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

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Recent Publications on This Topic

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 Woodhouse1, Alan Goodrich1, Robert Margolis1, Ted L James1, Martin Lokane2, and Roderick Eggert2

Proceedings of the 2012 IEEE Photovoltaics Specialist Conference, and corresponding 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?

Where:
- $d$ = Layer thickness (in $\mu$m)
- $\rho$ = Layer density (in g·cm$^{-3}$)
- $X_A$ = The mass fraction of element A within the layer
- $\eta$ = 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.

$$I_A = \frac{d \times \rho \times X_A}{10^{-3} \times \eta \times U_A} \left[1 - R_A\right]$$
KAP2  Looks like a couple of the symbols on the left are jumbled because of the PC/Mac confusion.
Kendra, 10/19/2012

KAP3  Changed font to Calibri. Minor punctuation changes.
Kendra, 10/19/2012

KAP26 I'd recommend shorter, more general slide titles-- less like a sentence. Then almost all the words are capped in the title, and more information from the title can be put into the slide text.
Kendra, 10/19/2012
The sensitivity of PV module manufacturing costs to the price for the element’s precursor

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

\[P_A = \text{Price of the element at a standard grade of purity (}/ \text{kg})\]

\[T = \text{Tolling charge to refine the element to ‘solar grade’, and to meld it into its appropriate precursor for manufacturing (}/ \text{kg})\]

\[X_Y = \text{Weight percentage of A in the precursor compound (0.53 for CdTe, 1 for In and Ga in CIGS, 0.61 for Ga(CH}_3)_3)\]

\[R_A = \text{Net recovery fraction of A from the manufacturing line, after the appropriate deposition and recovery processes}\]

\[R_{VA} = \text{Recovery value of A (}/ \text{kg}).\]
Tellurium in Single-Junction Polycrystalline CdTe

### BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY FOR TELLURIUM IN CdTe. 2011 BASELINE.

<table>
<thead>
<tr>
<th>Element A of interest</th>
<th>d (μm)</th>
<th>ρ (g/cm³)</th>
<th>X₂</th>
<th>η (W/m²)</th>
<th>Uₐ (MT/GW)</th>
<th>Pₐ &amp; T</th>
<th>Cₐ+T</th>
</tr>
</thead>
</table>

### 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.

The material constraint if relying upon byproduct recovery at present efficiencies

≈ 600/69

9 GW

\[ Iₐ = \frac{d \times \rho \times X₂}{10^{-3} \times \eta \times Uₐ} \left[ 1 - Rₐ \right] \]

\[ Cₐ+T ($/W_p) = \frac{Iₐ}{10^6} \left[ \frac{Pₐ + T \pm (Rₐ \times R_{VA})}{Xₐ (1 - Rₐ)} \right] \]

Cost Model Results for CdTe Module Manufacturing

\[ \eta = 11.7\% , 2.5μm CdTe, Malaysian Production Location \]

Cost: $1.07/W

$0.74/W

$0.60/W

$0.40/W

$0.20/W

$0.00/W

AM 1.5 (hν)

Maintenance
Depreciation Expense (Equipment & Building)
Utility
Labor (Malaysia)
CdTe
Other Module Materials
Estimated Minimum Sustainable Average Selling Price for Modules (19% WACC)
### BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY FOR INDIUM IN CIGS. 2011 BASELINE.

| Element A of interest | d (µm) | ρ (g cm⁻³) | Xₐ | η (W m⁻²) | Uₐ | Iₐ (MT/GW) | Pₐ & T | Cₐ+T
|-----------------------|--------|------------|-----|------------|-----|------------|--------|--------
| In in CIGS            | 2.0    | 5.75       | ≈ 0.22¹ | 157        | 0.55² | 23         | $750/kg | $0.024/ W |

#### Estimated 2011 Material Supply Base for Indium

Primary annual production from Zn byproduct recovery

\[
Iₐ = \frac{d \times ρ \times Xₐ}{10^{-3} \times η \times Uₐ} [1 - Rₐ] 
\]

550 - 650 MT [20, 21]

Notes and References:

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.
Indium in Cu[In_{(1-x)Ga_x}ySe_2, or ‘CIGS’

### BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY FOR
INDIUM IN CIGS. 2011 BASELINE.

<table>
<thead>
<tr>
<th>Element A of interest</th>
<th>d (µm)</th>
<th>ρ (g cm(^{-3}))</th>
<th>X(_A)</th>
<th>η (W m(^{-2}))</th>
<th>U(_A)</th>
<th>R(_A)</th>
<th>I(_A) (MT/GW)</th>
<th>P(_A) &amp; T</th>
<th>C(_{A+T})</th>
</tr>
</thead>
<tbody>
<tr>
<td>In in CIGS</td>
<td>2.0</td>
<td>5.75</td>
<td>≈ 0.22</td>
<td>157</td>
<td>0.55</td>
<td>0.20</td>
<td>23</td>
<td>≈ $750/ kg</td>
<td>$0.024/ W</td>
</tr>
</tbody>
</table>

**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]

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.

Material constraint if relying upon byproduct recovery at present efficiencies

≈ 650/ 23

28 GW
## BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY AND COST FOR GALLIUM IN CIGS. 2011 BASELINE.

<table>
<thead>
<tr>
<th>Element A of interest</th>
<th>d (µm)</th>
<th>ρ (g cm⁻³)</th>
<th>η (Wm⁻²)</th>
<th>Uₐ</th>
<th>RA</th>
<th>IA (MT/GW)</th>
<th>PA &amp; T</th>
<th>CA+T ($/Wp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In in CIGS</td>
<td>2.0</td>
<td>5.75</td>
<td>≈ 0.07¹</td>
<td>157</td>
<td>0.55²</td>
<td>7.5</td>
<td>0.20⁴</td>
<td>$0.009/ W</td>
</tr>
</tbody>
</table>

### 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]  

\[
C_{A+T} ($/Wp) = \frac{I_A \pm (P_A \times RV_A)}{X_Y (1 - R_A)}
\]

Notes and References:

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.

---

1. [9]
2. [10]
4. [12]
5. [14]
**BEST-EFFORTS ANALYSIS OF THE MATERIAL INTENSITY AND COST FOR GALLIUM IN CIGS. 2011 BASELINE.**

<table>
<thead>
<tr>
<th>Element A of interest</th>
<th>$d$ (µm)</th>
<th>$\rho$ (g cm$^{-3}$)</th>
<th>$X_A$</th>
<th>$\eta$ (W m$^{-2}$)</th>
<th>$U_A$</th>
<th>$I_A$ (MT/GW)</th>
<th>$P_A &amp; T$</th>
<th>$C_{A+T}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>In in CIGS</td>
<td>2.0</td>
<td>5.75</td>
<td>$\approx 0.07^1$</td>
<td>157$^2$</td>
<td>0.55$^3$</td>
<td>7.5</td>
<td>$P_{Ga}$ ≈ $900/\text{kg}$</td>
<td>$T_{In}$ ≈ $100/\text{kg}^3$</td>
</tr>
</tbody>
</table>

**Estimated 2011 Material Supply Base for Gallium**

Primary annual production from Bauxite (Al) byproduct recovery

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

250 – 300 MT [22, 23]

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

Notes and References:

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 used 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.

Material constraint if relying upon byproduct recovery at present efficiencies

$$\approx 300/7.5$$

**40 GW**
# Gallium in Single-Junction GaAs

## Best-Efforts Analysis of the Material Intensity and Cost Contributions for Gallium in Single-Junction GaAs. 2011 Baseline.

<table>
<thead>
<tr>
<th>Element A of interest</th>
<th>(d) ((\mu)m)</th>
<th>(\rho) (g cm(^{-3}))</th>
<th>(X_A)</th>
<th>(\eta) (Wm(^{-2}))</th>
<th>(U_A)</th>
<th>(I_A) (MT/GW)</th>
<th>(P_A &amp; T)</th>
<th>(C_{A+T})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga in Single-Junction GaAs (MOCVD)</td>
<td>2.5</td>
<td>5.32</td>
<td>0.48</td>
<td>235</td>
<td>0.30</td>
<td>91</td>
<td>(\approx $900/\text{kg})</td>
<td>(\approx $1600/\text{kg})</td>
</tr>
<tr>
<td>Ga in Single-Junction GaAs (HVPE)</td>
<td>2.5</td>
<td>5.32</td>
<td>0.48</td>
<td>235(^7)</td>
<td>0.30</td>
<td>91</td>
<td>(\approx $900/\text{kg})</td>
<td>(\approx $100/\text{kg})</td>
</tr>
</tbody>
</table>

### 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]

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

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.
- 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.
- Estimated price of around $2500/ kg for large volume purchasing contracts of Ga(CH\(_3\))\(_3\), provided by a relevant major supplier.
- 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. 2011 BASELINE.

<table>
<thead>
<tr>
<th>Element A of interest</th>
<th>d (μm)</th>
<th>ρ (g cm⁻³)</th>
<th>X_A</th>
<th>η (Wm⁻²)</th>
<th>U_A</th>
<th>R_A</th>
<th>I_A (MT/GW)</th>
<th>P_A &amp; T</th>
<th>C_A+T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga in Single-Junction GaAs (MOCVD)</td>
<td>2.5</td>
<td>5.32 [15-17]</td>
<td>0.48</td>
<td>235 [19]</td>
<td>0.30</td>
<td>0.00⁵</td>
<td>91</td>
<td>$P_{Ga} ≈ $900/ kg [14] $T_{TMG} ≈ $1600/ kg [6]</td>
<td>$0.371/ W</td>
</tr>
<tr>
<td>Ga in Single-Junction GaAs (HVPE)</td>
<td>2.5</td>
<td>5.32 [18]</td>
<td>0.48</td>
<td>235⁷</td>
<td>0.30</td>
<td>0.00⁵</td>
<td>91</td>
<td>$P_{Ga} ≈ $900/ kg [14] $T_{Ga} ≈ $100/ kg</td>
<td>$0.091/ W</td>
</tr>
</tbody>
</table>

## Estimated 2011 Material Supply Base for Gallium

Primary annual production from Bauxite (Al) byproduct recovery

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

\[
C_{A+T}($/W_p) = \frac{I_A}{10^6} \left[ \frac{P_A + T ± (R_A \times R_{VA})}{X_{Y}(1 - R_A)} \right]
\]

**250 – 300 MT [22, 23]**

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(CH3)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].

Material constraint if relying upon byproduct recovery at present efficiencies

\[
\approx 300/ 91
\]

3 - 4 GW
Are these energy-significant levels of deployment?

Projected trends in primary power consumption: \( \approx 15 \text{ TW in 2004}; \approx 30 \text{ TW in 2050} \)

Pre-Industrial \( \text{CO}_2 \) concentration: 280 ppm

Carbon-free power requirements (including efficiency) in 2035 to keep \( \text{CO}_2 < 550 \text{ ppm} \): \( \approx 10 \text{ TW} \)

In 2050 to keep \( \text{CO}_2 < 550 \text{ ppm} \): A LOT

WRE= Wigley, Richels, and Edmonds model.


(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?

Figure 11 - 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.

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: DoE (EIA) Data
Getting to the Fundamental Question

From R Eggert et al.,
“Depletion and Future Availability of Petroleum Resources,”
The fundamental supply question for these energy-critical elements

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

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

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

<table>
<thead>
<tr>
<th>Element A of interest</th>
<th>d (µm)</th>
<th>ρ (g cm⁻³)</th>
<th>Xₐ</th>
<th>η (W m⁻²)</th>
<th>Uₐ (Rₐ = 0)</th>
<th>IA (MT/GW)</th>
<th>Cₐ+T (2011 Pₐ &amp; T)</th>
<th>Byproduct Material Constraint (At 2011 Primary Production)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te in CdTe</td>
<td>1.0</td>
<td>5.85</td>
<td>0.53</td>
<td>180</td>
<td>1.0</td>
<td>17.0</td>
<td>$0.016/ W</td>
<td>35 GW</td>
</tr>
<tr>
<td>In in CIGS</td>
<td>1.0</td>
<td>5.75</td>
<td>≈ 0.22</td>
<td>200</td>
<td>1.0</td>
<td>6.3</td>
<td>$0.0054/ W</td>
<td>103 GW</td>
</tr>
<tr>
<td>Ga in CIGS</td>
<td>1.0</td>
<td>5.75</td>
<td>≈ 0.07</td>
<td>200</td>
<td>1.0</td>
<td>2.0</td>
<td>$0.002/ W</td>
<td>150 GW</td>
</tr>
<tr>
<td>Ga in Single-Junction GaAs (MOCVD)</td>
<td>1.0</td>
<td>5.32</td>
<td>0.48</td>
<td>250</td>
<td>1.0</td>
<td>10.0</td>
<td>$0.042/ W</td>
<td>30 GW</td>
</tr>
<tr>
<td>Ga in Single-Junction GaAs (HVPE)</td>
<td>1.0</td>
<td>5.32</td>
<td>0.48</td>
<td>250</td>
<td>1.0</td>
<td>10.0</td>
<td>$0.010/ W</td>
<td>30 GW</td>
</tr>
</tbody>
</table>

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 single-junction polycrystalline modules in average commercial production.
The fundamental supply question for these energy-critical elements

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

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

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.
References

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