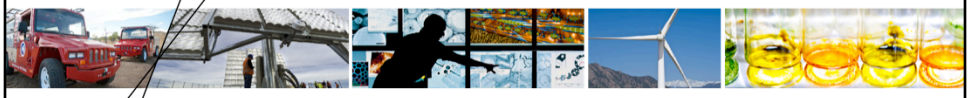
The Present, Mid-Term, and Long-Term Supply Curves for Tellurium; and Updates in the Results from NREL's CdTe PV Module Manufacturing Cost Model



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Motivations and Objectives

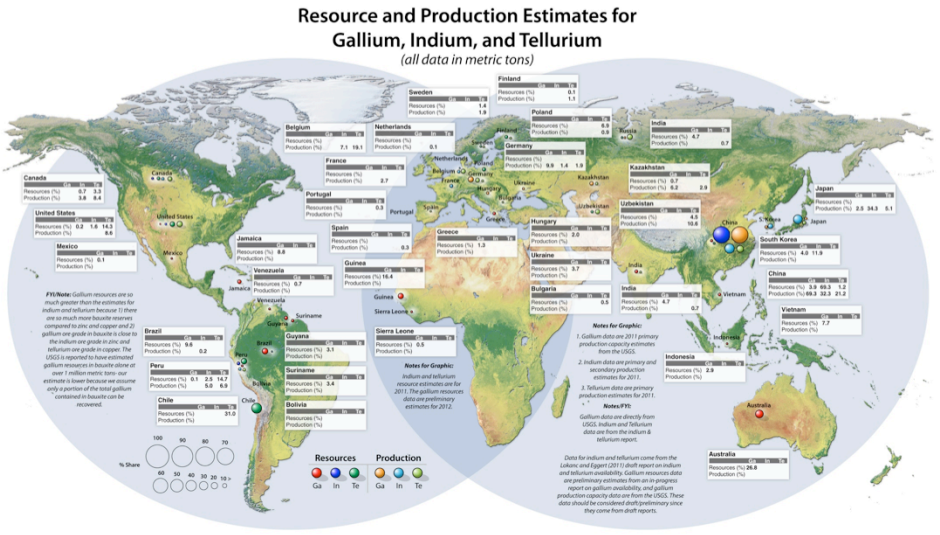
- For those PV technologies that rely upon Te, In, and Ga, first-order observations and calculations hint that there may be resource constraints that could inhibit their successful deployment at a SunShot level.
- These are only first-order approximations, however, and the possibility for an expansion in global Te, In, and Ga supplies needs to be considered in the event that there are upward revisions in their demand and prices.
- It is crucial to establish how potential changes in the price for these critical elements could affect future PV manufacturing costs.

Executive Summary

We examine the current, mid-term, and long-term prospects of Tellurium (Te) for use in PV:

- The current global supply base of Tellurium would support <10 GW of annual traditional CdTe PV manufacturing production.
- The preliminary cumulative availability curves that are compiled here, however, suggest significant upside potential in the supply base for Te—principally *vis a vis* increasing demand and higher prices.
- Without significantly compromising their cost-competitive position within the PV industry, CdTe manufacturers could conceivably afford to pay a much higher future price for Te .
- Primarily by reducing the Tellurium intensity in manufacturing and by increasing the recovery efficiency of Te in Cu refining processes, we calculate that it may prove affordable to PV manufacturers to expand the supply base for Te such that 100 GW, or greater, of annual CdTe PV production is possible in the 2030 – 2050 timeframe.

2012 PV Materials Resource Availability and Production



Source of Figure: NREL and Colorado School of Mines
Note that the percentages for each element do not add up to 100%.
This is because only the top 8 – 20 countries in resources and production are shown for each element.

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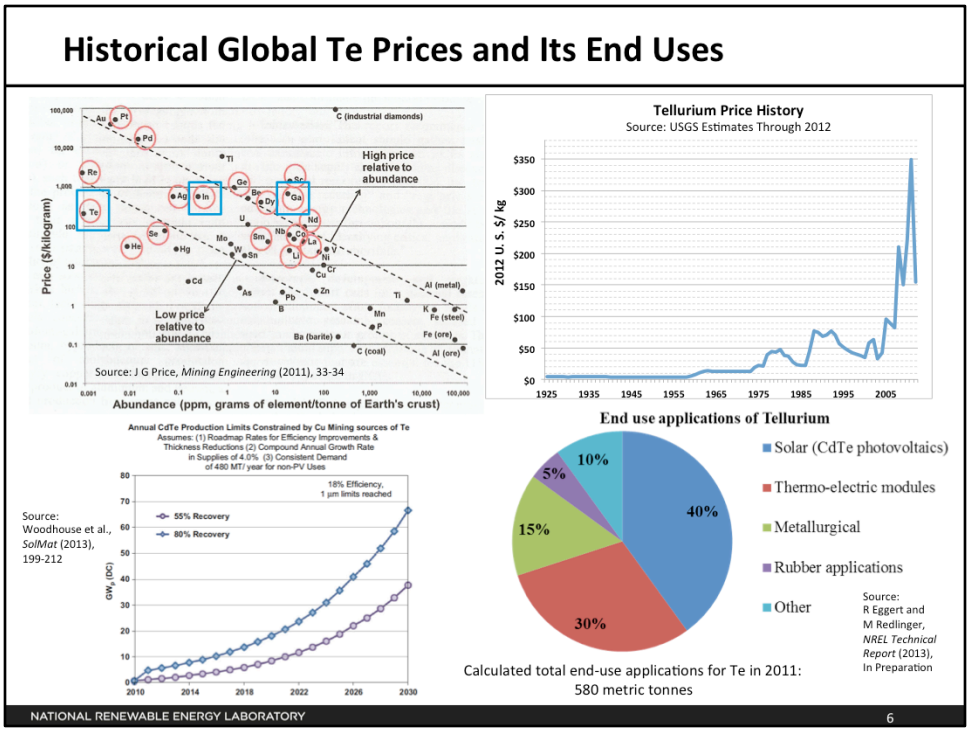
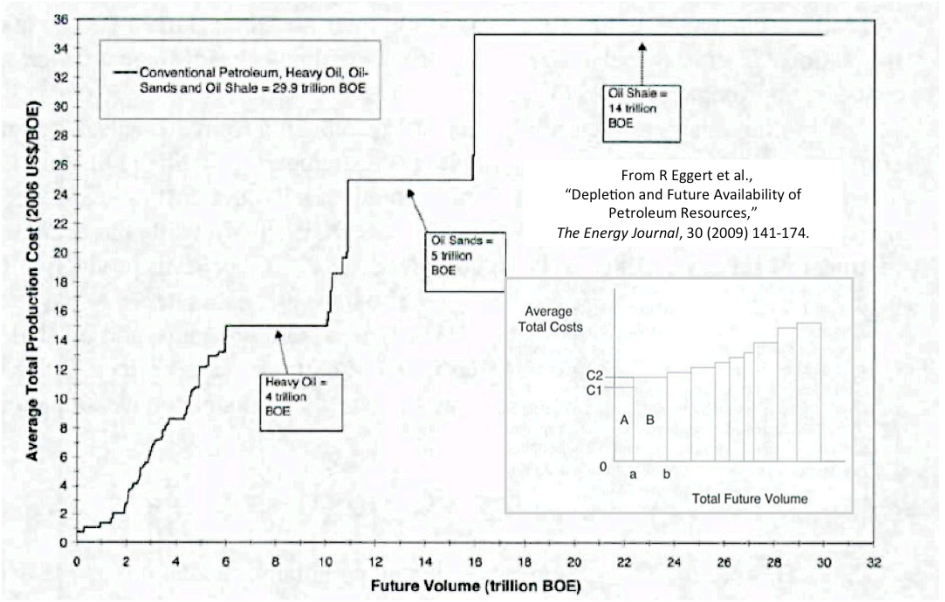
This map shows the global distribution of gallium, indium, and tellurium resources and production. The volume of each sphere represents a country's percent share of either resources or production.

1. Gallium
    a) Resources
        i. The red spheres show that gallium resources are fairly well distributed around the world with no single country holding a dominant share of total resources.
        ii. Total gallium resources for 2012 are estimated to be 543 MT. Australia, Guinea, Brazil, and Jamaica are the largest holders of gallium resources.
    b) Production
        i. The gold spheres show that crude gallium primary production capacity in 2011 is highly concentrated in China, which held 69% of total capacity. This is despite the fact that China is estimated to contain only 4% of total resources.
        ii. Other countries producing crude gallium include Germany, Kazakhstan, South Korea, and others.
2. Indium
    a) Reserves
        i. The dark blue spheres show that indium resources are heavily concentrated in China, which contained about 69% of total resources in 2011.
        ii. Total global indium resources are estimated to be 15,000 MT.
    b) Production
        i. The light blue spheres represent both primary and secondary indium production, and show that Japan and China are the world's major suppliers.
        ii. Total primary and secondary production in 2011 was 1,340 MT.
3. Tellurium
    a) Resources
        i. The green spheres show each country's share of global tellurium resources, which is estimated to be about 24 thousand metric tons in 2011.
        ii. Chile, Peru, and the U.S. have the largest shares of tellurium resources.
    b) Production
        i. The light green spheres show the distribution of refined tellurium production by country.
        ii. China, Belgium, and Uzbekistan, and Russia are the top four producers of tellurium metal with 21%, 19%, 11%, and 10% shares, respectively.



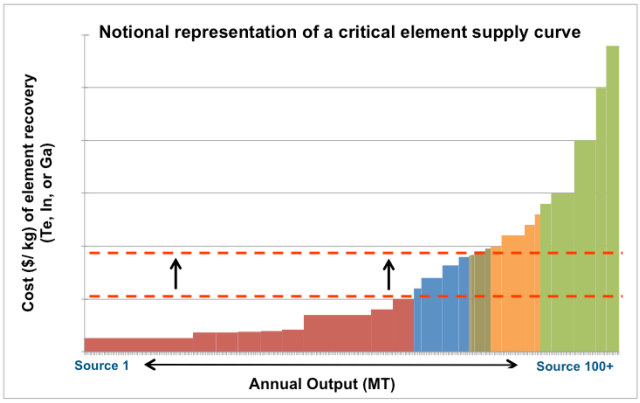
1. The source of the figure in the upper left is J. G. Price, *Mining Engineering* 2011, 33-34.
2. The source of the curve in lower left is Michael Woodhouse, Alan Goodrich, Robert Margolis, Ted L James, Ramesh Dhere, Tim Gessert, Teresa Barnes, Roderick Eggert and David Albin. "Perspectives on the Pathways for CdTe Photovoltaic Module Manufacturers to Address Expected Increases in the Price for Tellurium". *Solar Energy Materials and Solar Cells* 115 (2013) 199 - 212.
3. The price history for Te can be found online: http://minerals.usgs.gov/minerals/pubs/commodity/selenium/. And no, it is not a typo. Tellurium and Selenium are located on the same web page.
4. The pie chart in the lower right is compiled within a developing technical report being written by Professor Eggert's group at the Colorado School of Mines.

Getting to the Fundamental Question: The Production of any Resource Typically Expands with Upward Changes in Demand and Prices



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



By-product recovery at current efficiencies (e.g. 18% net recovery efficiency from mined Cu ores, with 55% recovery efficiency from Cu anode slimes)

By-product recovery at enhanced recovery efficiency (e.g. 80% slime recovery for Te)

Increased recycling in manufacturing and recovery from expired modules, displays, etc. (Secondary Production)

Recover comingled precious or other commodity metals.

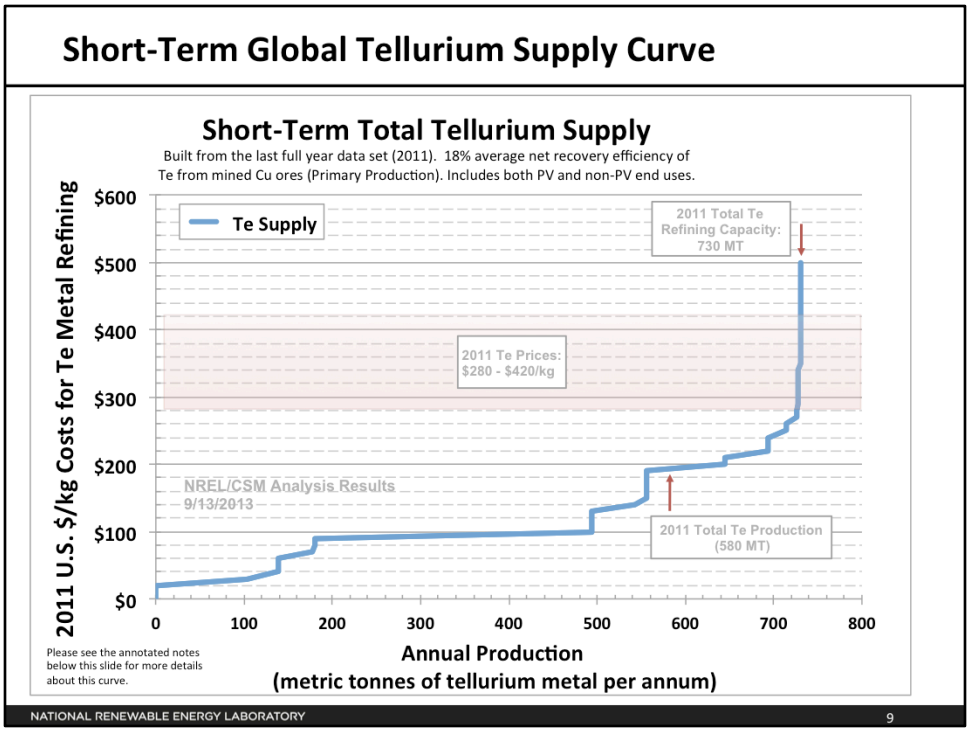
Main-product supply of element (i.e., Direct Mining)

↑ Augmented supply base with higher element price

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

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

From M Woodhouse, A Goodrich, R Margolis, T L James, M Lokanc and R Eggert "Supply-Chain Dynamics of Te, In and Ga Within the Context of PV Module Manufacturing Costs", *IEEE Journal of Photovoltaics* , 3 (2) 833-837



1. The short-term tellurium supply curve shows the annual amount of tellurium (Te) that will be produced at various tellurium price levels. For example, at a price of $100/kg, about 500 tonnes per year will be produced globally.

2. This supply curve shows that in the short term, global tellurium production capacity is about 730 tonnes per year. About 500 tonnes per year of production is possible at a Te price of $100/kg, and about 700 tonnes per year of production is possible at a Te price of around $250/kg.

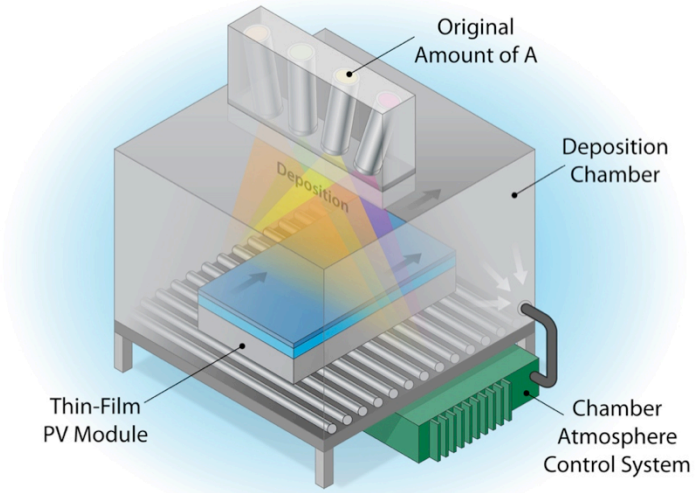
3. This supply curve was derived using the following information:
   a. Public information on the tellurium prices necessary for producers to cover their variable costs (operating costs)
   b. The Te grade of the copper anode slime used by specific facilities to produce tellurium metal
   c. The estimated production capacity of existing tellurium producers

   d. First, the unit cost for a tellurium producer with an estimated Te grade of 2.9% in their copper anode slime is assumed to be $100/kg of Te based on public statements by producers and recent Te prices. Second, data on the Te grade of specific producers is used to estimate their corresponding unit cost (e.g. a producer with a Te grade of 5.8% is expected to have half the unit cost ($50/kg) of a producer with a Te grade of 2.9%). Third, the production capacity for each facility is used to estimate their potential production. Tellurium is primarily produced as a by-product of copper refining and to a lesser extent a by-product of lead.

4. The Dashuigou mine in China is believed to be the only mine currently producing tellurium as a main-product, where tellurium is the primary metal of economic interest. Based on the market prices when interest in developing the Dashuigou mine arose (2008 and 2009), we estimate a variable unit cost of $250/kg of tellurium for this mine.

5. Note that we state an 18% average net recovery efficiency of Te from mined Cu ores. This is not to be confused with the recovery efficiency most typically discussed—the recovery efficiency from Cu anode slime—which is typically cited as being 40-60% efficient.

Factors Influencing the Material Intensity ($I_{A,}$ in MT per GW) of an Element A for Use in PV Manufacturing—1.



Michael Woodhouse, Alan Goodrich, Robert Margolis, Ted L James, Martin Lokanc and Roderick Eggert. "Supply-Chain Dynamics of Tellurium, Indium and Gallium Within the Context of PV Module Manufacturing Costs." *IEEE Journal of Photovoltaics*. (3:2); pp. 833-837.

Factors Influencing the Material Intensity ($I_{A,}$ in MT per GW) of an Element A for Use in PV Manufacturing—2.

Where:

d = Layer thickness (in μm)

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

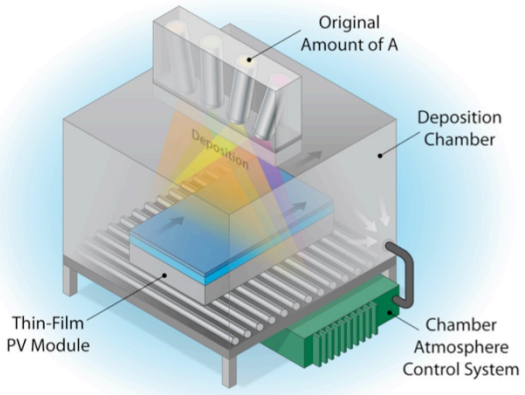
X_A = The mass fraction of element A within the layer

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 deposition onto the module and after the appropriate recovery steps.

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



Michael Woodhouse, Alan Goodrich, Robert Margolis, Ted L James, Martin Lokanc and Roderick Eggert. "Supply-Chain Dynamics of Tellurium, Indium and Gallium Within the Context of PV Module Manufacturing Costs." *IEEE Journal of Photovoltaics*. (3:2); pp. 833-837.

This is more completely described in the peer-reviewed journal article by Michael Woodhouse, Alan Goodrich, Robert Margolis, Ted L James, Martin Lokanc and Roderick Eggert. "Supply-Chain Dynamics of Tellurium, Indium and Gallium Within the Context of PV Module Manufacturing Costs". *IEEE Journal of Photovoltaics*, 3 (2) 833-837.

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 $Ga(CH_3)_3$ in MOVPE)

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).

Michael Woodhouse, Alan Goodrich, Robert Margolis, Ted L James, Martin Lokanc and Roderick Eggert. "Supply-Chain Dynamics of Tellurium, Indium and Gallium Within the Context of PV Module Manufacturing Costs." *IEEE Journal of Photovoltaics*. (3:2); pp. 833-837.

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Using the Material Intensity Concept to Calculate Manufacturing Costs

TABLE I
BEST EFFORTS ANALYSIS OF THE MATERIAL INTENSITY AND COST CONTRIBUTIONS OF THE ENERGY CRITICAL ELEMENTS TELLURIUM, INDIUM, AND GALLIUM. 2012 BASELINE

Element A of interest	d	ρ ($g cm^{-3}$)	X_A	η ($W m^{-2}$)	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
In in CIGS	2.0 μm [8]	5.75 [9]	≈ 0.22[1] [8, 10]	157 [4, 11]	0.55[2] / 0.25	23	P_{In} ≈ \$520/ kg [12] T_{In} ≈ \$100/ kg[3]	\$0.018/ W
Ga in CIGS	2.0 μm [8]	5.75 [9]	≈ 0.07[1] [8, 10]	157 [4, 11]	0.55[2] / 0.25[4]	7.5	P_{Ga} ≈ \$400/ kg [13] T_{Ga} ≈ \$100/ kg[3]	\$0.005/ W
Ga in Single-Junction GaAs (MOCVD)	2.5 μm [14-16]	5.32 [17]	0.48	235 [18]	0.30 / 0.00[5]	91	P_{Ga} ≈ \$400/ kg [13] T_{TMG} ≈ \$2100/ kg[6]	\$0.373/ W
Ga in Single-Junction GaAs (HVPE)	2.5 μm	5.32 [17]	0.48	235[7]	0.30 / 0.00[5]	91	P_{Ga} ≈ \$400/ kg [13] T_{Ga} ≈ \$100/ kg	\$0.046/ W

Estimated 2011 Material Supply Base
(Reported primary annual production levels from byproduct recovery, which is predominantly from Cu (Te), Zn (In), and Bauxite (Ga) mining)

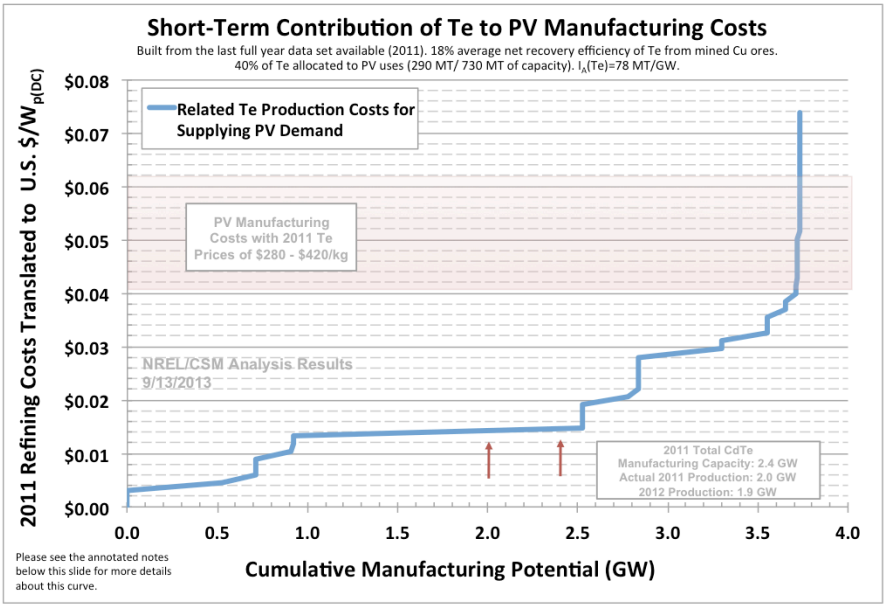
Tellurium: 500 - 600 MT [19], Indium: 550 – 650 MT [20, 21], Gallium: 250 - 300 MT [22, 23]

Michael Woodhouse, Alan Goodrich, Robert Margolis, Ted L James, Martin Lokanc and Roderick Eggert. "Supply-Chain Dynamics of Tellurium, Indium and Gallium Within the Context of PV Module Manufacturing Costs." *IEEE Journal of Photovoltaics*. (3:2); pp. 833-837.

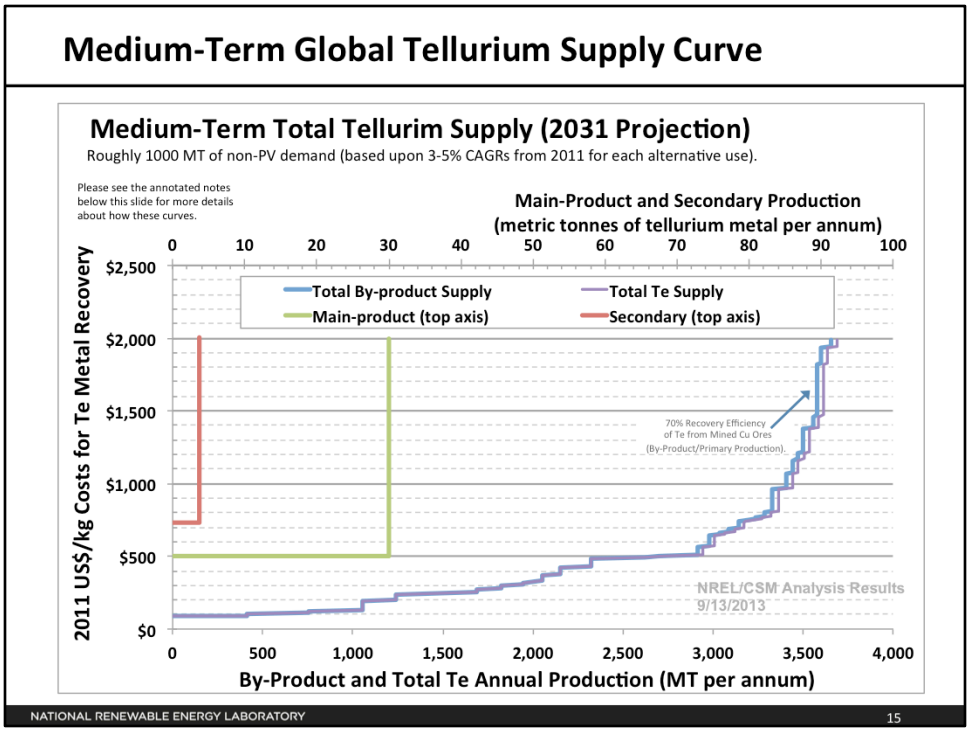
Notes:

1. Please see the later slides for how these I_A and C_{A+T} values might change over time.

Sensitivity of PV Manufacturing Costs and Manufacturing Potential Based upon the Short-Term Global Tellurium Supply Curve



1. This curve is derived from the data and formulas represented in slides 9, 10, 11 and 12. For calculating the material intensity (I_A) and $\$/W_p$ cost, it is assumed that the near-term thickness (d) is **2.5** micron, the Te utilization (U_A) is **70%**, the CdTe density is **6.20** $g \cdot cm^{-3}$, the recovery of Te in manufacturing (R_A) is **20%**, X_A = **0.53**, and the sunlight power conversion efficiency is **12**%. This gives a calculated I_A of 78 MT/GW.
2. One could use this I_A to translate the curves on slide 9 to the manufacturing potential that is represented above. Remember to include the non-PV demand for Te as well (we calculate a 60% demand share for Te in 2013 for the non-PV uses**).**
3. The tolling charge (T) is not included because these costs are for the Te contribution only.
4. The source of CdTe manufacturing capacity estimates and commercial production average efficiencies: M Ahearn, M Widmar, and D Brady 'First Solar 2012 Guidance' (Presentation from First Solar); and "First Solar to Boost Production as Profit, Sales Climb," *Wall Street Journal,* August 1, 2012. Available online at: http:// sec.online.wsj.com/article/BT-CO-20120801-722119.html?mod=crnews.
5. Note that we state an 18% average net recovery efficiency of Te from mined Cu ores. This is not to be confused with the recovery efficiency most typically discussed—the recovery efficiency from Cu anode slime—which is typically cited as being more in the 40-60% range.



1. The medium-term tellurium supply curve shows the annual amount of tellurium (Te) that might be produced at various price levels in 2031.

2. This supply curve shows that in the medium term, global tellurium production could reach over 3,500 tonnes per year. At price levels of $350, $600, and $1,200, the corresponding annual Te production levels are about 2,000, 3,000, and 3,500 tonnes, respectively.

3. Total tellurium supply in 2031 will come from three principal sources:
    a. By-product supply associated with copper production
    b. Main-product supply from mines where Te is the mineral of primary economic interest
    c. Secondary supply from recycled CdTe solar panels

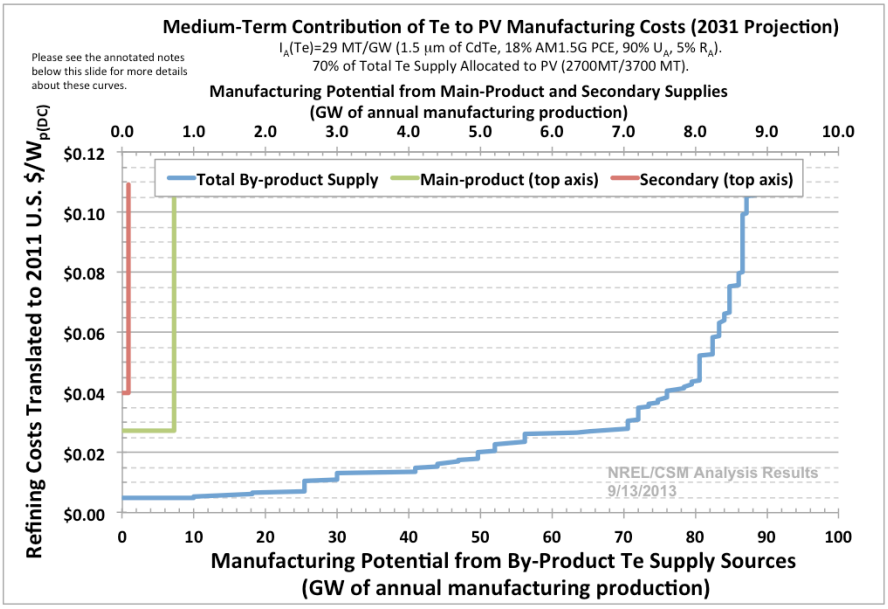
    d. We expect by-product supply to be the dominant source of supply in 2031 with main-product and secondary supply making up only a minor share of total supply.

4. The by-product supply curve is similar to the short-term supply curve with three modifications:
    a. Capital cost are included in the total tellurium production cost in addition to the variable cost (or operating cost) included in the short-term supply curve. Capital cost estimates are based on public information of the capital investments made for existing tellurium recovery facilities.
    b. Tellurium recovery efficiencies are improved based on recent technologies and better recovery throughout the tellurium supply chain. Currently, only 10-30% of mined tellurium is recovered as refined Te metal. With adoption of new technologies and minimizing tellurium losses, recovery could reach 70%.
    c. Growth in copper production will allow for more tellurium to be potentially recovered in 2031. We estimate a range of annual growth in copper production of 0.8% to 3.0% with a base case of 2.6%.

5. The main-product supply curve is derived using estimates of the potential annual production and production costs of three main-product tellurium mines: Dashuigou and Majiugou in China (Apollo Solar) and La Bambolla in Mexico (Minera Teloro). A minimum Te price of $500/kg to economically develop these projects is estimated by UK Energy Research Centre (2013).

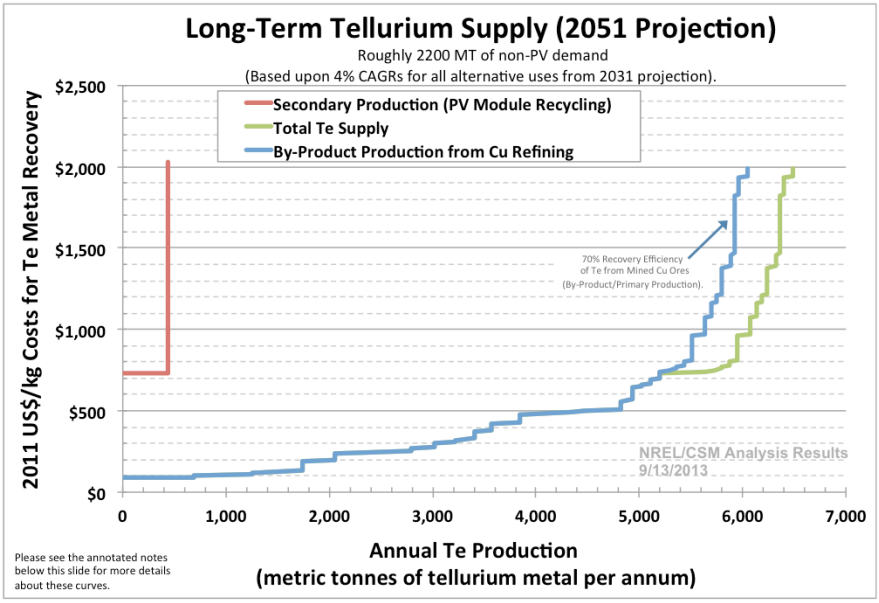
6. The secondary supply curve is derived from estimates of the cost of recovering tellurium from recycled CdTe solar panels, the tellurium

Sensitivity of PV Manufacturing Costs and Manufacturing Potential Based upon the Medium-Term Global Tellurium Supply Curve



1. This curve is derived from the data and formulas represented in slides 10, 11, 12 and 15. For calculating the material intensity (I_A) and \$/W_p cost, it is assumed that the medium-term thickness (d) is **1.5** micron, the Te utilization (U_A) is **90%**, the CdTe density is **6.20** g·cm^{-3}, the recovery of Te in manufacturing (R_A) is **5%**, X_A = **0.53**, and the sunlight power conversion efficiency is **18**%. This gives a calculated I_A of 29 MT/GW.
2. One could compare this I_A to the curves on slide 14 to verify the manufacturing potential that is represented. Remember to include the non-PV demand for Te as well (we calculate a 30% demand share in 2031 for the non-PV uses with 3-5% CAGRs for those alternative uses). By category, the assumed CAGRs were: Thermoelectrics (**5.0%**) Metallurgy (**3.0%)** and Chemicals (**3.0%).**
3. The tolling Charge (T) is not included because these costs are for the Te contribution only.

Long-Term Global Tellurium Supply Curve



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1. The long-term tellurium supply curve shows the annual amount of tellurium that might be produced at various price levels in 2051.

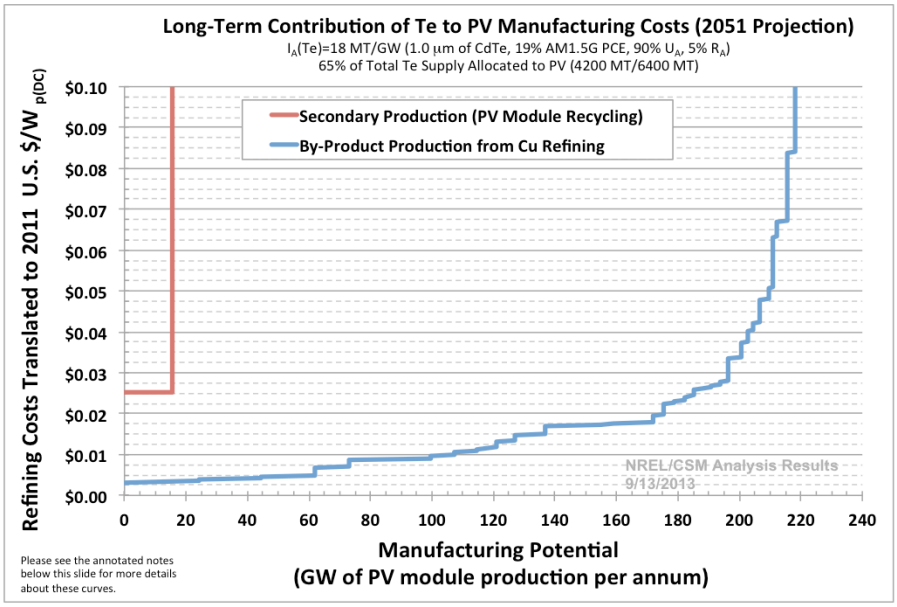
2. This supply curve shows that, in the long term, global tellurium production could reach over 6,500 tonnes per year. At price levels of $200, $500, and $1,000, the corresponding annual Te production levels are about 2,000, 4,500, and 6,000 tonnes, respectively.

3. Total tellurium supply in 2051 could come from three principal sources:
   a. By-product supply associated with copper production
   b. Main-product supply from mines where Te is the metal of primary economic interest
   c. Secondary supply from recycled CdTe solar panels

4. We expect by-product supply to be the dominant source of supply in 2051 with secondary production having the potential to contribute a sizable share of total production. There is insufficient information on potential main-product production over the long term to include it in the long-term supply curve.

5. The long-term supply curves are similar to the medium-term supply curves with exception that supply is estimated for the year 2051 rather than 2031. We expect that in 2051, greater copper production and recycled CdTe solar panels will allow for more tellurium production.

Sensitivity of PV Manufacturing Costs and Manufacturing Potential Based Upon the Long-Term Global Tellurium Supply Curve



1. This curve is derived from the data and formulas represented in slides 10, 11,12 and 17. For calculating the material intensity (I_A) and $\$/W_p$ cost, it is assumed that the long-term thickness (d) is **1.0** micron, the Te utilization (U_A) is **90%**, the CdTe density is **6.20** $g \cdot cm^{-3}$, the recovery of Te in manufacturing (R_A) is **5%**, X_A = **0.53**, and the sunlight power conversion efficiency is **19**%. This gives a calculated I_A of 18 MT/GW.
2. One could compare this I_A to the curves on slide 16 to verify the manufacturing potential that is represented. Remember to include the non-PV demand for Te as well (we calculated a 35% demand share in 2051 when assuming 4% CAGR in non-PV demand growth from the mid-term, 2031, projection).
3. The tolling Charge (T) is not included because these costs are for the Te contribution only.

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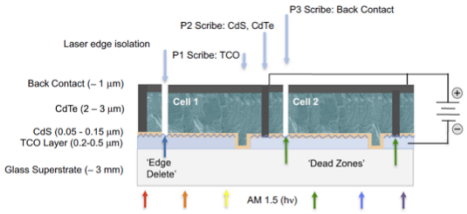
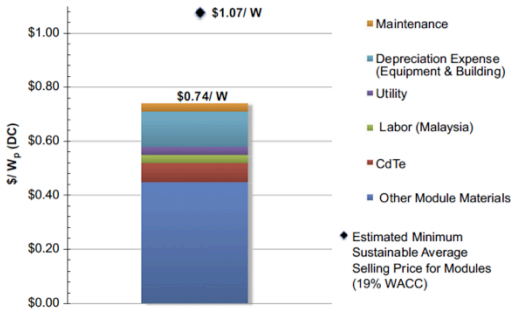
Updates in the Results from NREL's CdTe PV Module Manufacturing Cost Model

Benchmark and Modeled Costs for CdTe
(First Version Based Upon 2011/ 1H 2012 Efficiencies, CapEx, etc.)



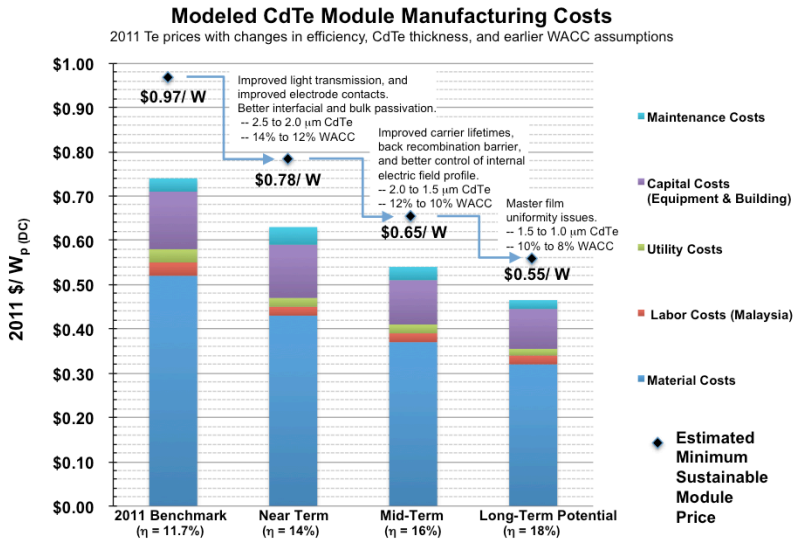
Cost Model Results for CdTe Module Manufacturing
η = 11.7%, 2.5µm CdTe, Malaysian Production Location



Michael Woodhouse, Alan Goodrich, Robert Margolis, Ted L James, Ramesh Dhere, Tim Gessert, Teresa Barnes, Roderick Eggert and David Albin. "Perspectives on the Pathways for CdTe Photovoltaic Module Manufacturers to Address Expected Increases in the Price for Tellurium". *Solar Energy Materials and Solar Cells* 115 (2013) 199 - 212.

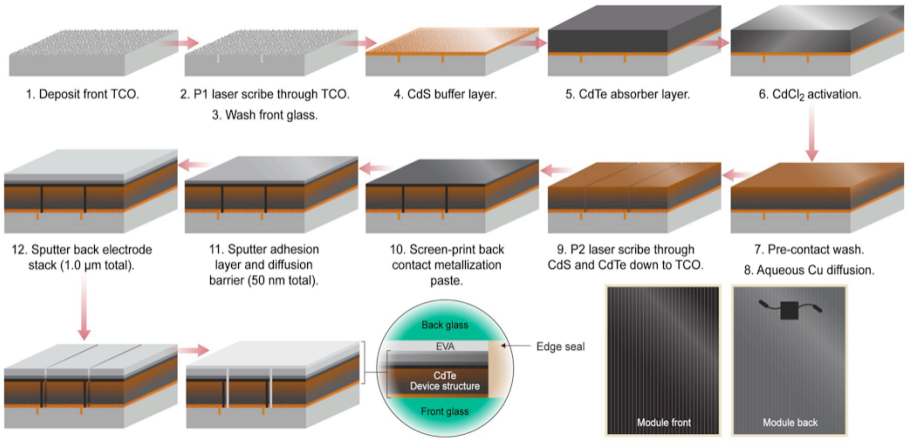
Benchmark and Modeled Costs for CdTe

(First Version Based Upon 2011/ 1H 2012 Efficiencies, CapEx, etc.)



Michael Woodhouse, Alan Goodrich, Robert Margolis, Ted L James, Ramesh Dhere, Tim Gessert, Teresa Barnes, Roderick Eggert and David Albin. "Perspectives on the Pathways for CdTe Photovoltaic Module Manufacturers to Address Expected Increases in the Price for Tellurium". *Solar Energy Materials and Solar Cells* 115 (2013) 199 - 212.

Benchmark and Modeled Costs for CdTe: The Process Flow Assumed for the Cost Model



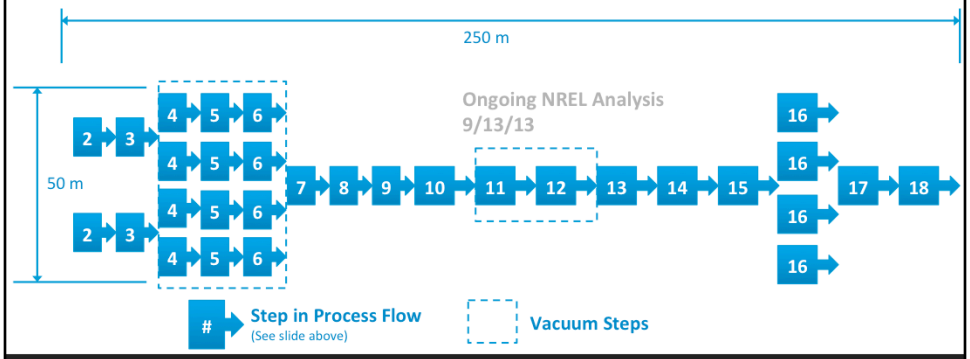
Ongoing NREL Analysis
9/13/2013

The Factory Layout Assumed for the Cost Model

Module Efficiency	Annual Line Run Rate	Source
11.6%	62.6 MW	FSLR Q4 2010 Earnings Call
13%	70.6 MW	Calculation for 2013
15%	81.5 MW	Calculation for 2014
17%	92.3 MW	Calculation for 2016/17
19%	103 MW	Calculation for Long-Term

Steps	Total Average Cycle (TACT) Time (350 days/yr, 24 hr/day, 0.72 m² modules, total times include availability/maintenance considerations)
2 & 3	1.35 min/module
4, 5, 6 & 16	2.69 min/ module
7-15, 17 & 18	0.673 min/module

Reported 'CapEx' at 11.6% efficiency ≈$1.2/W



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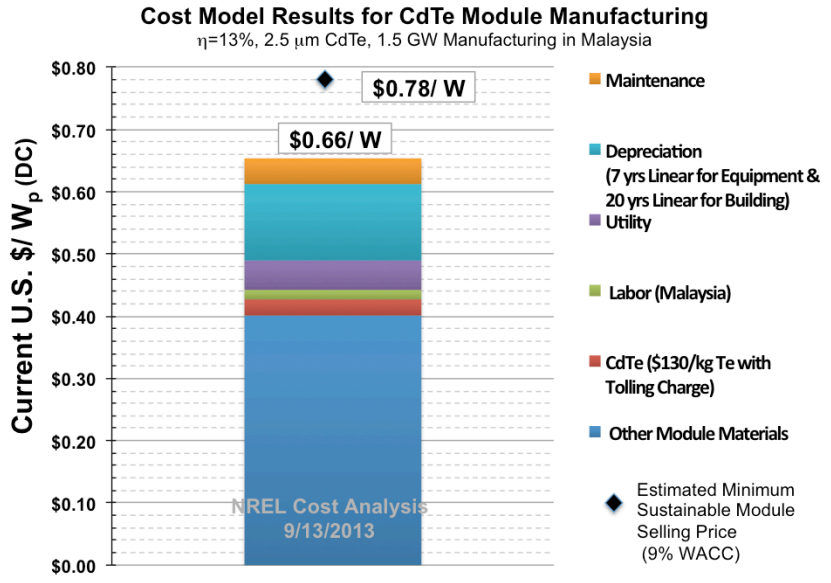
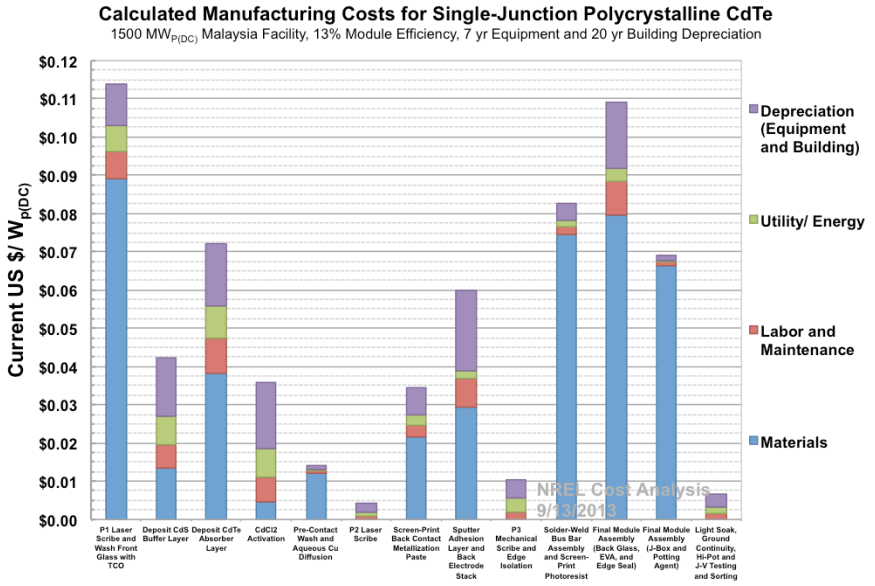
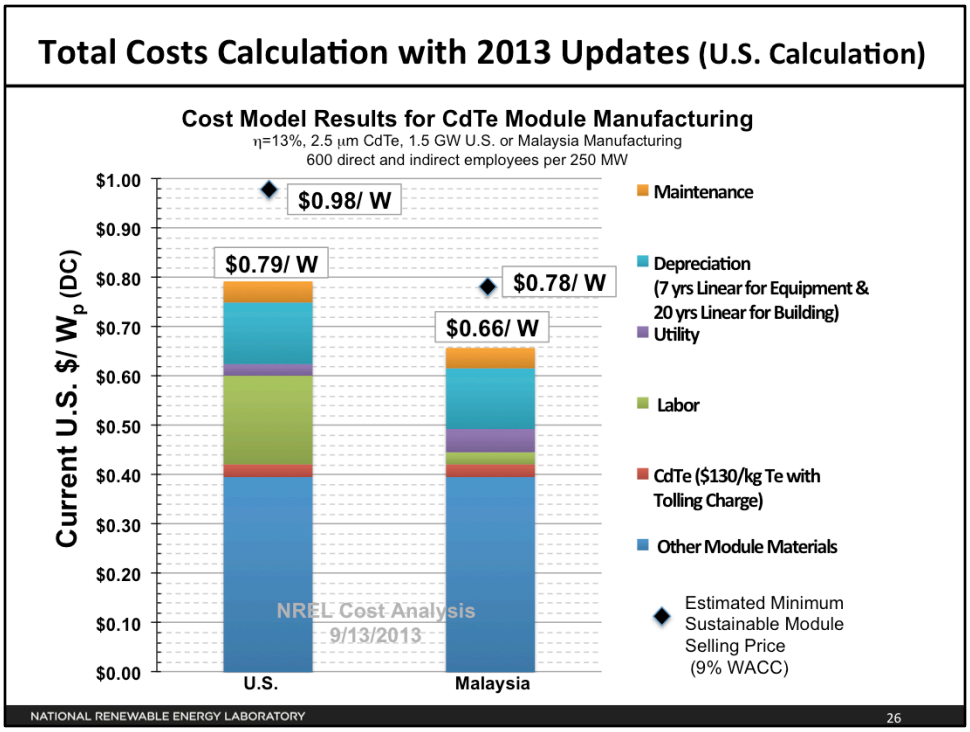
Total Costs Calculation with 2013 Updates



Breakdown of Calculated Costs by Step (2013 Benchmark)





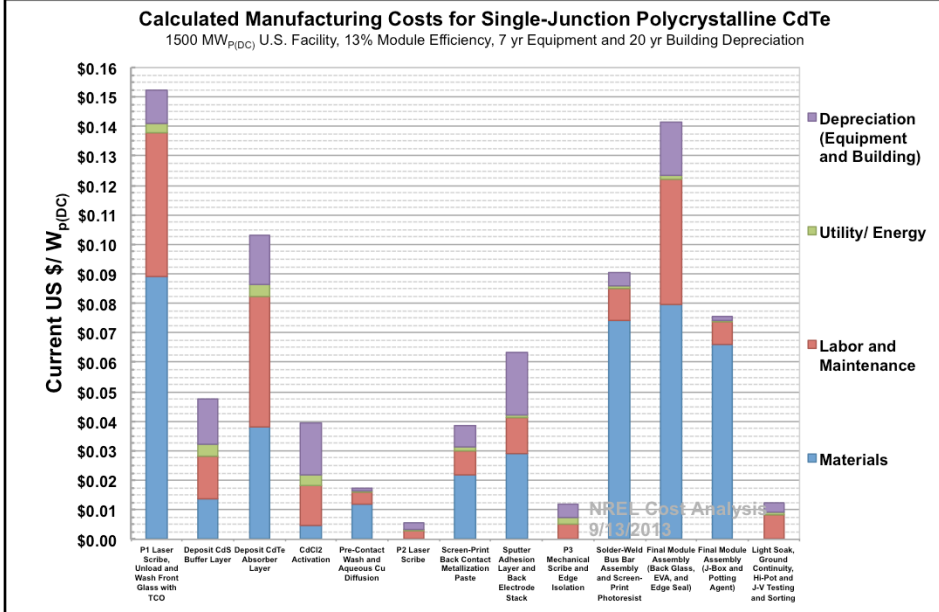
As the reader will notice, the major cost difference between the U.S. and Malaysia production locations is the labor costs. As the basis of our calculated manufacturing costs, we assume 600 direct and indirect employees per 250 MW (at 11.6% efficiency and 63 MW line run rates) for both U.S. and Asian manufacturing locationss. This assumption is largely based upon the following press releases:

http://www.pv-tech.org/news
first_solar_breaks_ground_on_its_pv_module_manufacturing_plant_in_vietnam

and

http://www.pv-tech.org/news/print/
made_in_the_usa_first_solar_selects_mesa_az_as_site_for_second_domestic_pv

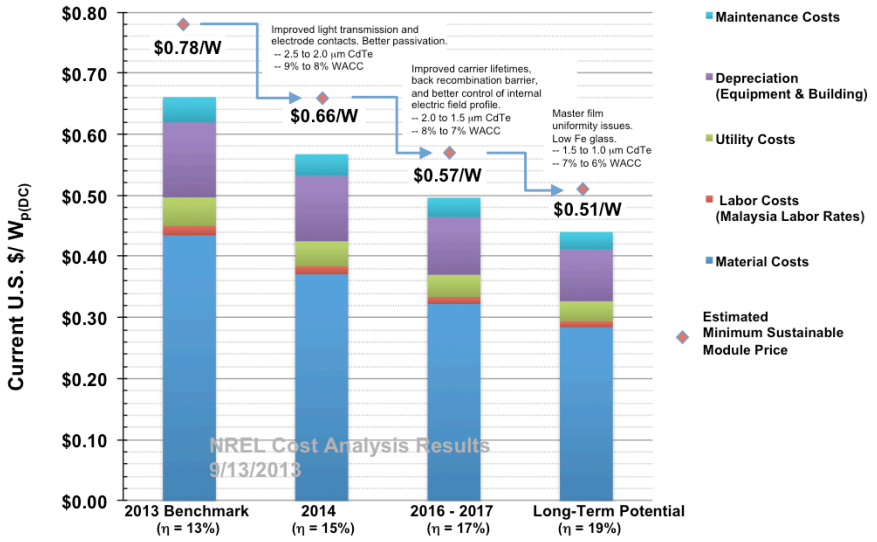
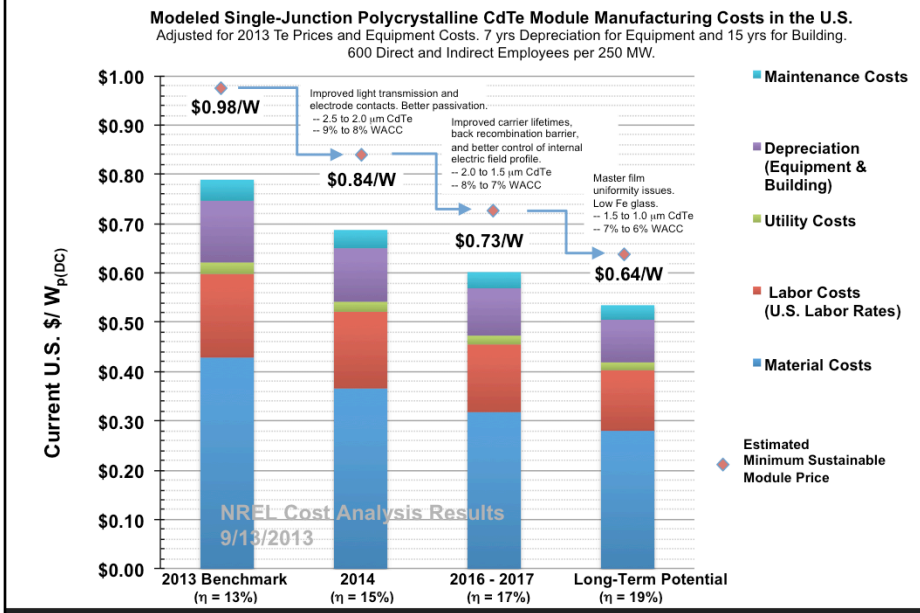
Breakdown of Calculated Costs by Step (2013 Benchmark, U.S. Calculation)



Projected Module Costs: Updates to Our Model Results

Modeled Single-Junction Polycrystalline CdTe Module Manufacturing Costs

Adjusted for 2013 Te Prices and Equipment Costs. 7 yrs Depreciation for Equipment and 15 yrs for Building.



Projected Module Costs: Model Results for U.S. Production