



Metals Production Requirements for Rapid Photovoltaics Deployment

AN MIT *FUTURE OF SOLAR ENERGY* STUDY
WORKING PAPER

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Abstract

If global photovoltaics (PV) deployment grows rapidly, the required input materials need to be supplied at an increasing rate. In this paper, we quantify the effect of PV deployment levels on the scale of metals production. For example, we find that if cadmium telluride (copper indium gallium diselenide) PV accounts for more than 3% (10%) of electricity generation by 2030, the required growth rates for the production of indium and tellurium would exceed historically-observed production growth rates for a large set of metals. In contrast, even if crystalline silicon PV supplies all electricity in 2030, the required silicon production growth rate would fall within the historical range. More generally, this paper highlights possible constraints to the rate of scaling up metals production for some PV technologies, and outlines an approach to assessing projected metals growth requirements against an ensemble of past growth rates from across the metals production sector. The framework developed in this paper may be useful for evaluating the scalability of a wide range of materials and devices, to inform technology development in the laboratory, as well as public and private research investment.

1. Introduction

Photovoltaics (PV) is a low-carbon technology that has the potential to reduce greenhouse gas emissions if deployed at large scale.^{1,2,3} As of 2012, PV provides only 0.4% of the world's electricity.⁴ Its deployment is growing rapidly, however, at an average rate of 30% per year,⁵ as the technology steadily improves and costs decline.^{6,7,8,9,10}

The future growth of PV has been estimated in various energy scenarios, based on projections of energy demand and the cost and performance of technologies in the future. Various international organizations,^{11,12} environmental agencies and industry associations,^{13,14} energy companies and other corporations^{15,16} and academic institutions and researchers^{17,18} have contributed to this literature. Another group of studies focuses on resource constraints and the potential for future PV deployment. For example, various researchers have analyzed the material constraints on PV deployment that are imposed by annual metal production levels or reserves^{19,20,21,22} and have discussed the potential for increasing PV deployment by reducing the material intensity of PV technologies.^{23,24,22,25}

While these studies address the production scale of metals eventually needed, they do not directly address the time frame over which scaling up should be achieved. In this paper, we ask whether metals production can be scaled up at a pace that matches the rapidly increasing PV deployment levels put forward in aggressive low-carbon energy scenarios. Based on the projected PV deployment levels

in 2030, we estimate the growth rates required for metals production to satisfy the metal demand by the PV sector. We present a new perspective on the metal requirements of PV deployment by comparing the required growth rates with the growth rates observed in the past by a large set of metals (the full set of metals for which yearly production data is available for all years in the period 1972 to 2012). (See Section 1 of Supplementary Information for details.[†])

We include in our analysis the absorber layer materials of three PV technologies manufactured and sold today: crystalline silicon (c-Si) technology (roughly 90% of annual PV production today)²⁶ and two thin-film PV technologies, cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) (with roughly 5% and 2% of annual PV production today),²⁶ building on our earlier, preliminary results.²⁷ Whereas c-Si is based on an abundant metal, silicon, CdTe and CIGS utilize metals that have low crustal abundance and are obtained as byproducts of other metals' production.

In this paper we aim to provide a thorough analysis of the required growth rates for silicon in c-Si, tellurium in CdTe, and indium, gallium and selenium in CIGS to meet a range of projected PV growth scenarios. To complement this analysis of past and projected metals growth rates, we also compare the projected levels of metals production to their estimated scalability potential based on metals reserves. The approach developed in this paper may also be useful for studying the scalability potential of other technologies as well, in light of the production growth requirements of raw materials.

2. Methods

We estimate the growth rates required for metals production to meet the metal demand associated with projected global PV deployment levels in 2030. These projected levels are based on a number of published energy scenarios ranging from low to high PV deployment (Table 1). We note that providing a high proportion of the total electricity through PV would require energy storage technologies that would also entail material requirements.²⁸ This paper concentrates on the materials used in PV technologies but could be extended to analyze energy storage technologies.

The analysis begins with estimating the required annual production in 2030 for each PV metal of interest. We then calculate the annual growth rate needed for the metals production to reach the required level in 2030. To estimate the required metal production in 2030, we consider the projected demand for the metal by both the PV sector and non-PV end-use sectors of the metal,

$$P_{\beta} = X_{\alpha} I_{\alpha\beta} + N_{\beta} (1 + n_{\beta})^{18} \quad (1)$$

where

- P_{β} required production for metal β in 2030 [metric tons/year (t/y)]
- X_{α} deployment for PV technology α during 2030 [GW/y]
- $I_{\alpha\beta}$ intensity of metal β for PV technology α [t/GW]
- N_{β} metal β used by non-PV end-uses in 2012 [t/y]
- n_{β} annual growth rate in non-PV end-uses of metal β [unitless]

The projected demand for a metal β by a PV technology α in 2030 is determined by the projected annual deployment level of the PV technology in 2030, X_α , and the anticipated material intensity of metal β in 2030, $I_{\alpha\beta}$. We calculate the annual PV deployment in 2030, X_α , by using the cumulative installed PV capacity for 2030 projected by the energy scenarios (Table 1) and assuming a constant percent annual growth from 2012 to 2030. The material intensity, $I_{\alpha\beta}$ (in g/W or t/GW), for a metal in a PV module is given by

$$I_{\alpha\beta} = \frac{t_\alpha p_\alpha w_{\alpha\beta}}{\sigma n_\alpha U_{\alpha\beta} \gamma_\alpha} \quad (2)$$

where

- t_α thickness of absorber layer for PV technology α [μm]
- p_α density of layer for PV technology α [g/cm^3]
- $w_{\alpha\beta}$ mass fraction of metal β within the layer for PV technology α [unitless]
- n_α module efficiency for PV technology α [unitless]
- σ solar constant [$1000 \text{ W}/\text{m}^2$]
- $U_{\alpha\beta}$ utilization fraction of metal β in manufacturing PV technology α [unitless]
- γ_α yield in cell and module manufacturing for PV technology α [unitless]

For each PV metal, we consider a range of estimates for material intensity in 2030. Table 2 provides the parameters used to obtain these estimates and the resulting high, medium and low material intensity values. The ranges for material intensity considered are 10–30 t/GW for In, 2–10 t/GW for Ga, and 20–160 t/GW for Se in CIGS; 20–160 t/GW for Te and 20–140 t/GW for Cd in CdTe; and 640–6630 t/GW for Si in c-Si when material losses during manufacturing are considered. The high material intensity estimate corresponds to today's level.

Table 1 Cumulative Installed PV Capacity Projections for 2030

Energy Scenario	Cumulative Installed PV Capacity (GW)	Approximate % of Global Electricity from PV
IEA WEO ^a	720	3
Solar Generation 6 ^b	1,850	8
GEA ^c	3,000	13
Shell ^d	5,500	2

^a 450 scenario¹¹

^b Paradigm shift scenario¹⁴

^c GEA-supply, conventional transportation, full portfolio scenario¹⁷

^d Scramble scenario¹⁵

Note: Installed capacity figures rounded to nearest ten GW. Approximate percentage of global electricity is calculated assuming 15% capacity factor for PV¹⁴ and a total global electricity generation of 30000 TWh in 2012.¹¹

The demand by non-PV end-uses of each metal in 2030 is estimated by using the median of the historical growth rates of that metal over all 18-year periods between 1972 and 2012. To account for the variability in the historical growth rates and the uncertainty regarding the future of the non-PV end-uses of the metal, we also calculate a confidence interval around the median growth of the non-PV end-uses defined by the 1st and 3rd quartiles of the distribution of historical growth rates over all 18-year periods between 1972–2012.

Table 2 Parameters for Material Intensity and the Resulting Material Intensity, $I_{\alpha\beta}$, for Each Element

Elements	Cases	t_{α} (μm)	n_{α} (%)	$U_{\alpha\beta}$ (%)	y_{α} (%)	ρ_{α} (g/cm^3)	$w_{\alpha\beta}$ (%)	$I_{\alpha\beta}$ (t/GW)
In in CIGS	high	2.0	14.0	75	73			28
	medium	1.2	15.7	80	90	5.75	22	13
	low	1.1	20.0	95	98			7
Ga in CIGS	high	2.0	14.0	75	73			9
	medium	1.2	15.7	80	90	5.75	7	4
	low	1.1	20.0	95	98			2
Se in CIGS	high	2.0	14.0	30	85			161
	medium	1.2	15.7	60	90	5.75	50	41
	low	1.1	20.0	95	98			17
Te in CdTe	high	2.5	11.7	50	85			156
	medium	2.0	14.0	70	90	5.85	53	70
	low	1.0	18.0	95	97			19
Cd in CdTe	high	2.5	11.7	50	85			138
	medium	2.0	14.0	70	90	5.85	47	62
	low	1.0	18.0	95	97			17
Si in c-Si	high	180.0	14.8	45	95			6629
	medium	120.0	18.0	55	98	2.33	100	2882
	low	50.0	20.5	90	99			638

In, Ga, Se: t_{α} high^{24,25}; t_{α} medium, t_{α} low²⁵; n_{α} high²⁹; n_{α} medium, p_{α} , $w_{\alpha\beta}$ for In, $w_{\alpha\beta}$ for Ga²⁴; n_{α} low³⁰; $U_{\alpha\beta}$ high for In, $U_{\alpha\beta}$ high for Ga²⁴, other $U_{\alpha\beta}$ values³⁰; $w_{\alpha\beta}$ for Se³¹; y_{α} high for In, y_{α} high for Ga²⁴, other y_{α} values³⁰.

Te, Cd: t_{α} high, p_{α} , $w_{\alpha\beta}$ for Te²⁴; n_{α} high, n_{α} low³²; t_{α} medium, t_{α} low, $U_{\alpha\beta}$ high for Te, $U_{\alpha\beta}$ low for Te, y_{α} high, y_{α} medium³⁰; n_{α} medium²⁵; $U_{\alpha\beta}$ medium for Te³³; y_{α} low³⁴. $U_{\alpha\beta}$ values for Cd are assumed to be the same as Te. $w_{\alpha\beta}$ for Cd is $1-w_{\alpha\beta}$ for Te.

Si: p_{α} ³⁵; all remaining parameters³⁶.

We calculate the growth rate, r_β , required for the metals production in 2012 to reach the required level in 2030 by assuming a constant percentage annual growth rate and using Equation (3):

$$P_\beta = P_{0\beta} \times (1 + r_\beta)^{18} \quad (3)$$

where

$P_{0\beta}$ production of metal β in 2012 [t/y]
(from^{38,39,40,41,42,43})

P_β production of metal β in 2030 [t/y]
(found in Eq. 1)

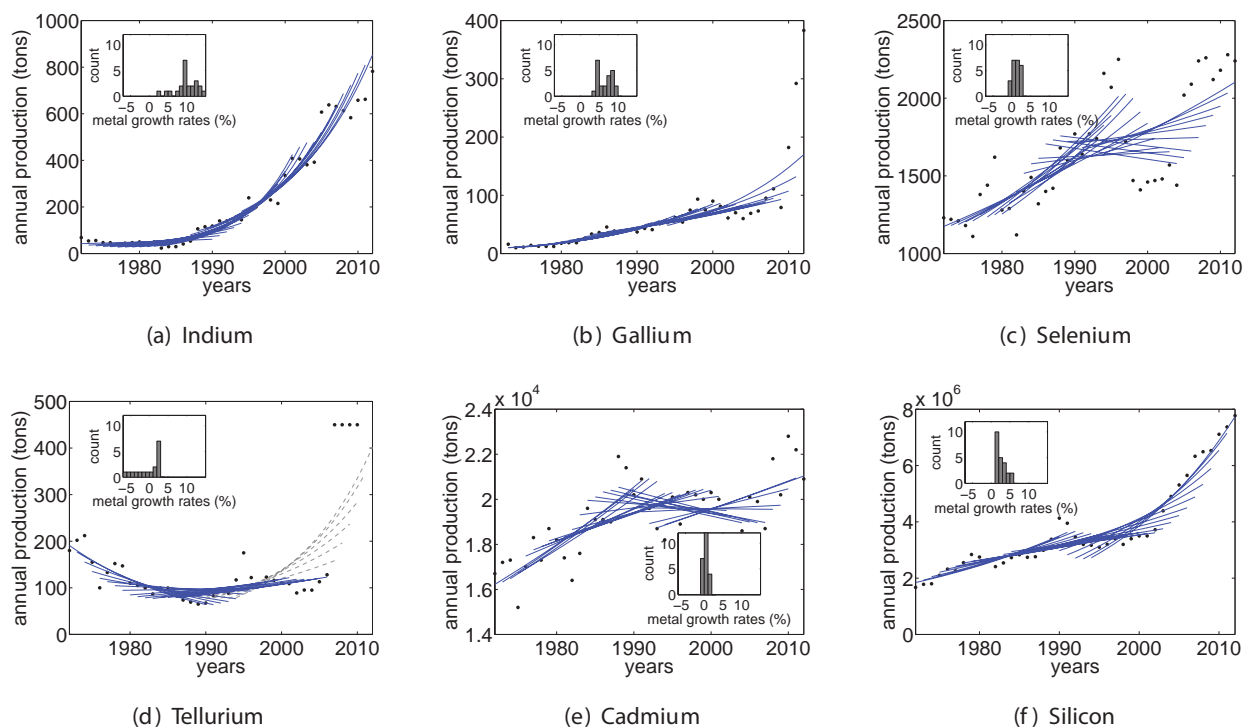
After obtaining the required growth rates, r_β , we compare them to historical growth rates of metals production in order to determine whether the required growth rates have historical precedent. When studying the historical growth rates, we use a large set of metals to obtain a more complete picture of the metals production sector. We obtain the annual global production values for 32 metals for the last 40 years from the U.S. Geological Survey.^{38,39,40,41,42,43} These represent all metals for which continuous yearly production data is available.

We study material resources at the purity grade reported by the US Geological Survey. (See Table S1 in the Supplementary Information.) We note that byproduct metals such as Te are generally tracked at higher levels of purity than primary metals such as Si, since only the refined byproduct is globally traded. Because of this, we carry out an additional analysis on metallurgical grade Si, a higher purity form that is the precursor to most (97%) Si used in solar cells^{44,45,46}, to see whether this partially-refined material with

smaller production scale is able to support deployment of Si-based PV. This analysis also limits the raw Si resource, since currently metallurgical grade Si is produced more selectively from silica deposits with relatively low starting level of impurities.⁴⁷ We note that data on MG-Si is limited to the period from 1990–2012, and that data prior to 2004 excludes production by China, further limiting the number of observations. To maintain consistency with other metals, in Figures 1–4 we use total production of Si given in the USGS data, for which a full 40 year history of most recent production data is available.

We calculate the historical annual growth rates for each metal for all overlapping 18-year periods between 1972–2012. Annual growth rates are calculated based on 18-year time horizons to match the time horizon of the metals growth projections considered (2012–2030). Because we are interested in growth rates that are sustained over all possible 18-year periods, we measure the growth rates over overlapping periods rather than disjoint periods. The average annual growth rate of metals production over each 18-year period is estimated by fitting a straight line to the natural logarithm of the production over time using the least-squares method (Figure 1). This is not meant to be a high-fidelity model and we emphasize that the goodness-of-fit varies substantially across the metals and 18-year time periods studied. This level of fidelity is appropriate for answering the following question: If we approximate past and future growth in metals production as following an exponential trend over an 18-year period, how do future required growth rates compare to those observed in the past?

Figure 1 Annual Production of Metals Over Time, 1972–2012



Black points show the actual production data, while blue lines are obtained by fitting a line to the natural logarithm of the production data (using the least squares method) for each 18-year period in 1972–2012. The slope of the each fitted line represents the annual growth rate for that 18-year period. The inset in each figure is the histogram of the annual growth rates obtained by this curve fitting method. The goodness-of-fit varies substantially across the metals and time periods investigated. The method of reporting tellurium production data changed in 2007, resulting in an arbitrary jump.³⁷ Therefore the Te data for the last 6 years are not taken into account when estimating the growth rates. This is indicated by the gray color used for the last 6 fitted lines.

3. Results and Discussion

In this section, we first present historical growth rates in the production of metals. Next, we show the growth rates required for the PV metals to reach various projected annual PV installation levels in 2030, and compare these to historical growth rates. Third, we briefly discuss constraints on scaling up the production of byproduct metals based on the production levels of their host metals, as well as the estimated metals reserves.

3.1 HISTORICAL GROWTH RATES

Figure 1 shows the annual production values for a set of PV metals over time (1972–2012).

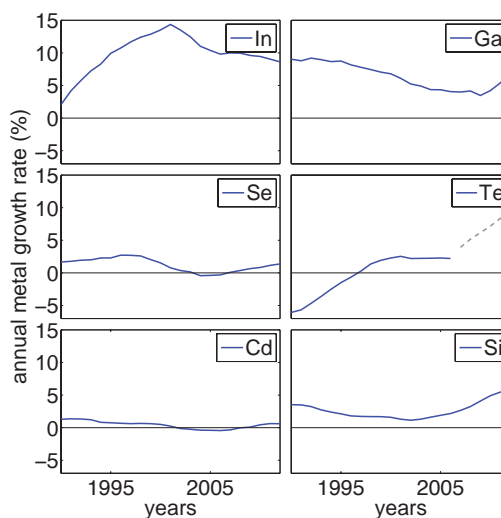
The inset in each plot shows a histogram of the annual growth rates for the corresponding metal over all 18 year periods. As can be seen in Figure 1, the variability in annual growth rates differs across metals but the distribution of growth rates is constrained to a fairly narrow range, falling below 10% growth per year for these metals with the exception of In.

The change in growth rates over time are different for each PV metal (Figure 2). In and Ga have experienced growth rates that are mostly above 5% per year, which is high compared to the other four metals. In, Ga, and Te growth rates have changed significantly over time, unlike Se and Cd rates, which have fluctuated within a small range between -1%

and 3% per year. Si growth rate has also been lower and more stable compared to In, Ga, and Te, and recently increased to 5% per year.

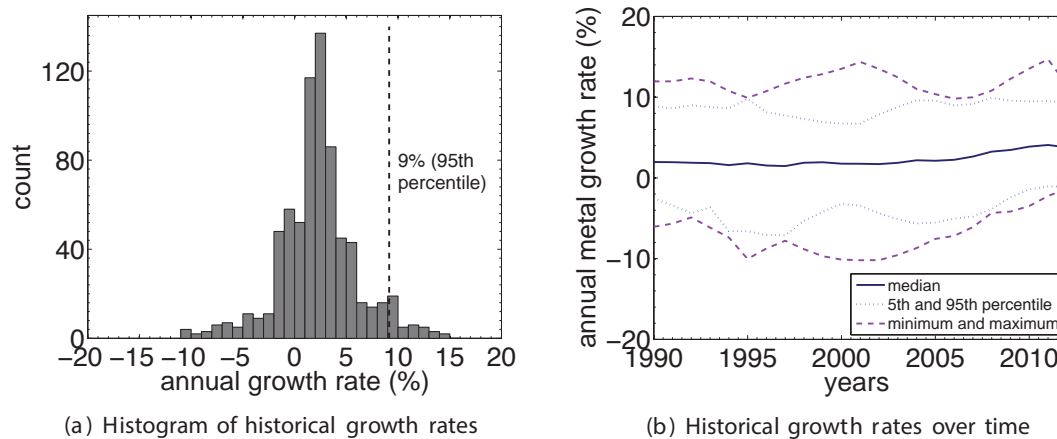
To gain a broader picture of the metals production industry, we also obtain the growth rates for the 32 metals available in the USGS database (Figure 3). Figure 3(a) shows the histogram of the aggregated growth rates observed by the set of 32 metals over all 18-year periods in 1972–2012. We see that the median growth rate is 2.3% per year. A growth rate of 9% per year at the 95th percentile of the aggregated growth rate distribution is marked with a vertical dashed line in Figure 3(a). We interpret 9% per year as an upper end of business-as-usual growth. If a growth rate of 9% per year is sustained over an 18-year period, the annual production will increase by almost a factor of 5 over this period. Also important to our analysis is the maximum growth rate that has been sustained over an 18-year period, which is 14.7% per year.

Figure 2 Historical Growth Rates over Time Are Shown for the Metals of Interest



Growth rates are calculated and plotted in a backward looking manner: The growth rate corresponding to a year is calculated using the production values from the previous 18 years. Reporting of the Te production data changed in 2007,³⁷ therefore the data for the last 6 years are not taken into account when estimating the growth rates.

Figure 3



(a): Histogram shows the distribution of the historical annual growth rates of production of 32 metals observed in 1972–2012 over 18-year periods. Growth rates are calculated by fitting lines to the natural logarithm of the production values in each of the 18-year periods in 1972–2012. The median 18-year average annual growth rate is 2.3%.

(b): 18-year average annual growth rates in metals production have been almost constant over time for the 32 metals studied. Annual growth rates are backward looking: they are calculated using the production values from the previous 18 years. The solid midline is the median of the growth rates of 32 metals for each year. The blue dotted lines show the 5th and 95th percentiles. The dashed purple lines show the minimum and the maximum growth rates observed. Note: The data coming from the last 6 years of Te production are excluded from both panel (a) and panel (b) due to a change in the reporting of the Te production data in 2007.³⁷

Figure 3(b) shows how the historical growth rates change over time. We observe that the median 18-year average growth rate has been mostly stable over time. An upward trend is observed in the median as well as the interval between the 5th and 95th percentiles after 2005. Even with this upward trend in recent years, the growth rates have been stable, and the median growth rate stayed below 5% per year.

Using overlapping time periods to obtain the 18-year average annual growth rates places greater weight on years falling in the middle of the time span considered (1972–2012). However we note that this does not introduce a bias in the histogram shown in Figure 3(a), as the annual production growth rates across the aggregated set of metals trend neither up nor down over the period considered (1972–2012), as shown in Figure S1 in Supplementary Information.

3.2 COMPARISON OF PROJECTED AND HISTORICAL GROWTH RATES

Figure 4 shows the annual growth rates required for the production of PV metals to meet the demand of a wide range of annual PV installation levels in 2030. The lower and upper ends of each colored band in Figure 4 are based on growth in non-PV end-uses at rates defined by the 1st and 3rd quartiles of the distribution of their historical 18-year average growth rates.

When explaining the results, we focus on the medium material intensity case and the annual PV installation level corresponding to the “Solar Generation 6, paradigm shift”¹⁴ scenario. The Solar Generation 6¹⁴ scenario projects a relatively modest growth in PV installations. In this scenario, the cumulative installed capacity reaches 1850 GW in 2030,¹⁴ and generates around 2,430 TWh in a year

assuming an average capacity factor of 15%. If the total annual global electricity generation in 2030 is 30,000 TWh,¹¹ then PV supplies around 8% of the world’s electricity in this scenario. When we assume that PV installation grows at a constant percentage annual growth rate starting from about 100 GW cumulative installed capacity in 2012, the annual PV installations in 2030 would be 275 GW to reach the 1850 GW cumulative installed capacity in 2030. In Figure 4, the vertical line marked with the “8% SolarGen6” corresponds to this annual installation level, and 8% refers to the portion of the global electricity provided by PV.

If CIGS provides all of the 275 GW annual installations projected by the Solar Generation 6¹⁴ scenario in 2030, the required growth rate for In is approximately 14% per year for the medium intensity case, as shown in Figure 4(a). This rate is almost unprecedented considering that the highest growth rate that has been observed historically by a large group of metals is 14.7% (as shown in Figure 3(a)). 14% per year is also high compared to In’s recent growth rates, where In production has been growing at a rate lower than 10% per year (Figure 2). A growth rate of 14% per year means that In production increases from 780 t/y in 2012 to 8,250 t/y in 2030, which is over a factor of 10 increase. In this scenario, the annual Ga and Se production each needs to grow at 11% per year, as shown in Figure 4(b) and Figure 4(c). These growth rates are greater than the majority of the historical growth rates experienced by all metals (Figure 3(a)). For Se, the projected 11% per year is significantly higher than the growth rates that Se has experienced in the last forty years (Figure 2), and corresponds to an increase in annual production of 2,240 t/y in 2012 to 14,660 t/y in 2030. On the other hand, the required growth rate for Ga, 11% per year,

is slightly above what Ga has been experiencing in the recent years (Figure 2). This rate means that Ga production increases from 380 t/y in 2012 to 2,490 t/y in 2030.

If we constrain metals growth rates to the maximum historical rate of 14.7%, the annual CIGS deployment levels in 2030 would be limited by In to 340 GW. Se and Ga would allow the annual CIGS deployment to be up to 580 GW and 700 GW, respectively, if CIGS were not limited by In.

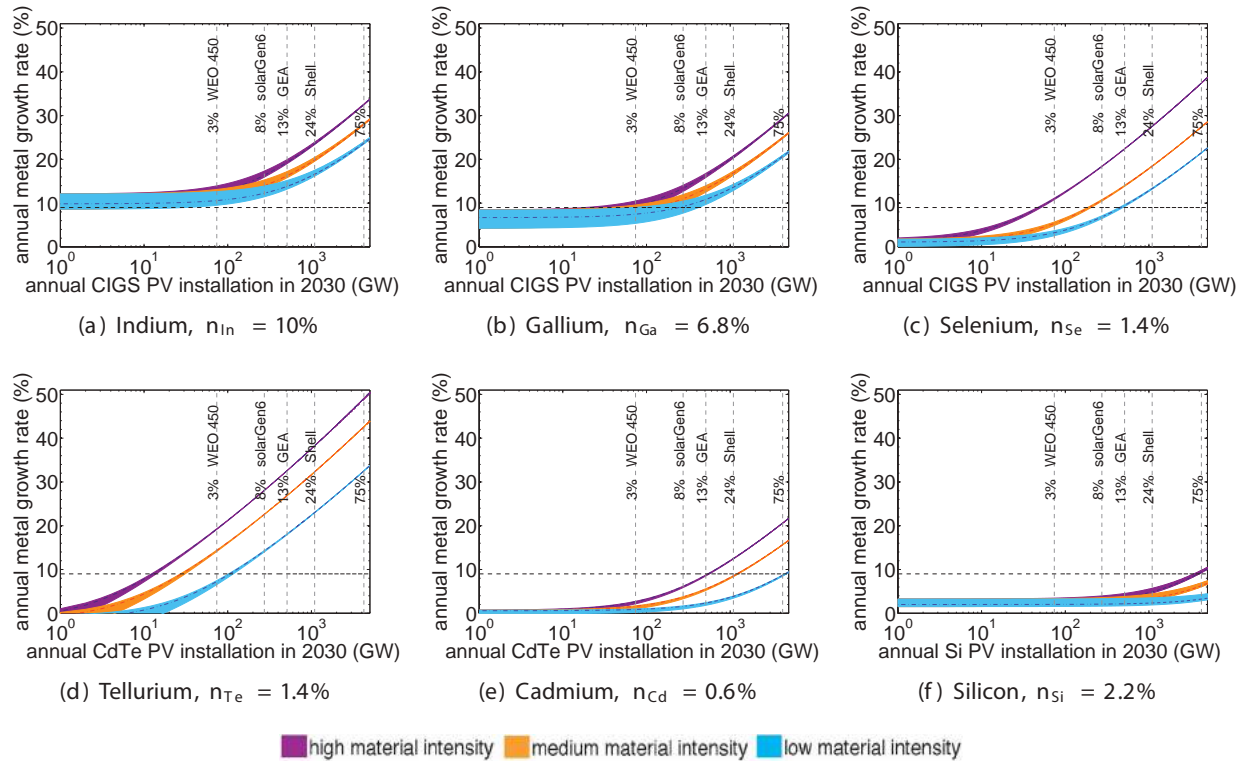
If CdTe provides 8% of the global electricity generation in 2030 corresponding to the Solar Generation 6¹⁴ scenario, in which case the annual CdTe installation in 2030 is 275 GW, Te production needs to grow at 23% per year for the medium material intensity case as shown in Figure 4(d). 23% per year is significantly higher than the highest historical growth rate observed for all of the 32 metals (Figure 3(a)). 23% per year growth rate corresponds to a more than fortyfold increase in the annual Te production — from 500 t/y in 2012 to 20760 t/y in 2030. Cd, on the other hand, requires only 4% per year growth rate in this scenario (Figure 4(e)) — an increase from 20,900 t/y to 42340 t/y. Historically, Cd production has been growing at very low rates and even decreased over sustained time periods as can be observed in the negative rates in Figure 2. 4% growth per year is relatively low compared to the required growth rates of other byproduct metals.

The maximum CdTe deployment in 2030 would be determined by Te, if Te growth rate does not exceed the maximum historically observed growth rate (14.7% per year) observed by all of the 32 metals. In this case, the annual CdTe deployment in 2030 would be limited to 80 GW. Cd would allow up to 3,600 GW annual CdTe deployment, if there were no constraints imposed by Te.

The median historical growth rates for In and Ga are $n_{In} = 10\%$ and $n_{Ga} = 6.8\%$, are on the higher end of the historical growth rates of all metals. Since we project the growth of non-PV end-uses based on the historical growth rates and the share of non-PV end-uses is very high compared to PV uses, the non-PV demand for both In and Ga is projected to be high. In comparison, a larger fraction (40%) of Te is used for PV compared to In and Ga, which have only up to 5% of their production dedicated to PV uses. For this reason, the required Te growth rates are more directly related to the level of PV installations than CIGS metals are as seen in Figure 4.

Instead of CIGS or CdTe, if all of the 275 GW annual PV installation comes from c-Si, Si production needs to increase only by 2.5% per year (Figure 4(f)). This growth rate is close to the median historical growth rate observed for all metals, 2.3% per year. Unlike byproduct metals, the increasing PV deployment does not cause much increase in the required growth rates for Si. This is mainly due to the fact that PV constitutes only a tiny fraction of Si's end-uses. For the medium material intensity case, the required growth rate for Si does not exceed 5% per year up to 1,000 GW of annual deployment. For all annual deployment levels explored in this analysis (up to 6,000 GW per year in 2030, supplying 100% of forecasted electricity consumption) the required growth rates for Si stay within the range of historical growth rates observed for all metals. (We estimate that silver production for use in contacts for c-Si cells can supply high levels of c-Si PV deployment (up to 80% of global electricity by c-Si in 2030) without exceeding historical growth rates. See the Supplementary Information for details. Silver might also be replaced with other materials.)^{48,49,50} We find the same results using only metallurgical grade Si (see Methods section)

Figure 4 Required Growth Rates for Metals Production to Reach a Range of Annual PV Installation Levels in 2030



The bands with different colors show the required growth rates for different levels of material intensities given in Table 2. The lower and upper ends of each band are obtained by assuming that the non-PV end-uses grow at rates equal to the 1st and 3rd quartiles, respectively, of the historical growth rate distribution of that metal over each 18-year period between 1972–2012. The median of the 18-year average growth rates observed between 1972–2012 for each metal, (n), is shown below each plot. The vertical lines indicate the assumed annual installation level for the PV technology corresponding to each energy scenario. The percentage on the left of the scenario names indicate the fraction of global electricity generation coming from PV. The energy scenarios originally report only the cumulative PV installations. By assuming a constant percent annual growth rate, we calculated the annual installation level in 2030. The horizontal line at 9% growth rate corresponds to the 95th percentile of the historical growth rates for all 32 metals as shown in Figure 3.

as the basis for Si growth rate measurements, rather than all Si. Applying the same analysis to this alternative measure of useable Si production, in the Supplementary Information, we find that required growth rates remain within the historical range with 100% of global electricity supplied by Si-based solar cells.

It is worth noting that although the growth rates are lower for Si, the increase in the amount of annual Si production from 2012 to 2030 is two to three orders of magnitude higher compared to other PV metals (In, Ga, Te, Se) because it is produced at a much larger scale. A growth rate of 2.5% per year correspond to an increase in Si production from 7.8 millions t/y in 2012 to 12.2 million t/y in 2030.

3.3 DISCUSSION OF CONSTRAINTS ON METALS PRODUCTION GROWTH

In, Ga, Se, Te, and Cd have low crustal abundances and are extracted economically today only as byproducts of other “host” metals. However a significant quantity of byproduct metal is never extracted from the mined ore. Below we briefly discuss the scalability potential of byproduct metals if they were recovered with 100% efficiency from the mined mineral at today’s production levels of host metals, and compare these production levels to those required to meet 8% of global electricity (corresponding to the Solar Generation 6 scenario.)¹⁴ We also compare the projected metals production requirements to estimates of global metals reserves. We note, however, that the reserves estimates are revised over time to reflect newly identified mineable deposits, and therefore should not be considered fixed constraints on metals production.^{51,52}

We find that for a scenario in which 8% of the global electricity in 2030 is provided by PV (CIGS, CdTe, or c-Si), and under the assumption of medium material intensity, the required levels of annual production for In, Te, and Se exceed the estimated potential production levels for today by large amounts. The required annual Te production in 2030 also exceeds the Te reserves,⁵³ while the required annual In production in 2030 approaches the estimated In reserves. The cumulative production by 2030 would far exceed the reserves for In and Te. Ga and Si production are less constrained as discussed further below. The amount of annually recoverable In is 1,350 t/y based on the average In content of the zinc ore, sphalerite (ZnS),⁵⁴ and the annual zinc production of 13.5 million tons in 2012.³⁸ The required annual In production in 2030 to meet 8% of electricity demand (~8,300 t/y) is

about 6 times the annually recoverable In (1,350 t/y), and close to the estimated global In reserves (11,000 t).⁵⁵

The potential Te and Se production can be estimated to be around 1,430 t/y and 5,500 t/y, respectively, based on the average Te and Se content of the anode in the electrolytic copper refineries⁵⁶ and the global electrolytic copper refinery production in 2011.⁵⁷ The required production for Te to meet 8% of electricity demand in 2030 (~20,800 t/y) is an order of magnitude larger than the potential production (~1,400 t/y) and almost equal to the estimated reserves (24,000 t).⁵³ The required production for Se in 2030 (~14,700 t/y) is more than twice the potential recoverable amount (~5,500 t/y). The estimated Se reserves (120,000 t)⁵³ would be sufficient for around 8 years, at the required 2030 annual production levels.

The amount of Cd that is potentially recoverable from zinc ores can be estimated to be about 40500 t/y, based on the average Cd content of the zinc ore, sphalerite (ZnS),⁵⁴ and the annual zinc production of 13.5 million tons in 2012³⁸. For Cd, the required production in 2030 for the Solar Generation 6 scenario¹⁴ (~42,300 t/y) is also above the potential production (~41,000 t/y); however, the difference is proportionately less compared to In, Te, and Se. If the required level of annual Cd production is sustained, the estimated Cd reserves (500,000 t)⁵³ would be sufficient for around 12 years.

Ga has the highest crustal abundance among all of the byproduct metals analyzed in this paper. Ga availability can be estimated to be 12,500 t/y based on the average content of bauxite ores,⁵⁸ and the annual bauxite production in 2012, 250 million tons.³⁸ The required

Ga production in 2030 for the Solar Generation 6 scenario¹⁴ (~2,500 t/y) is almost an order of magnitude below the estimated maximum recoverable Ga based on today's bauxite production levels (~12,500 t/y), and much lower than the estimated Ga reserves (400,000 t).⁵⁹

Unlike the byproduct metals discussed above, Si is abundant: it comprises about 28% of the Earth's crust as a constituent of various minerals.⁶⁰ Although the U.S. Geological Survey does not report quantitative estimates of Si reserves, it states that the reserves are ample.⁵³ If the annual Si production grows at its historical average annual growth rate of 2.2% (as shown in Figure 1), then the annual Si production in 2030 will reach 11.5 million t/y in 2030. This is only 6% lower than the annual Si production level required by the Solar Generation 6 scenario¹⁴ in 2030, which is 12.2 million t/y.

4. Conclusion

Continued rapid growth in PV deployment could require significant growth in the supply of some metals. In this paper, we estimate the growth rates needed in metals production to match PV deployment projections in 2030 for a range of future energy scenarios. We compare the required growth rates for six PV metals (In, Ga, Se, Te, Cd, and Si) with the historical growth rates observed for a large set of metals. We also compare the required production levels of the byproduct metals to their scalability potential based on metals reserves estimates.

The annual growth rates required for the byproduct metals (In, Ga, Te, and Se) production to satisfy the energy scenario-projected PV demand levels in 2030 are either unprecedented or fall on the higher end of the

historical growth rates distribution. Growth projections for CdTe (CIGS) to supply 3% (10%) or greater electricity demand by 2030 would require unprecedented metals production growth rates for Te {In}. These estimates are for the medium material intensity case. The required metals growth rates will be even higher if material intensity remains at today's levels, the "high materials intensity" case. In contrast, our results suggest that c-Si technology can provide up to 100% of global electricity in 2030 without Si production exceeding the historical growth rates observed across a large set of metals.

The scalability potential of In, Te, and Se also fall short of the required production levels for these metals in 2030 based on estimated metals reserves. Ga has a higher scalability potential based on its higher abundance in bauxite ores. The Cd supply does not appear to be constraining because of its higher abundance in ores and decreasing demand by non-PV uses due to its toxicity. Finally, Si supply restrictions do not appear to pose a binding scalability constraint, due to the abundance of this metal.

This paper focuses on three main PV technologies that have been commercialized, CdTe, CIGS and c-Si. We find that at least one of these technologies, c-Si, is scalable based on the analysis of required metals production growth rates and Si availability. When the high processing costs of Si are considered, there is still room for improvement and possibly the introduction of non-Si based PV technologies, in order to reduce module costs. This study highlights, however, the importance from a scalability perspective of reducing the material intensity of other PV technologies (for example by using concentrators), or utilizing earth abundant materials. These general insights apply to a range of existing and future PV technologies.

In this paper, the required metals growth rates reported rely on estimates of the future demand for non-PV end-uses, based on the range of observed historical growth rates of these metals. We note that if non-PV end-uses grow more rapidly or slowly than observed historically, the comparison of projected and historical growth rates to meet PV scenarios would change.

The analysis of required growth rates in the context of historical growth rates provides a new perspective for assessing the raw material needs for future energy deployment scenarios. This approach can also be useful for analyzing the materials requirements of other technologies, to assess their scalability and inform technology development and research investment. We note that while the availability of raw materials is a necessary condition for scaling up technology production, other factors including production energy requirements^{61,44,45} and the regional distribution of resources,⁴⁷ should also be considered in an analysis of sufficient conditions for scalability.

Acknowledgment

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Supplementary Information

METALS ANALYZED FOR HISTORICAL GROWTH RATES

We analyze the growth rates in the historical production of 31 metals and 1 metal group: Ag, Al, As, Au, Be, Bi, Cd, Co, Cr, Cu, Ga, Ge, Hg, In, Mg, Mn, Mo, Nb, Ni, platinum group metals, Pb, Re, Sb, Se, Si, Sn, Sr, Ta, Te, V, W, Zn. Metals are chosen on the basis of available data from the U.S. Geological Survey. Elements whose production are reported in gross weight (e.g. oxides) are not included in this analysis (B, Fe, Li, Ti, Zr, rare earth elements). Other elements are not included due to lack of world production data (Cs, Hf, Th, Tl), although USGS provides other information for these elements.

PURITY OF METALS TRACKED BY US GEOLOGICAL SURVEY

Metals are produced and traded at a variety of purity levels based on market standards. For many byproducts the raw material has already been partially refined to higher levels of purity. See Table S3.

Table S3 Purity of Metals Tracked by the US Geological Survey^{62,63,64,65,66}

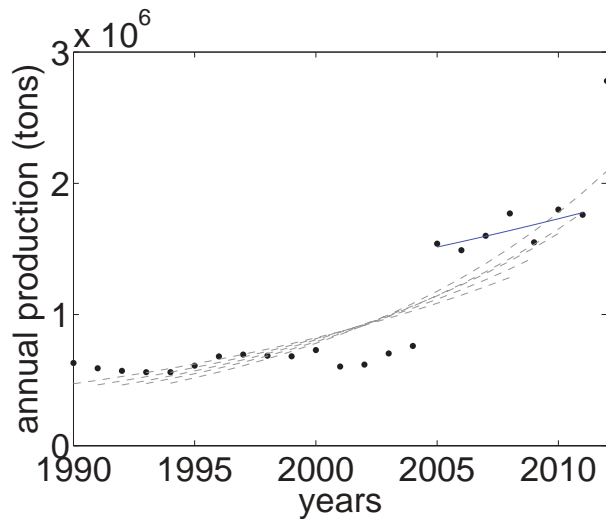
Metal	Range of purity in production data
In	99.97% – 99.99%
Ga	99.99% – 99.99999%
Se	90%+
Cd	99.95% – 99.99%
Te	99.99%
Si	55% – 99.99%+
MG-Si	98% – 99%

ANALYSIS OF MG-SI

Purity grade reported by the US Geological Survey (USGS) varies. (See Table S1.) Byproduct metals such as Te are generally tracked at higher levels of purity than primary metals such as Si, since only the refined byproduct is globally traded. Because of this, we carry out an additional analysis on metallurgical grade Si (MG-Si), a higher purity form of Si that is the precursor to most (97%) Si used in solar cells,^{44,45,46} to see whether this similarly partially-refined material with smaller production scale is able to support deployment of Si-based PV. This analysis also limits the raw Si resource, since currently metallurgical grade Si is produced more selectively from silica deposits with relatively low starting level of impurities.⁴⁷

We obtain data for MG-Si from the USGS, which publishes world production of MG-Si starting in 1990. (Fig. S1.) Beginning in 2005, the production data for MG-Si began including production from China, leading to a significant jump upward in the data series. As in the case of tellurium, due to this change in the method of reporting we do not use data prior to 2005. The most recent data year is 2012, and has production noticeably higher than the rest of the series. We note that recent commodity summaries^{67,68,66} have often revised the most recent year's production as new data becomes available, which may explain the jump in 2012. Because it is not clear that the method of reporting is the same for this year we have removed it. From 2005 to 2011, the average growth rate in MG-Si is 2.7% per year. Below we also report the results if we do not make these exclusions and instead use all data from 1990 to 2012.

Figure S1 Historical Production of MG-Si (gross weight), 1990–2012

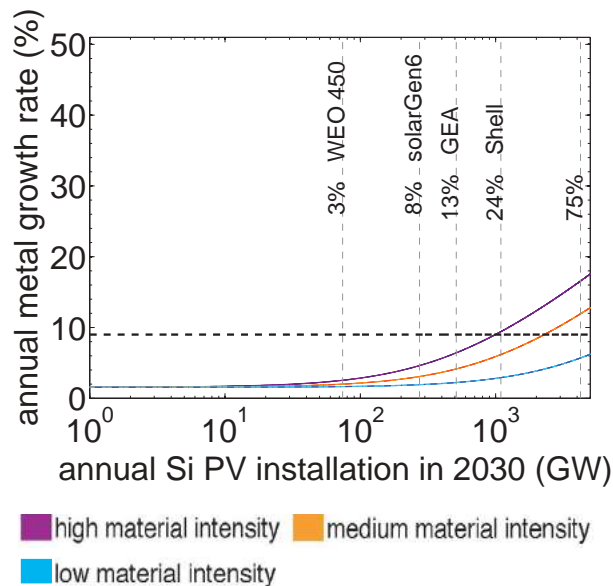


Black points show the actual production data obtained from USGS mineral yearbooks from 1994 to 2012. Lines are obtained by fitting a line to the natural logarithm of the production data (using the least squares method) for each 18-year period in 1990–2012. The slope of the each fitted line represents the annual growth rate for that 18-year period. The method of reporting MG-Si production data changed in 2008, resulting in an arbitrary jump from 2004 to 2005. The most recent value (2012) is also artificially high. See text for discussion. Only the 2005–2011 period is used here to estimate the average annual growth rate (blue fitted line).

Most production (around 80%) is used to produce silicones, aluminum alloys, and chemicals, while about 20% is used to produce polycrystalline Si.²² Of the amount that goes toward polycrystalline Si, around 90–93% is used by the solar industry,^{69,66} with the remainder going to the semiconductor industry. Thus we estimate that about 82% of the 2012 production represents non-PV end uses of MG-Si.

Required growth rates for MG-Si are shown in Fig. S2. Under a medium material intensity, when non-PV end uses of MG-Si grow at 2.7%, required growth rates exceed the historical rates when providing above 100% of electricity generation. Even if we take the MG-Si data at face value and include years before 2005 and the year 2012 for measuring the MG-Si growth rate, the median growth rate over all 18 year periods is 6.8% per year. In this case, required growth rates still exceed the historical rates only when providing above 100% of electricity generation.

Figure S2 Required Growth Rates for MG-Si to Reach a Range of Annual PV Installation Levels in 2030



Non-PV end uses of MG-Si are assumed to grow at the historical growth rate for MG-Si between 2005 and 2011 ($n_{MG-Si} = 2.7\%$). The bands with different colors show the required growth rates for different levels of material intensities given in Table 2 of the main article. See caption of Fig. 4 of the main article for additional detail.

HISTORICAL YEAR-TO-YEAR GROWTH RATES

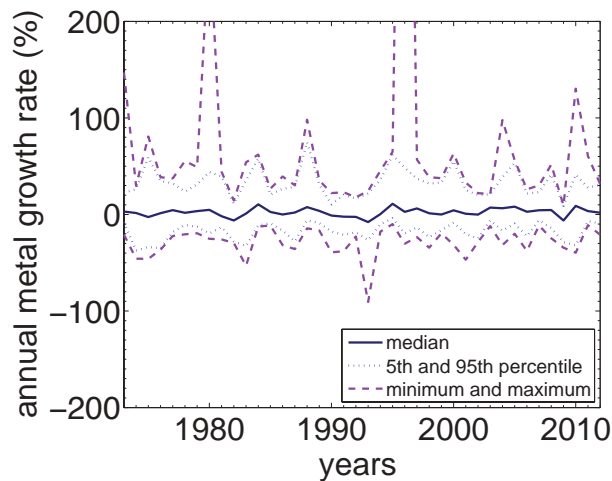
See Figure S3.

REQUIRED GROWTH RATES FOR SILVER

See Figure S4 for estimates of the required growth rates for silver. The current material intensity for silver used in c-Si technology is estimated at 57 metric tons/GW.³⁵ This is used for the high material intensity case in Figure S4. The medium intensity case of 47 tons/GW is

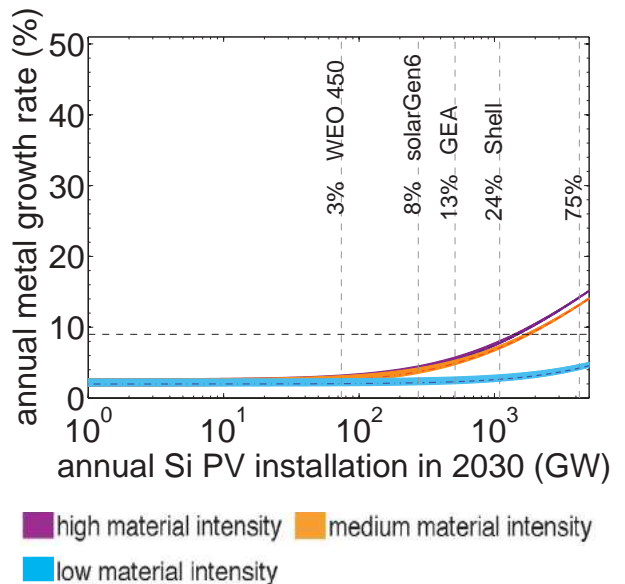
calculated based on an efficiency improvement in the c-Si technology from 14.8% to 18% in 2030.³⁶ The low intensity case is estimated by using a contingency scenario from the literature,⁷⁰ in which silver is almost completely eliminated from the c-Si technology. By using this paper's prediction of a tenfold decrease in silver intensity per cell area and considering an efficiency improvement of about 40% compared to today,³⁶ the low intensity case is estimated at 4 tons/GW.

Figure S3 Year-to-Year Growth Rates in Metals Production



Year-to-year growth rates in metals production have no apparent trend up or down over time. The solid midline is the median of the growth rates of 32 metals for each year. The blue dotted lines show the 5th and 95th percentiles. The dashed purple lines show the minimum and the maximum growth rates observed.

Figure S4 Required Growth Rates for Silver



Required growth rates for silver for a range of material intensity estimates and annual c-Si deployment levels in 2030. The lower and upper ends of each band are obtained by assuming that the non-PV end-uses grow at rates equal to the 1st and 3rd quartiles, respectively, of the historical growth rate distribution of that metal over each 18-year period between 1972–2012.

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