduct recovery

$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

250 – 300 MT [22, 23]

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

Notes and References:

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[6] Estimated price of around $2500/ kg for large volume purchasing contracts

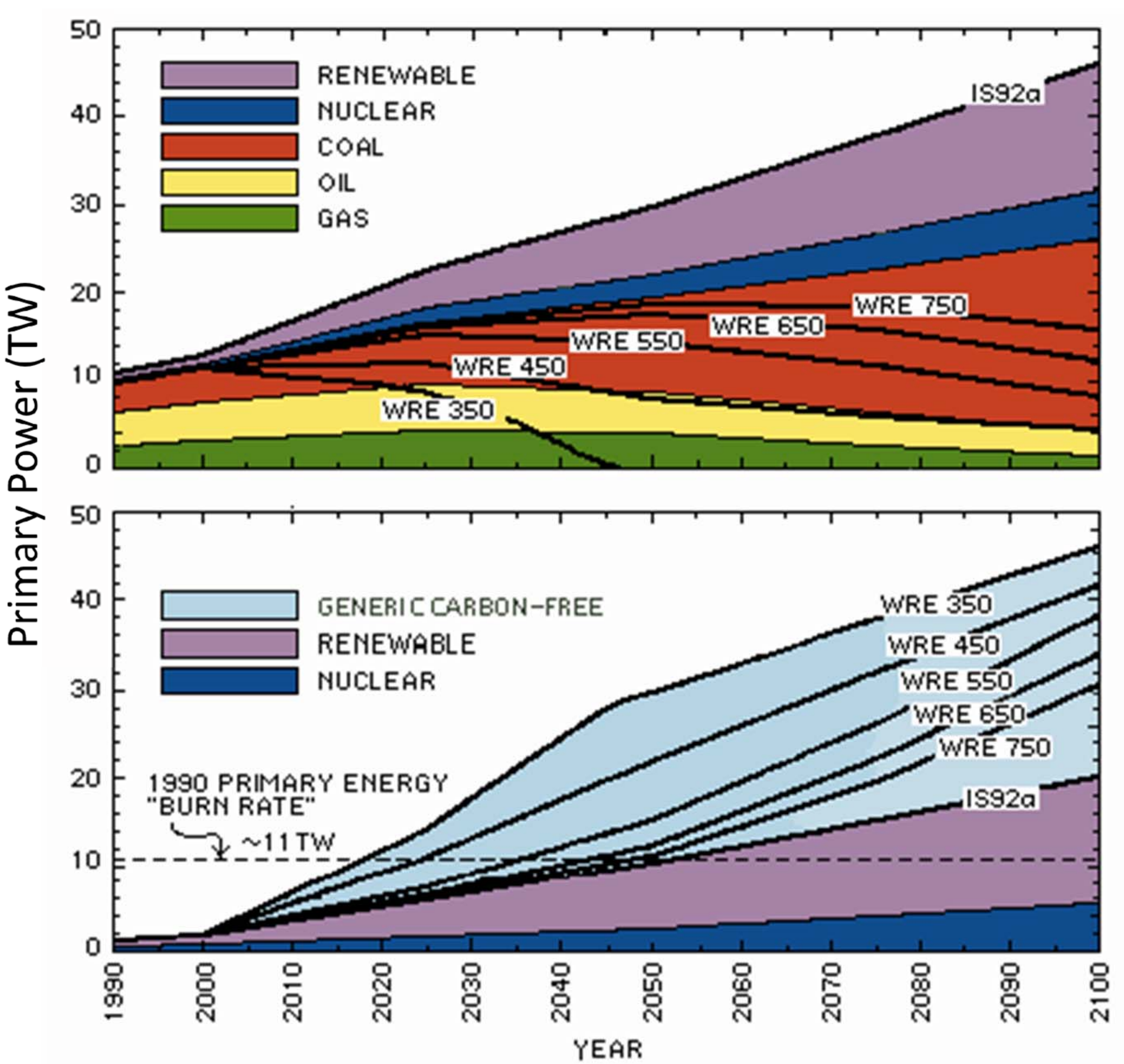
[7] This module efficiency has not been demonstrated and is used for illustrativ
has been reported in reference [24].

Material constraint if relying upon byproduct recovery at present efficiencies

≈ 300/ 91

3 - 4 GW

Are these energy-significant levels of deployment?



Source: Hoffert et al. (1998). *Nature,* 395, 881.

Projected trends in primary power consumption: **≈15 TW in 2004; ≈30 TW in 2050**

Pre-Industrial CO_2 concentration: **280 ppm**

Carbon-free power requirements (including efficiency) in 2035 to keep CO_2 <550 ppm:
≈10 TW

In 2050 to keep CO_2 <550 ppm: **A LOT**

WRE= Wigley, Richels, and Edmonds model.

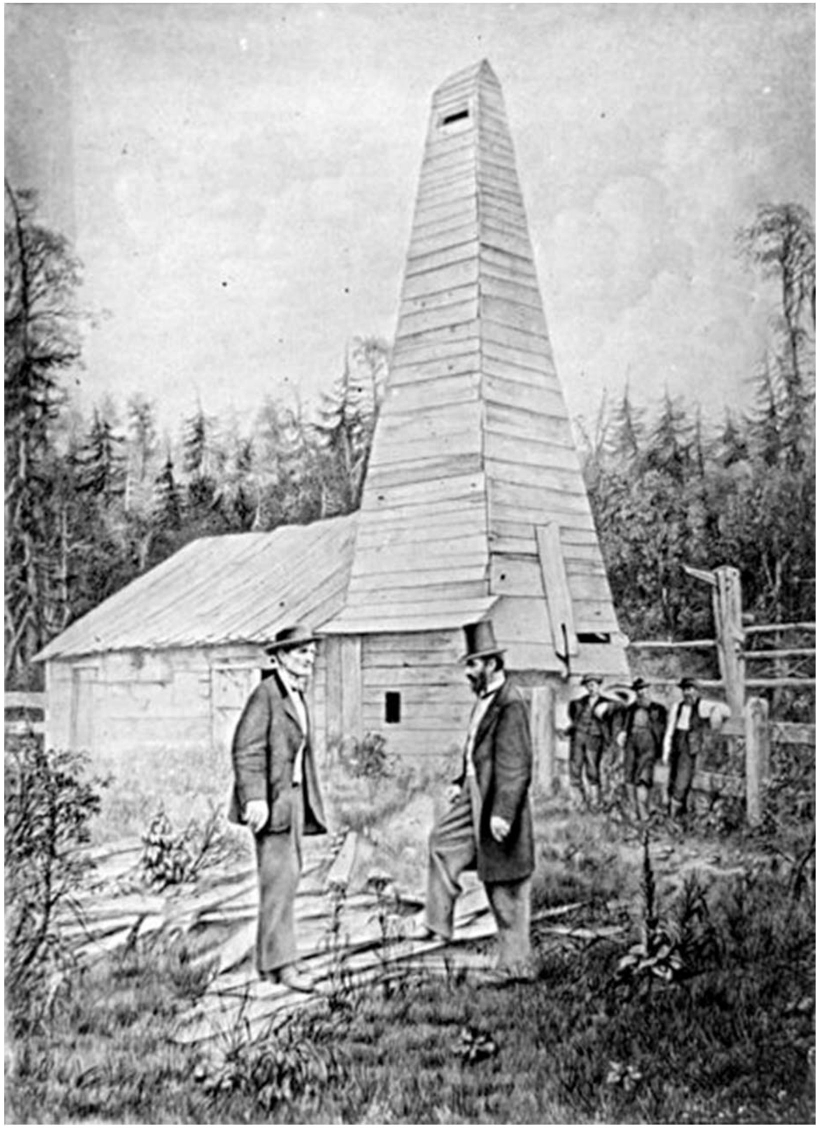
CO_2 Concentration (ppm)	Global Mean Temperature Increase Above Pre-Industrial Levels
445-490	2.0-2.4
490-535	2.4-2.8
535-590	**2.8-3.2** ('Dire Increase')
590-710	3.2-4.0
710-855	4.0-4.9
855-1130	4.9-6.1

(Table 3.5 in IPCC Fourth Assessment Report)

Is there a precedent for a predicament such as this?

Edwin Drake

George Bissel



Titusville, Pennsylvania (1859)

How did the thinking evolve?

NUCLEAR ENERGY AND THE FOSSIL FUELS

BY

M. KING HUBBERT

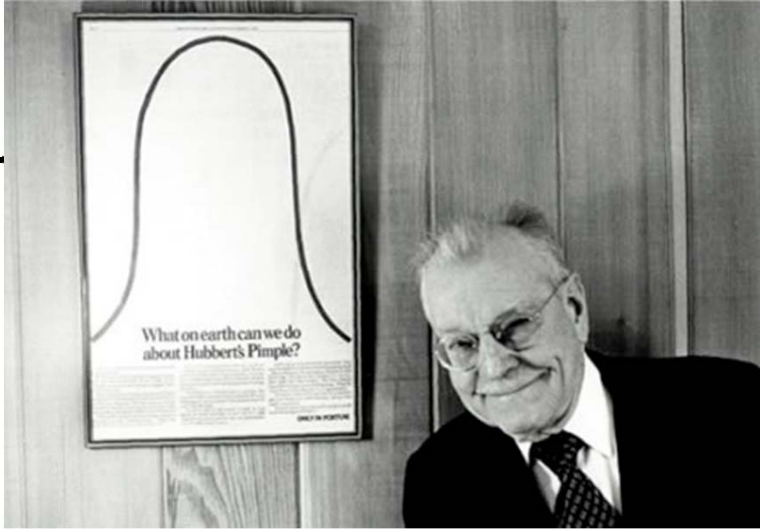
PUBLICATION NO. 95

SHELL DEVELOPMENT COMPANY

EXPLORATION AND PRODUCTION RESEARCH DIVISION

HOUSTON, TEXAS

JUNE 1956



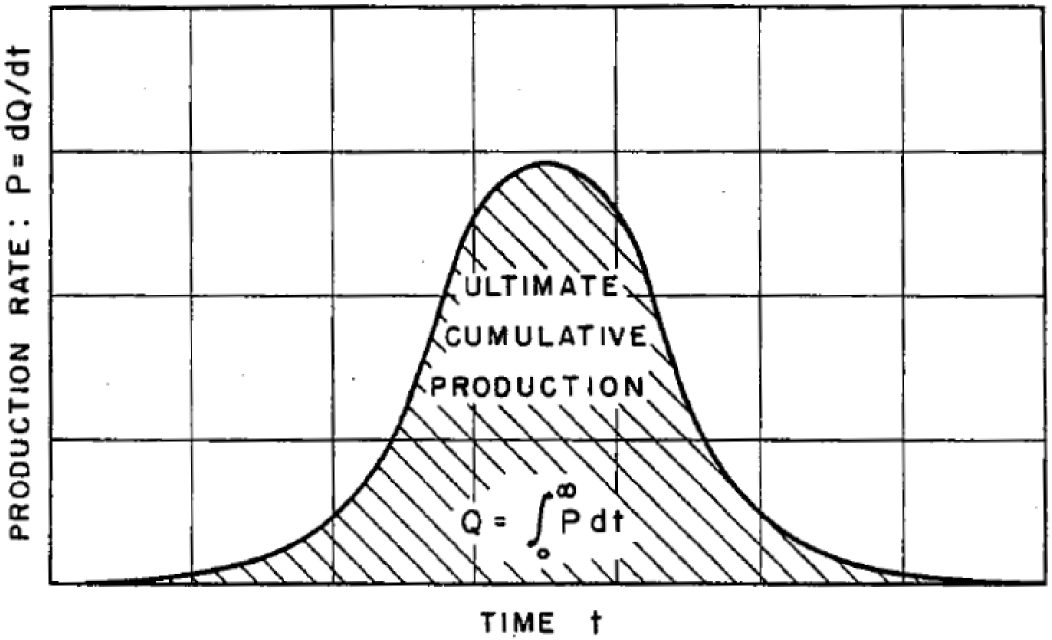


Figure II – Mathematical relations involved in the complete cycle of production of any exhaustible resource.

How did the thinking evolve?

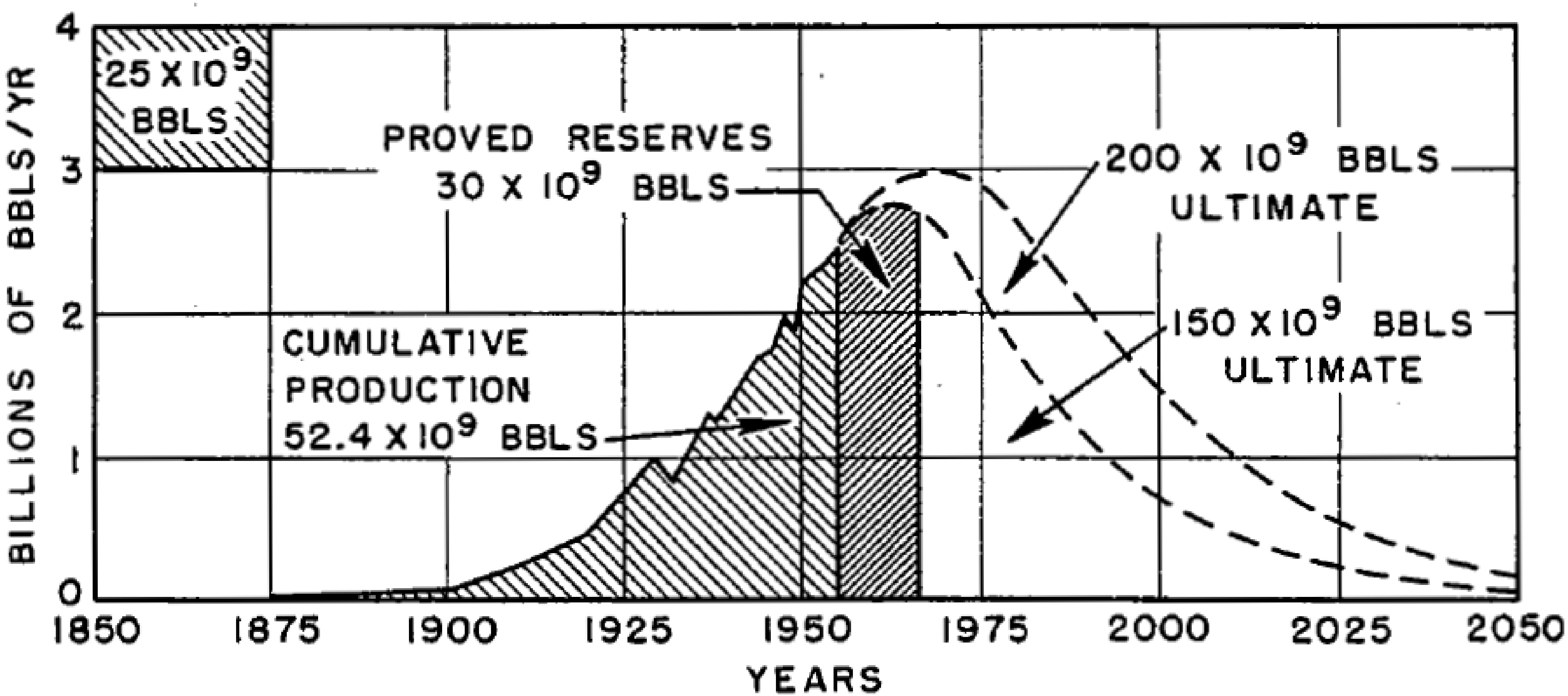


Figure 21 – Ultimate United States crude-oil production based on assumed initial reserves of 150 and 200 billion barrels.

Source: Hubbert, M.K. (1956). Shell Oil Development Company, Publication 95.

How did it actually play out?

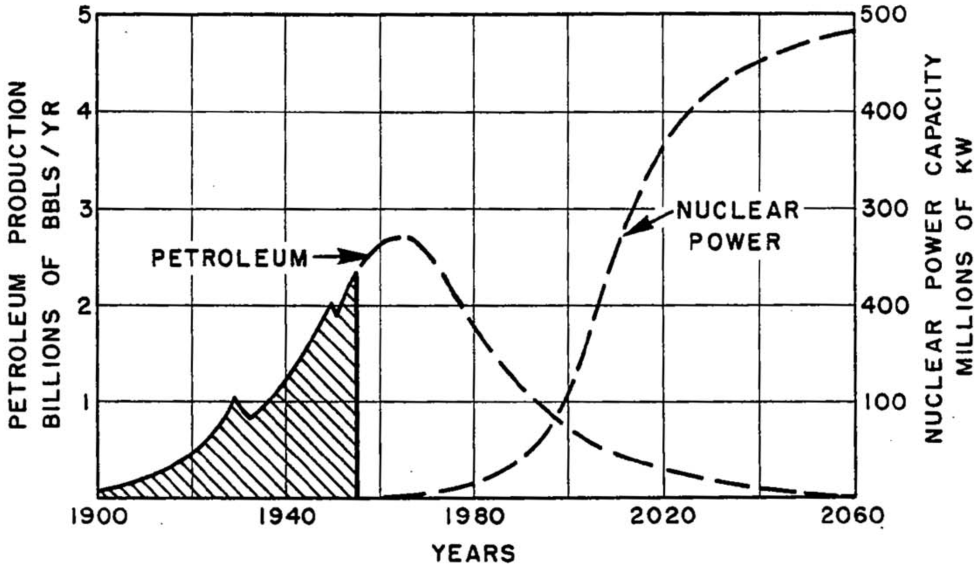
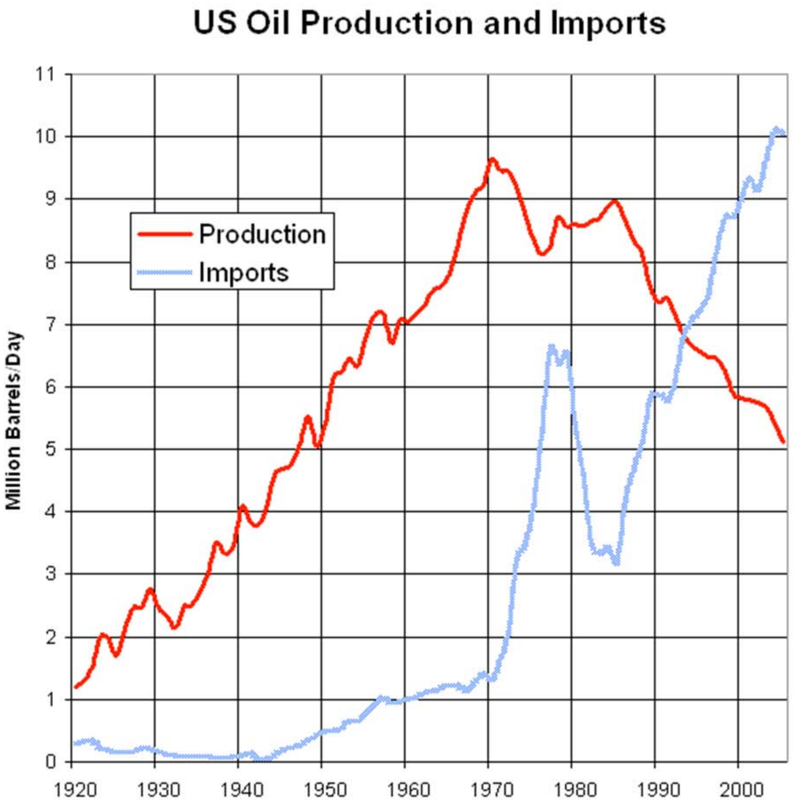


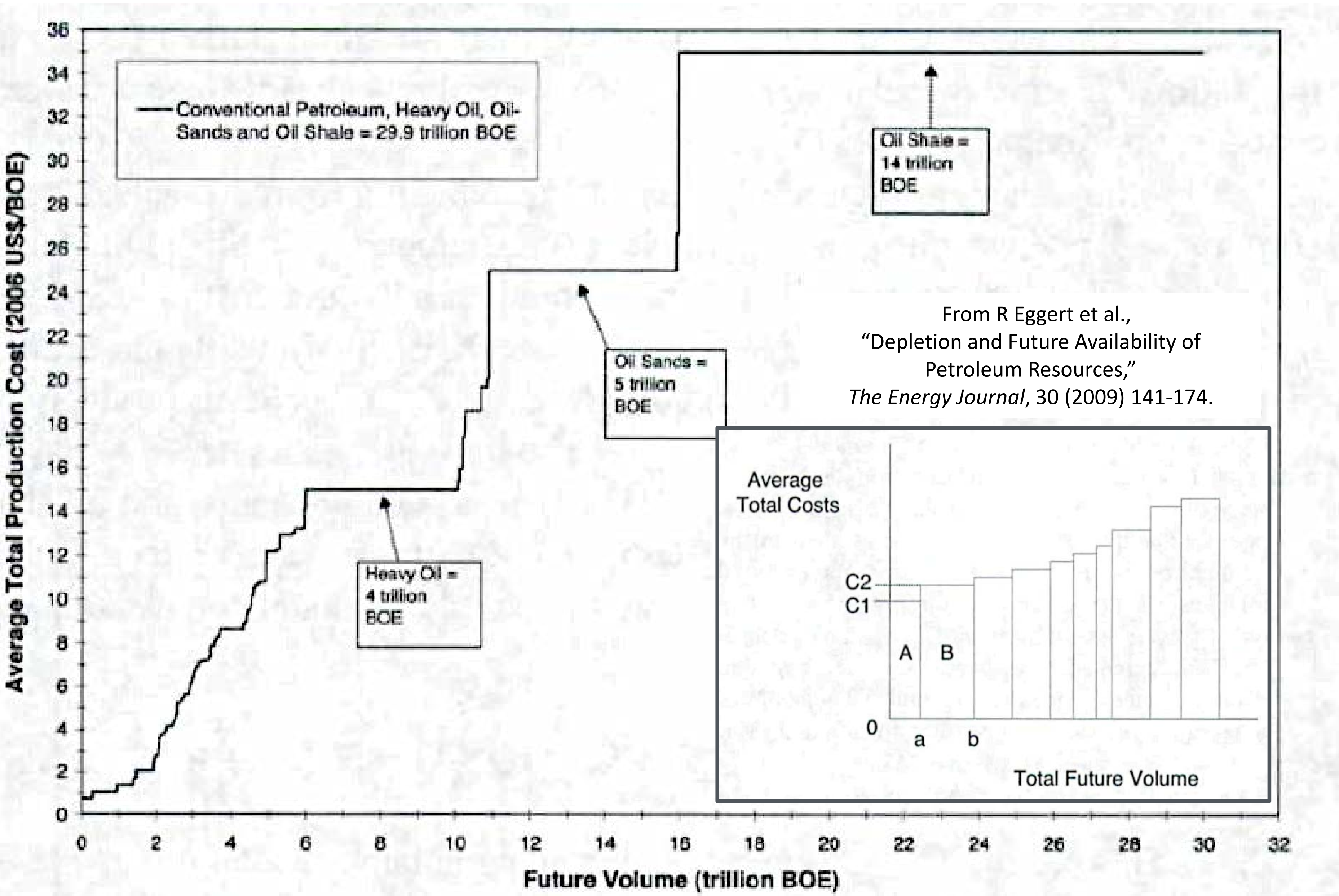
Figure 29 - Concurrent decline of petroleum production and rise of production of nuclear power in the United States.

Source: Hubbert, M.K. (1956). Shell Oil Development Company, Publication 95.



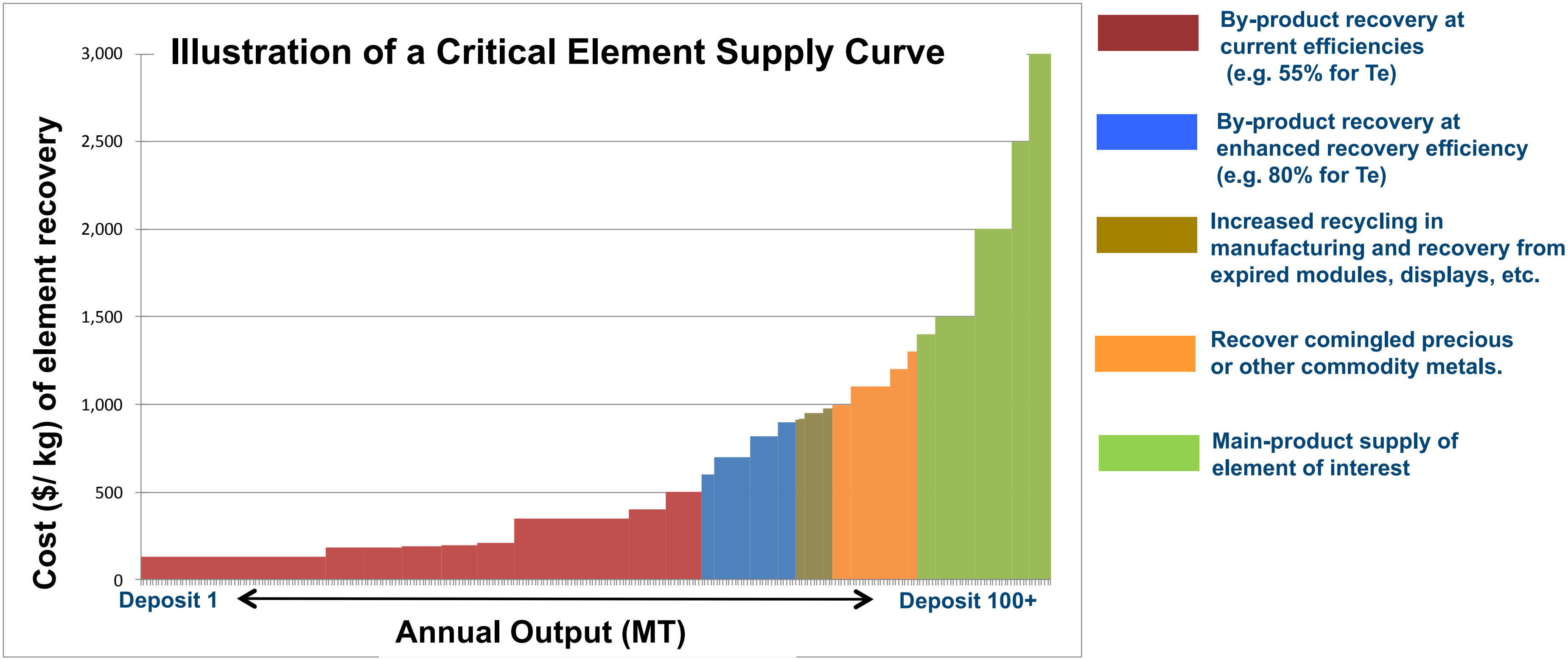
Source: DoE (EIA) Data

Getting to the fundamental question



From R Eggert et al.,
"Depletion and Future Availability of Petroleum Resources,"
The Energy Journal, 30 (2009) 141-174.

The fundamental supply question for these energy-critical elements



$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

From Woodhouse, M.; Goodrich, A.; Margolis, R.; James, T.; Lokanc, M.; Eggert, R. "Supply-Chain Dynamics of Te, In, and Ga Within the Context of PV Module Manufacturing Costs," accepted by *The Journal of Photovoltaics.*

Potential improvements in the material intensity for each element leads to an ability to absorb potential price increases

BEST-CASE MATERIAL INTENSITIES FOR THESE ENERGY CRITICAL ELEMENTS, AND COST CALCULATIONS WITH 2012 METAL PRICES								
Element A of interest	d	ρ ($g \cdot cm^{-3}$)	X_A	η ($W \cdot m^{-2}$)	U_A ($R_A = 0$)	**I_A (MT/ GW)**	C_{A+T} (With 2012 P_A & T)	Byproduct Material Constraint (At 2011 Primary Production)
Te in CdTe	1.0 µm	5.85	0.53	180	1.0	**17**	**$0.0083/ W**	**35 GW**
In in CIGS	1.0 µm	5.75	≈ 0.22	200	1.0	**6.3**	**$0.0049/ W**	**103 GW**
Ga in CIGS	1.0 µm	5.75	≈ 0.07	200	1.0	**2.0**	**$0.0013/ W**	**150 GW**
Ga in Single-Junction GaAs (MOCVD)	1.0 µm	5.32	0.48	250	1.0	**10.**	**$0.041/ W**	**30 GW**
Ga in Single-Junction GaAs (HVPE)	1.0 µm	5.32	0.48	250	1.0	**10.**	**$0.005/ W**	**30 GW**

Estimated 2011 Material Supply Base

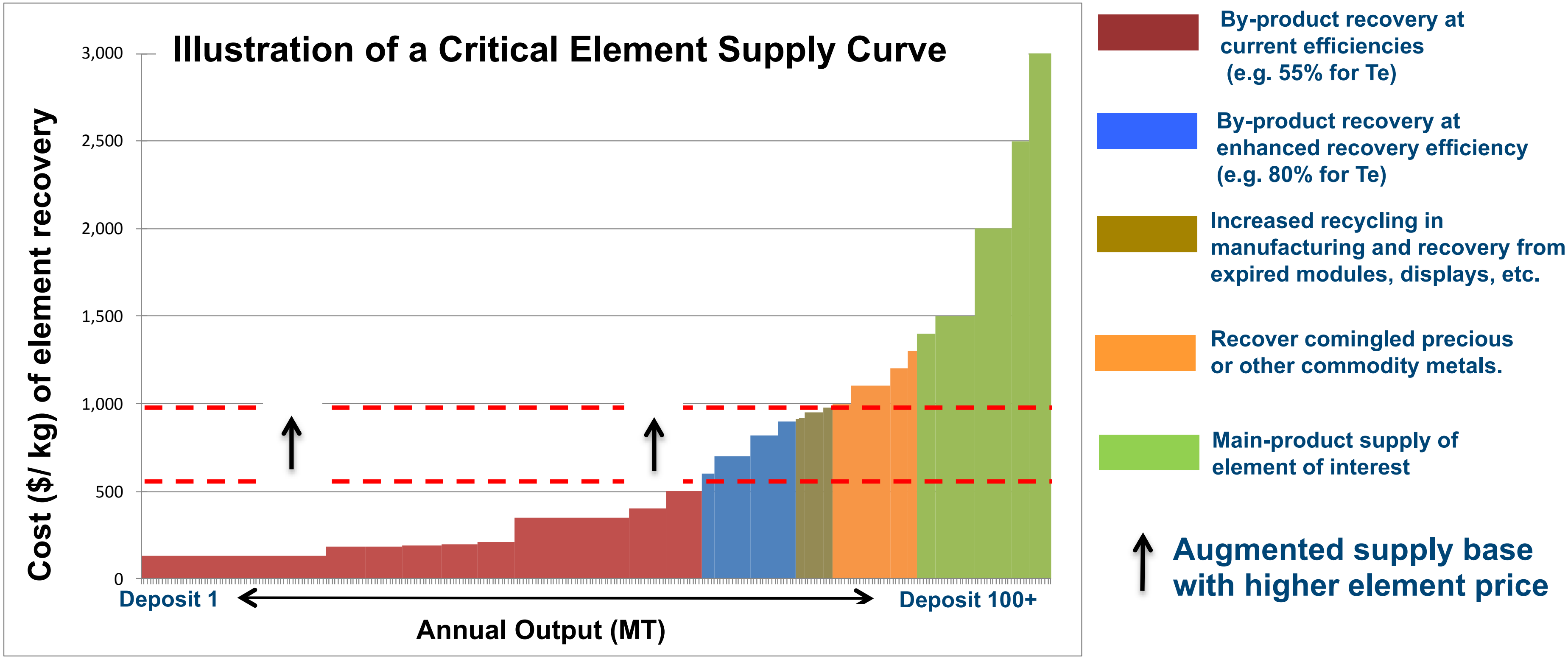
(Primary annual production levels from byproduct recovery, predominantly Cu (Te), Zn (In), and Bauxite (Ga) mining)

Tellurium: 500 - 600 MT [8], Indium: 550 – 650 MT [20, 21], Gallium: 250 - 300 MT [22, 23]

Notes:

CdTe and CIGS assumptions are based upon predicted full-potential module efficiencies and active layer thicknesses, for the case of single-junction polycrystalline modules in average commercial production.

The fundamental supply question for these energy-critical elements



$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A}[1 - R_A]$$

$$C_{A+T}(\$/W_p) = \frac{I_A}{10^6}\left[\frac{P_A + T \pm (R_A \times RV_A)}{X_Y(1 - R_A)}\right]$$

From Woodhouse, M.; Goodrich, A.; Margolis, R. James, T.; Lokanc, M.; Eggert, R. "Supply-Chain Dynamics of Te, In, and Ga Within the Context of PV Module Manufacturing Costs," accepted by *The Journal of Photovoltaics.*

Concluding Thoughts

[1] At present recovery efficiencies, the primary production of Tellurium from Copper, Indium from Zinc, and Gallium from bauxite is not enough to support energy-significant levels of PV.

[2] At metal prices typical for 2011, the contribution of each critical element to total module manufacturing costs would have been tractable.

[3] With improvements in the net material intensity, there is also the potential for these PV technologies to absorb even higher element prices—perhaps even up to an order of magnitude for each.

[4] The ability to absorb such potential price increases leads to the possibility of an augmented supply base for each element.

[5] To avert potentially debilitating increases in the price for any mineral resource, TIMING IS OF THE ESSENCE, and so it will be advantageous to GET ENGAGED EARLY.

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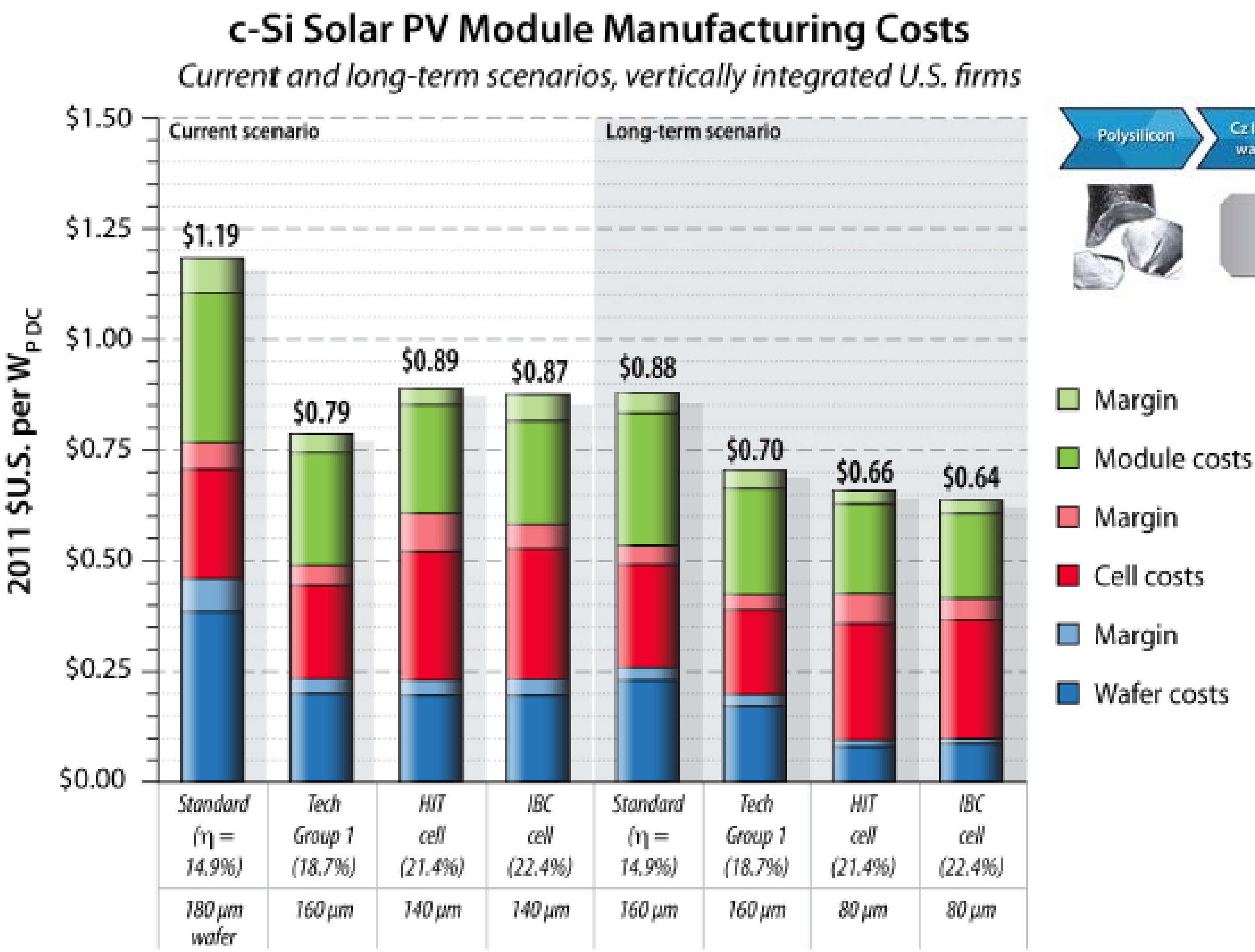
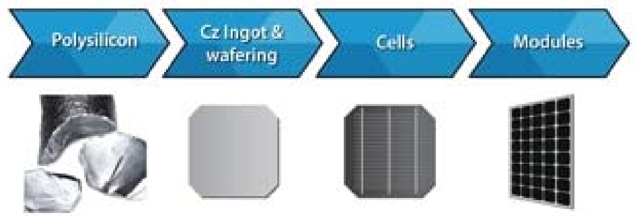
References

[1] K. Zweibel, The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics, Science, 328 (2010) 699-701.
[2] A. Gupta, V. Parikh, A.D. Compaan, High Efficiency Ultra-Thin Sputtered CdTe Solar Cells, Solar Energy Materials and Solar Cells, 90 (2006) 2263-2271.
[3] CRC Handbook of Chemistry and Physics, CRC Press, Boca Raton, FL, 1986.
[4] M.A. Green, K. Emery, et. al., Solar Cell Efficiency Tables, Progress in photovoltaics: research and applications, 19 (2011) 565-572.
[5] V Fthenakis, Long-term estimates of primary and secondary sources of thin-film PV materials: recycling and sustainability of PV, Presentation at the 35th IEEE PVSC, (2010) Slide 6.
[6] Representative 2011 price from:http://www.metal-pages.com/metals/tellurium/metal-prices-news-information/.
[7] Private conversation with a major CdTe material supplier, on the condition of anonymity. September 2011.
[8] M. Woodhouse, A. Goodrich, R. Margolis, T. James, R.Dhere, T. Gessert, T. Barnes, R. Eggert, D. Albin, Perspectives on the Pathways for Cadmium Telluride Photovoltaic Module Manufacturers to Address Expected Increases in the Price for Tellurium, Sol Energy Materials and Solar Cells, (2012) In press
[9] W.N. Shafarman, L. Stolt, Cu(InGa)Se_2 Solar Cells, in: Handbook of photovoltaic science and engineering, A. Luque, S. Hegedus (Eds.) John Wiley & Sons, Ltd, West Sussex, England, 2003.
[10] D. Suri, K. Nagpal, G. Chadha, Journal of Applied Cystallography, 22 (1989) 578.
[11] R. Kamada, W.N. Shafarman, R.W. Birkmire, Cu(In,Ga)Se_2 film formation from selenization of mixed metal/ metal-selenide precursors, Solar Energy Materials and Solar Cells, 94 (2010) 451-456.
[12] http://www.miasole.com.
[13] Representative 2011 price from: http://www.metal-pages.com/metals/indium/metal-prices-news-information/.
[14] Representative 2011 price from: http://www.metal-pages.com/metals/gallium/metal-prices-news-information/.
[15] G.J. Bauhuis, P. Mulder, E.J. Haverkamp, J.C.C.M. Huijben, J.J. Schermer, 26.1% thin-film GaAs solar cells using epitaxial lift-off, Solar Energy Materials and Solar Cells, 93 (2009) 1488-1491.
[16] A.V. Geelen, P.R. Hageman, G.J. Bauhuis, P.C.v. Rijsingen, P. Schmidt, L.J. Giling, Epitaxial lift-off of GaAs solar cell from a reusable GaAs substrate, Materials Science and Engineering, (1997) 162-171.
[17] J.J. Schermer, G.J. Bauhuis, P. Mulder, E.J. Haverkamp, J.v. Deelen, A.T.J.v. Niftrik, P.K. Larsen, Photo confinement in high-efficiency, thin film III-V solar cells obtained by epitaxial lift-off, Thin Solid Films, (2006) 645-653.
[18] O. Madelung, U. Rossler, M. Schulz, Table showing GaAs Debye temperature, density, heat capacity, and melting point., in Semiconductors: Group IV elements, II-VI and III-V compounds., Springer-Verlag, 2002.
[19] M.A. Green, K. Emery, Y. Hishikawa, W. Warta, E.D. Dunlop, Solar cell efficiency tables, Progress in photovoltaics: research and applications, 20 (2012) 12- 20.
[20] C. Gowans, The Indium Corporation. Indium 101—Earth Abundant Material or Rare? (2010) Available online at: http://blogs.indium.com/blog/carol-gowans/indium-101-earth-abundant-material-or-rare
[21] Minerals Commodity Summary: Indium, US Geological Survey and US Department of the Interior, (2011) Available online at: http://minerals.usgs.gov/minerals/pubs/commodity/indium/
[22] D. Bauer, D. Diamond, J. Li, M. McKittrick, D.Sandalow, P. Telleen, B. Wanner, in, Critical Materials Strategy, U. S. Department of Energy, Washington, DC, 2011. Available online at: http://energy.gov/pi/office-policy-and-international-affairs/downloads/2011-critical-materials-strategy/
[23] Minor Metals: March 2012, The Mining Journal. Available online at: http://www.mining-journal.com/reports/minor-metals-march-2012.
[24] J.C.C. Fan, C.O. Bozler, R.L. Chapman, Simplified fabrication of GaAs homojunction solar cells with increased conversion efficiencies, Applied Physics Letters, 32 (1978) 390-392.
[25] F. Ojebuoboh, First Solar & Supplementing Byproduct Tellurium For the Evolving CdTe Solar Market, in: Presentation to the Denver Mining Club, Denver, CO, August 8, 2011.

Supplemental Slide: The Incumbent PV Technology (c-Si)





Goodrich, A.; Hacke, P.; Wang, Q.; Sopori, B.; Margolis, R.; James, T.; Woodhouse, M. "*A Wafer-Based Monocrystalline Silicon Photovoltaics Road Map: Utilizing Known Technology Improvement Opportunities for Further Reductions in Manufacturing Costs,*" accepted by *Solar Energy Materials and Solar Cells*.

Image Sources

Slide 11

[1] Edwin Drake: http://en.wikipedia.org/wiki/Edwin_Drake

[2] George Bissel: http://www.forbes.com/2009/09/03/oil-daniel-yergin-business-energy-oil.html

[3] Drilling rig in Titusville, PA, owned by the Pennsylvania Rock Oil Company: http://en.wikipedia.org/wiki/File:First_Oil_Well.jpg

Slide 12

[4] M King Hubbert: http://mkinghubbert.wordpress.com

For a history of the development of the global petroleum industry, and additional images, please also read:

Yergin, D. (2009). ***The Prize: The Epic Quest for Oil, Money and Power*****, Free Press, New York.**