

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

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**Abstract**—If humankind is to implement more sustainable energy choices, it will be crucial for energy systems such as photovoltaics (PV) to demonstrate success both soon and over the long-term quest. To that end, both the crystalline silicon and thin-film technologies have made, and continue to make, remarkable strides toward providing solutions that are quickly becoming more competitive against the traditional sources for power generation. But, within the thin-film segment of this industry the highest demonstrated sunlight power conversion efficiencies have thus far come from material sets containing relatively rare constituent elements. These include tellurium in the cadmium telluride technology, and indium and/ or gallium in the CIS/copper indium gallium diselenide and III–V families of technologies. In this paper we show that the current global supply base for these three energy-critical elements is not sufficient for enabling energy-significant levels of PV deployment, but also show that each of the thin-film PV technologies that are described has an ability to absorb potential increases in the price for these constituent element(s). This ability then leads to the possibility that the supply base for each element can be augmented.

**Index Terms**—Gallium, indium, tellurium, thin-film photovoltaic (PV).

## I. DISCUSSION AND ANALYSIS

WHEN discussing the supply-and-demand dynamics for any element of interest to a photovoltaic (PV) technology, the first useful term to consider is the required material intensity  $I$  for the element when it is incorporated within a layer in a PV module. It is rather straightforward to show that  $I$  to use a particular element A within a layer in a PV module can be calculated by

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

where

- $d$  layer thickness (in  $\mu\text{m}$ );
- $\rho$  compound layer density (in  $\text{g}\cdot\text{cm}^{-3}$ );

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- $X_A$  mass fraction of element A within the layer;
- $\eta$  area-based module power rating (in  $\text{W}/\text{m}^2$ ), calculated from the power conversion efficiency;
- $U_A$  utilization fraction of element A in manufacturing, representing the fraction of the initial amount of A that is actually captured within the completed module;
- $R_A$  recovery fraction of element A in manufacturing, representing the initial amount of A that is reclaimed and reused after the appropriate deposition on the module, and after the appropriate recovery steps.

By using the stated units for each input within this expression, and with the scaling factor seen in the denominator, the resulting units for  $I_A$  will be metric tonnes (MT) per GW. The specific value for the  $R_A$  term will depend upon how efficiently the element can be recovered from, for example, the chamber walls and the forest of plumbing systems within the manufacturing line and whether its price even justifies recovery in the first place (after considering the loss in uptime of the capital equipment, any applicable solvent extraction and reprocessing costs, etc.). Thus,  $U_A + R_A \leq 1$ .

It is also straightforward to calculate the effect of the price for the element's precursor upon module manufacturing costs

$$C_{A+T} (\$/\text{W}_p) = \frac{I_A}{10^6} \left[ \frac{P_A + T \pm (R_A \times RV_A)}{X_Y (1 - R_A)} \right] \quad (2)$$

where  $P_A$  is the price for the element when purchased at the commonly traded standard grade of purity, and  $T$  is the "tolling charge" for further refinement of the element to solar-grade purity, as well as to meld it into the appropriate precursor for use in manufacturing—such as when combining Cd with Te in the case of the CdTe compound, to make a sputtering or evaporation target in the case of copper indium gallium diselenide (CIGS), or to synthesize the appropriate organometallic precursor in the case of the metal-organic chemical vapor deposition (MOCVD) approach to deposit III–V materials. Both  $P_A$  and  $T$  terms have the units of dollars per kilogram in this expression, as does the net recovery value for the element ( $RV_A$ ). This recovery value can either lower the net manufacturing costs (for example, if the element can be recovered and sold back to the original supplier) or raise the net manufacturing costs (for example, if the spent element is chemically hazardous, and has an associated handling and disposal charge). Due to the different form factors for each element's precursor,  $X_Y = X_A = X_{Te}$  in the case of CdTe (which is 0.53);  $X_Y =$  the weight percent of Ga in the organometallic precursor for MOCVD of a GaAs case (which

is 0.61 if using  $\text{Ga}(\text{CH}_3)_3$ ; and  $X_Y = 1$  for the depositions that are characteristic of CIGS and the hydride vapor phase epitaxy (HVPE) method to deposit GaAs. By using these units for each input within the second expression, and with the scaling factor, the final result will be in dollars-per-watt peak ( $\$/W_p$ ).

In Table I, we provide our best efforts analysis of the current inputs and results of (1) and (2).

In the case of the III–V solar cells, we restrict the discussion to single-junction, one-sun GaAs. This, of course, grossly overestimates the material intensity if III–V solar cells were to be employed within concentrating PV applications (in which case the material intensity would be reduced in proportion to the concentration ratio, all other inputs being constant). In addition to the MOCVD approach to fabricate these devices, because it might offer a much cheaper form factor for the Ga precursor, we also highlight the undemonstrated HVPE method but state up front that the ability of the method to offer a lower overall net module cost would be contingent upon whether it can also achieve high enough sunlight power conversion efficiencies. While also an important consideration when utilizing III–V materials, we have not included an additional material intensity or cost term for the parent epitaxial substrate. These additional terms would scale in proportion to the number of substrate reusages and, at current GaAs parent epi-substrate prices, would have to be extremely small anyway, because the number of substrate reusages must be on the order of hundreds for single-junction, one-sun GaAs to be economically viable in the first place.

It is thought provoking to compare the estimates of the material intensity for each element with the corresponding supply base, as this gives the first-order overview of how much PV manufacturing could conceivably be supported if these technologies were—somehow—immediately scaled up. The supply base which is shown for each element is the estimated total amount of global primary production for each in 2011. The demand for these elements currently includes PV, which became the primary consumer of Te for the first time in 2010 [23], [25], [26], and a number of other competing uses, principally including ITO manufacturing in the case of In, and manufacturing integrated circuits and optoelectronic devices in the case of Ga. By simply comparing the current material intensity for each element with the corresponding supply base, it would appear that—even if the total supply base for each element was solely dedicated to PV—these material sets are constrained to a finite level, with a 9 GW/yr limitation for Te in CdTe, a 28 GW/yr limitation for In in CIGS, and a slightly less than 3 GW/yr limitation for Ga in one-sun GaAs.

This first-order overview of potential elemental limitations is not the complete picture, however, because each of the technologies being discussed may be able to make significant improvements to the crucial parameters detailed in (1) and (2). Also, over time, the supply base for each of these elements could change in response to changes in their demand and prices.

In the case of CdTe, if we limit the discussion to the single-junction polycrystalline case, the layer thickness in a module could conceivably be reduced to around  $1.0 \mu\text{m}$ , the module-area efficiency could be improved to around 18%, and there

is some room for improvement in the utilization efficiency term [19], [27]. If these targets were realized, the material intensity could be reduced from around 69 to 17 MT/GW. Additionally, at current Te prices, the tellurium cost contribution would essentially become insignificant, at less than 1 penny-per-watt. Thus, achieving a lowered material intensity target not only just increases the amount of CdTe manufacturing that can be supported by the limited supply base, but also affords an ability to absorb potential increases in the price for Te.

For CIGS, the first point of note is that the material intensity is relatively small for the two elements of interest. This is because the majority of the mass in a CIGS layer is comprised of Cu and Se. And just as in CdTe, there is also significant opportunity to lower the material intensity in CIGS as well. If we again limit the discussion to the polycrystalline single-junction case, the PV layer thickness can also be similarly reduced and the efficiency can likely be improved to at least 20%, in consideration of cell efficiencies around this value already demonstrated [18], [28], [29]. Looking at the  $R_A$  term, there is also the opportunity for CIGS manufacturers to resell the unspent material on the sputtering or evaporation targets. If all of the remaining material on the sputtering or evaporation source can be completely recovered and recycled, with 20% module efficiencies and  $1.0 \mu\text{m}$  of the assumed CIGS stoichiometry, the material intensity for indium could be reduced to 6.3 MT/GW, and as in CdTe, a potential increase in the price for the critical element could be accommodated. Practically speaking, this ability to absorb a price increase could be an important bargaining chip in the attempt to outbid industries such as ITO manufacturing—which is currently the primary consumer of In, and which currently has an ability to pay much more for the element on an areal basis than PV can. (Although, as different transparent electrodes are being explored for the display industry, it may also prove to be the case that this competitor for may disappear in the future.)

In the case of GaAs without optical concentration, if we assume that 25% module efficiencies can be achieved in commercial production with  $1.0 \mu\text{m}$  of active layer, then we derive that the material intensity could be lowered from 91 to 34 MT/GW. This does improve the picture quite a bit, but, more significantly, the Ga will more than likely need to be recovered from the module reactors in a long-term technology scenario (in which case,  $I_A$  could perhaps be as low as 10 MT/GW, if assuming a final net utilization efficiency of unity).

With these opportunities to reduce the material intensity, the picture of potential supply limitations begins to appear less ominous for all of these material sets. But it still does not appear as though the current supply base for these critical elements is enough to support thin-film PV manufacturing at the hundreds of GW scale—even if this industry somehow managed to establish a complete monopoly over each element.

There are lessons, however, to be learned from the oil and natural gas industries: If there needs to be an expansion in the supply of critical feedstock materials, one can consider using both the cheaper, conventional sources of recovery (vertical on-shore drilling in the case of oil and gas and traditional byproduct

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	$\rho$ (g·cm <sup>-3</sup> )	$X_A$	$\eta$ (W·m <sup>-2</sup> )	$U_A$	$I_A$ (MT/GW)	$P_A$ & $T$	$C_{A+T}$
					$R_A$			
Te in CdTe	2.5 $\mu$ m [1, 2]	5.85 [3]	0.53	128 [4]	0.70 [5]	69	$P_{Te}$ $\approx$ \$150/ kg [6] $T_{CdTe}$ $\approx$ \$110/ kg [7]	\$0.034/ W
					0.20 [5]			
In in CIGS	2.0 $\mu$ m [8]	5.75 [9]	$\approx$ 0.22 <sup>1</sup> [8, 10]	157 [4, 11]	0.55 <sup>2</sup>	23	$P_{In}$ $\approx$ \$520/ kg [12] $T_{In}$ $\approx$ \$100/ kg <sup>3</sup>	\$0.018/ W
					0.25			
Ga in CIGS	2.0 $\mu$ m [8]	5.75 [9]	$\approx$ 0.07 <sup>1</sup> [8, 10]	157 [4, 11]	0.55 <sup>2</sup>	7.5	$P_{Ga}$ $\approx$ \$400/ kg [13] $T_{Ga}$ $\approx$ \$100/ kg <sup>3</sup>	\$0.005/ W
					0.25 <sup>4</sup>			
Ga in Single-Junction GaAs (MOCVD)	2.5 $\mu$ m [14-16]	5.32 [17]	0.48	235 [18]	0.30	91	$P_{Ga}$ $\approx$ \$400/ kg [13] $T_{TMG}$ $\approx$ \$2100/ kg <sup>6</sup>	\$0.373/ W
					0.00 <sup>5</sup>			
Ga in Single-Junction GaAs (HVPE)	2.5 $\mu$ m	5.32 [17]	0.48	235 <sup>7</sup>	0.30	91	$P_{Ga}$ $\approx$ \$400/ kg [13] $T_{Ga}$ $\approx$ \$100/ kg	\$0.046/ W
					0.00 <sup>5</sup>			

### 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]**

#### Notes:

The champion module efficiencies shown in this table are taken from Table II in reference [18]. 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.

<sup>1</sup>Representative weight percentage, calculated from the CIGS stoichiometry within the references cited.

<sup>2</sup>The material utilization of a rotary target used for sputtering is around 75%, while the material utilization of a planar target is around 30%. The net fraction of element that is captured within the module is then the product of this target utilization and the transfer efficiency to the module. 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.

<sup>3</sup>This will very much depend upon the chosen form factor, with rotatable targets generally being 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 reclamation value that is typically 25% of the original value, and also that the remaining In and Ga on the sputtering or evaporation targets is currently the only source of material returned for reprocessing.

<sup>4</sup>This may be deposited from a Cu-Ga composite target if sputtering.

<sup>5</sup>It is our understanding that Ga is not currently recovered from the MOCVD and HVPE processes for depositing GaAs, but this is very likely just due to the fact that these are currently only research-level investigations. It is also important to state that, while the current typical  $U_A$  for MOCVD was provided by a relevant equipment supplier, the  $U_A$  for HVPE is unknown at this time.

<sup>6</sup>Estimated price of around \$2500/ kg for large volume purchasing contracts of Ga(CH<sub>3</sub>)<sub>3</sub>, provided by a relevant major supplier. In consultation with the supplier, it can be said that the cost for synthesizing and purifying the metal-organic precursor is typically much higher than the original metal.

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

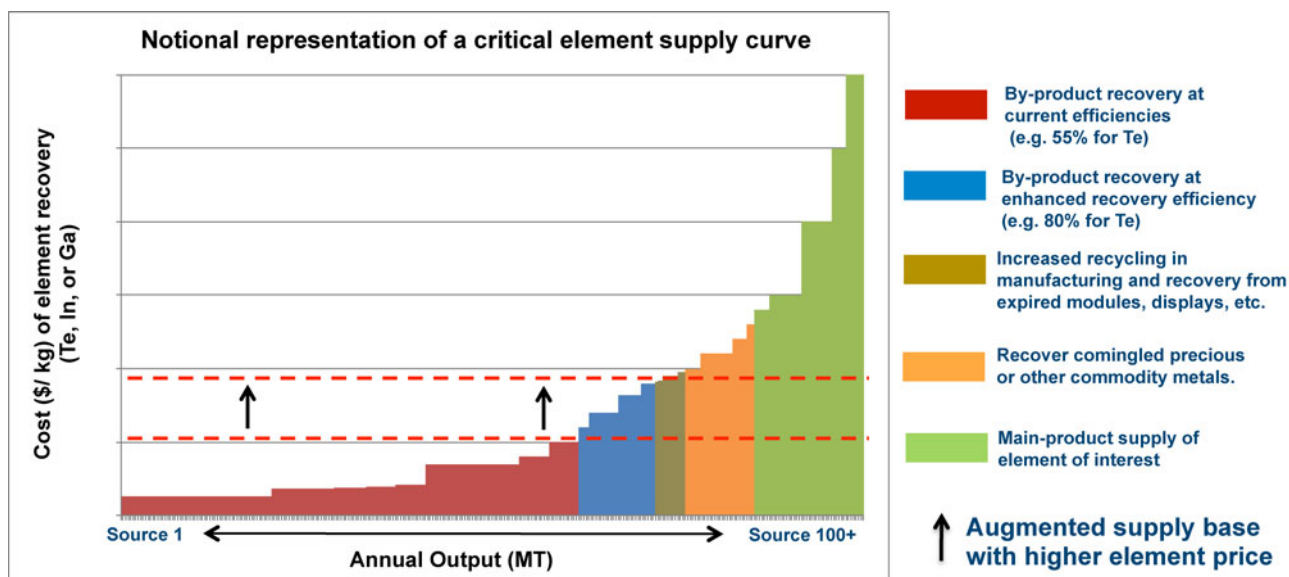


Fig. 1. Notional illustration of a cumulative availability curve for the critical elements of interest. The concept of this curve was adapted from [30], which was a similar analysis carried out for conventional and unconventional petroleum resources. The horizontal lines and arrow represent an increase in the supply base that could potentially be realized, if the higher range of recovery costs was still tolerable to thin-film PV manufacturers.

recovery in case of Te, In, and Ga) and the generally more costly unconventional sources of recovery (such as oil sands and hydraulic fracturing, and direct mining of the critical elements, to carry our analogy further) [30], [31]. In this pursuit, the guiding principle is to avert undesirable upward spikes in the price for the necessary feedstock materials—in which case, it is in timing the trajectory of supply to match that of the demand that can be of the essence [32], [33].

Admittedly, trying to project the future demand for these critical elements would be an extremely speculative endeavor, mostly because it is not yet clear which of the PV technologies might triumph over the others. And attaching dates to any projection of demand would be an even more speculative endeavor—not only because of this technology uncertainty, but also because the manufacturing and deployment of PV is, for the near-term at least, dependent upon a much broader uncertainty in international energy policies. Still, as the story of PV continues to unfold, it is incumbent upon the industry to understand and to anticipate any potential material supply constraints—and to determine, as accurately as possible, just when any additionally necessary supply options should be pursued.

In this determination, it is imperative to establish an understanding of what the recovery costs are for every conceivable supply option, as this provides some initial clues to the decisive question of just how much of each critical element can be obtained at prices that will not compromise the competitive position of their respective PV technologies—either against industry “rivals,” such as c-Si, or, in a long-term view, against the more traditional energy sources. To develop such an understanding, in Fig. 1, we provide an illustration of what we believe to be the most critical information that is lacking within the published literature for all three of these energy critical elements. Within the figure, the width of a particular bar represents the

annual production potential, in MT, of a given supply source. The height represents the costs to recover the element from that corresponding source. Integrating the curve over the allowable range of costs would then provide the total amount of the resource that is “economically recoverable” to PV manufacturers.

Of course, because most primary production of these elements is the result of byproduct recovery during base metal mining and refining, the broader response to a supply-demand imbalance might be to initiate a series of direct mining operations. It has been estimated that the recovery costs for this option are a simple inverse relationship to the average concentration of the element within the area surrounding a potential mining site [34]. While much credit needs to be given to the fact that this relationship was, to our knowledge, the first attempt to even try to quantify the essential question of recovery costs for Te and In from direct mining, the relationship oversimplifies the question because the actual costs for any real mining site will depend very specifically upon how the element might have concentrated into veins (and how deep below the surface they are), shipping costs to send the ore to the most appropriate refinery, potential environmental remediation costs, specific capital costs related to the type of recovery method that is to be employed, etc. It is also relevant to the case of mining Te, In, and Ga that the overall economic motivation to engage in a direct mining project may not just be in consideration of demand from the PV industry, because the economics of the other elements that are also typically comingled within each potential source—be it the base metals or also oftentimes many of the precious metals—must also be taken into consideration because their total recovery value is usually much higher [19], [26]. None of these are easy questions to fully understand and quantify, but they are the ones that need to be more fully understood and discussed across the PV community.

## II. CONCLUSION

For PV to achieve energy significance will require global annual production levels on the order of hundreds of GWs to TWs. If it is to become an industry of such a size, one key-enabling factor will be to avert potentially debilitating increases in the prices for critical feedstock materials. This will require a detailed plan, especially with regard to a timely coordination between the desired level of PV deployment and the corresponding supply of modules. To enable manufacturing the PV technologies that have been discussed at the hundreds of GWs to TWs level, it is apparent that the supply base for the critical elements tellurium, indium, and gallium will need to be expanded. Whether it is in increasing the recovery efficiency of these elements in traditional byproduct production, better capture and recycling in manufacturing, or in commencing direct mining projects, an expansion in their global supply base for PV purposes will be foremost contingent upon a higher price offering from module manufacturers. Through improvements in the net material intensity of the constituent elements, the thin-film technologies that have been profiled here have significant room to absorb such potential price increases and, thus, to expand their total potentially available supply base.

As another very valuable hedge to ensure that thin-film PV can be deployed at the hundreds of GWs to TW level, it is also increasingly clear that technologies based upon more earth-abundant elements may also be needed—and it would be most advantageous if such technologies can be commercially demonstrated to the same level of success as those profiled here.

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