Growth in Metals Production for Rapid Photovoltaics Deployment

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***Abstract*—If global photovoltaics (PV) deployment grows rapidly, the required input materials need to be supplied at an increasing rate. We quantify the effect of PV deployment levels on the scale of annual metals production. If a thin-film PV technology accounts for 25% of electricity generation in 2030, the annual production of thin-film PV metals would need to grow at rates of 15-30% per year. These rates exceed those observed historically for a wide range of metals. In contrast, for the same level of crystalline silicon PV deployment, the required silicon production growth rate falls within the historical range.**

***Index Terms*—gallium, indium, photovoltaics, thin-film photovoltaics, tellurium.**

I. Introduction

The large-scale adoption of low-carbon energy technologies such as PV is essential for reducing greenhouse gas emissions. Although PV provides only 0.4% of the world's electricity generation today [1], its deployment is growing at 30% per year [2]. The future level of PV adoption has been estimated by energy scenarios developed by international organizations [3], [4], industry associations and environmental agencies [5], [6], energy companies and other corporations [7], [8] and academic institutions and researchers [9], [10].

These energy scenarios project future PV deployment levels based on varied assumptions about the determinants of energy demand and the technology outlook. Other studies have explored the extent of PV deployment that is possible under certain metal constraints such as annual metal production levels or reserves [11]–[13]. These studies have also considered the potential for decreasing the material intensity of PV technologies.

In this paper, we provide a new perspective by putting the projected PV metal requirements into a historical context. We focus on the changes in metals production over time rather than the absolute amounts. Our motivating question is 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.

We explore the required growth rates of metals production for PV installations to reach the levels projected in a range of published energy scenarios. We focus on the elements used in the absorber layer of the major PV technologies in production today: silicon for crystalline silicon (c-Si), tellurium for cadmium telluride (CdTe), and indium, gallium and selenium for copper indium gallium diselenide (CIGS). (Future work may focus on additional PV technologies.) To assess the implications of the projected PV growth for the metals sector, we compare the required growth rates to the past production growth rates of a large set of metals.

II. Methods

In this paper, we estimate the required growth rates of metals production to satisfy projected PV deployment levels in 2030. We obtain the cumulative installed PV capacity figures from a number of published energy scenarios with projections ranging from low to high PV deployment (Table I).

In addition to considering published energy scenarios, we also explore the required growth rates in metals production if PV is to provide 25% of the projected global electricity generation in 2030 (30000 TWh [3]). Assuming an average capacity factor of 15% [5], the cumulative installed PV capacity needs to be approximately 5700 GWp to reach 25% of the global electricity generation (Table I, 5th row). Assuming that cumulative PV installations grow at a constant annual growth rate from 2012 to 2030, approximately 1100 GW of PV will be installed during 2030.

To calculate the required growth rates in metals production, we first estimate the required production in 2030 for each metal of interest (Si, Te, In, Ga, and Se). We then calculate the annual growth rate required to reach the 2030 metal production level.

When estimating the required metal production in 2030, we take into account the projected demand for the metal both by the PV sector and non-PV end-uses of the metal,

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

where

- P_β required production for metal β in 2030 (metric tons (t))
- X_α deployment for PV technology α during 2030 (GW)
- $I_{\alpha\beta}$ intensity of metal β for PV technology α (t/GW)
- N_β metal β used by non-PV end-uses in 2012 (t)
- n_β annual growth rate in non-PV end-uses of metal β

The metal demand by the PV sector in 2030 is determined both by the annual deployment of the relevant PV technology in 2030, X_α, and the material intensity of the PV technology, $I_{\alpha\beta}$, in 2030. The annual PV deployment in 2030, X_α, is calculated by using the cumulative installed PV capacity for

TABLE I
CUMULATIVE INSTALLED PV CAPACITY PROJECTIONS FOR 2030

Energy Scenario	Cumulative installed PV capacity (GW)
IEA WEO 450 [3]	720
Solar Gen. VI [5]	1850
GEA [9]	3000
Shell [7]	5500
25% of electricity from PV[1]	5700
Jacobson and Delucchi [10]	17000

Note: Installed capacity figures rounded to nearest ten GW.
[1] Assuming 30000 TWh electricity generation in 2030 [3], and an average capacity factor of 15% [5] for PV.

2030 projected by the energy scenarios (as shown in Table I) and assuming constant annual growth in installed capacity from 2012 to 2030. The material intensity, $I_{\alpha\beta}$, for a metal in a PV module is

$$I_{\alpha\beta} = \frac{t_\alpha \rho_\alpha w_{\alpha\beta}}{\sigma \eta_\alpha U_{\alpha\beta} y_\alpha} \tag{2}$$

where

- t_α thickness of absorber layer for PV technology α
- ρ_α density of layer for PV technology α
- $w_{\alpha\beta}$ mass fraction of metal β within the layer for PV technology α
- η_α module efficiency for PV technology α
- σ solar constant (1000 W/m^2)
- $U_{\alpha\beta}$ utilization fraction of metal β in manufacturing PV technology α
- y_α yield in cell and module manufacturing for PV technology α

We consider a range of material intensity estimates for each PV metal in 2030. Table II shows the parameters used to obtain high, medium and low material intensity values for each metal. The resulting material intensities are about 640-6630 t/GW for silicon in c-Si, 20-160 t/GW for tellurium in CdTe, 10-30 t/GW for indium, 2-10 t/GW for gallium, and 20-160 t/GW for selenium in CIGS after material losses during manufacturing are taken into account.

After calculating the required metal production in 2030, P_β, we calculate the growth rate, r_β, required for the 2012 metals production to reach the 2030 level by assuming a constant annual growth rate and using equation (3):

$$P_\beta = P0_\beta \times (1 + r_\beta)^{18} \tag{3}$$

where

- $P0_\beta$ production of metal β in 2012 (from [23]–[28])
- P_β production of metal β in 2030

In this analysis, we also compare the projected growth rates, r_β, to historical growth rates of metals production to understand the extent of production growth that happened in the past and whether the projected growth rates are historically precedented. To make these comparisons, rather than studying the historical growth rates of the PV metals alone, we include in our analysis a large set of other metals in order to obtain a more complete picture of the metals production sector. For this analysis, we use the annual global production values for 35 metals obtained from the U.S. Geological Survey for the last 40 years [23]–[28].

For each metal of interest, we calculate the historical annual growth rates for each overlapping 18-year period in the time frame of 1972-2012 by fitting lines to the natural logarithm of the production values using the least-squares method (Fig 1(a) - Fig. 1(e)). The slope of the fitted line in each overlapping 18-year period represents the growth rate of production in that period. By calculating the growth rates for these overlapping periods, we obtain a sample of growth rates over time for each metal. An 18-year time horizon is selected for fitting the lines because it matches the time horizon of the energy scenarios we are considering (2012-2030).

We then estimate the demand by non-PV end-uses in 2030 by using the median of the historical 18-year growth rates of the metal. In order to account for the variability in the historical growth rates and the uncertainty regarding the future, we calculate a confidence interval around the median growth of the non-PV end-uses by using the 1st and 3rd quartile of the historical growth rates.

III. RESULTS AND DISCUSSION

In this section, we show the growth rates for metals production required to reach various projected annual PV installation levels (Table I and Fig. 2) and compare them to historical growth rates in metals production (Figs. 1 and 2). We discuss the results obtained for different material intensity levels and focus on two of the energy scenarios: the GEA scenario [9] and the scenario in which a quarter of electricity is provided by PV.

Fig 1(a) - Fig. 1(e) show the annual production values for metals over time and the fitted lines used to estimate the historical annual growth rates in metals production. Fig. 2(f) shows the histogram of the historical annual growth rates of all the 35 metals obtained over all 18-year periods in 1972-2012. We obtain the historical annual growth rates as explained in the Methods section. The median annual growth rate observed is 2.4%. Based on the analysis of historical growth rates, we interpret 5% per year as an upper end of a business-as-usual growth. 20% of the growth rates are above 5% per year and only 3% of the growth rates are above 10% per year. A 10% annual growth rate means that the production of the metal increases by a factor of 5.5 over an 18-year period. No growth rates above 14% have been observed.

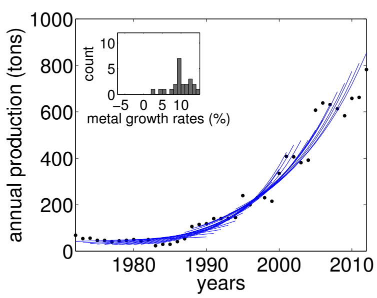
Fig. 2 provides the projected annual metals production growth rates associated with a wide range of PV installation targets in 2030 based on energy scenarios (Table I). To obtain the growth rates shown in Fig. 2, we assume that 90% of the annual installations in 2030 are c-Si, whereas CdTe and CIGS each have a 5% share, close to their current shares [16].

The metals growth rates required to meet the investigated PV growth scenarios are in several cases higher than 5% (our

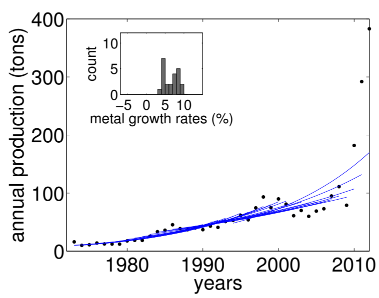
TABLE II
PARAMETERS FOR MATERIAL INTENSITY AND THE RESULTING MATERIAL INTENSITY, $I_{\alpha\beta}$, FOR EACH ELEMENT

Elements	Cases	t_α (μm)	η_α (%)	$U_{\alpha\beta}$ (%)	y_α (%)	ρ_α (g/cm^3)	$w_{\alpha\beta}$ (%)	$I_{\alpha\beta}$ (t/GW)
Si in c-Si	high	180	14.8	45	95	2.33	100	6629
	medium	120	18	55	98			2882
	low	50	20.5	90	99			638
Te in CdTe	high	2.5	11.7	50	85	5.85	53	156
	medium	2	14	70	90			70
	low	1	18	95	97			19
In in CIGS	high	2	14	75	73	5.75	22	28
	medium	1.2	15.7	80	90			13
	low	1.1	20	95	98			7
Ga in CIGS	high	2	14	75	73	5.75	7	9
	medium	1.2	15.7	80	90			4
	low	1.1	20	95	98			2
Se in CIGS	high	2	14	30	85	5.75	50	161
	medium	1.2	15.7	60	90			41
	low	1.1	20	95	98			17

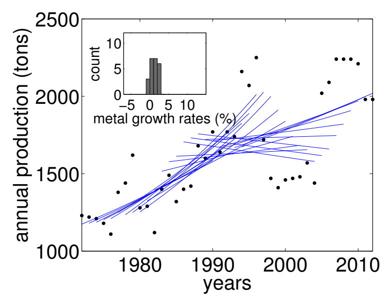
References:
Si: ρ_α [14]; all remaining parameters [15].
Te: t_α high, ρ_α, $w_{\alpha\beta}$ [13]; η_α high, η_α low [16]; t_α medium, t_α low, $U_{\alpha\beta}$ high, $U_{\alpha\beta}$ low, y_α high, y_α medium [17]; η_α medium [18]; $U_{\alpha\beta}$ medium [19]; y_α low [20].
In, Ga, Se: t_α high [13], [18]; t_α medium, t_α low [18]; η_α high [21]; η_α medium, ρ_α, $w_{\alpha\beta}$ for In, $w_{\alpha\beta}$ for Ga [13]; η_α low [17]; $U_{\alpha\beta}$ high for In, $U_{\alpha\beta}$ high for Ga [13], other $U_{\alpha\beta}$ values [17]; $w_{\alpha\beta}$ for Se [22]; y_α high for In, y_α high for Ga [13], other y_α values [17].



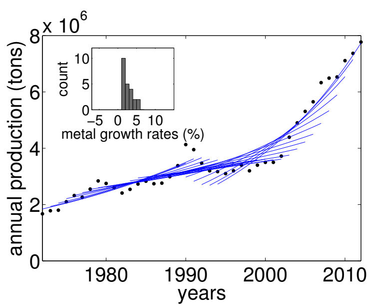
(a) Indium



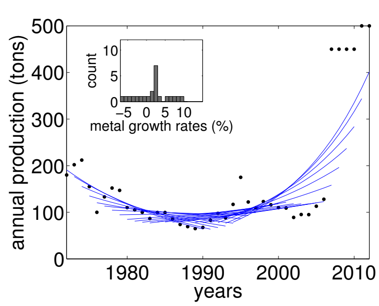
(b) Gallium



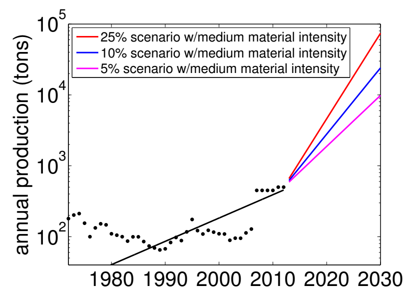
(c) Selenium



(d) Silicon

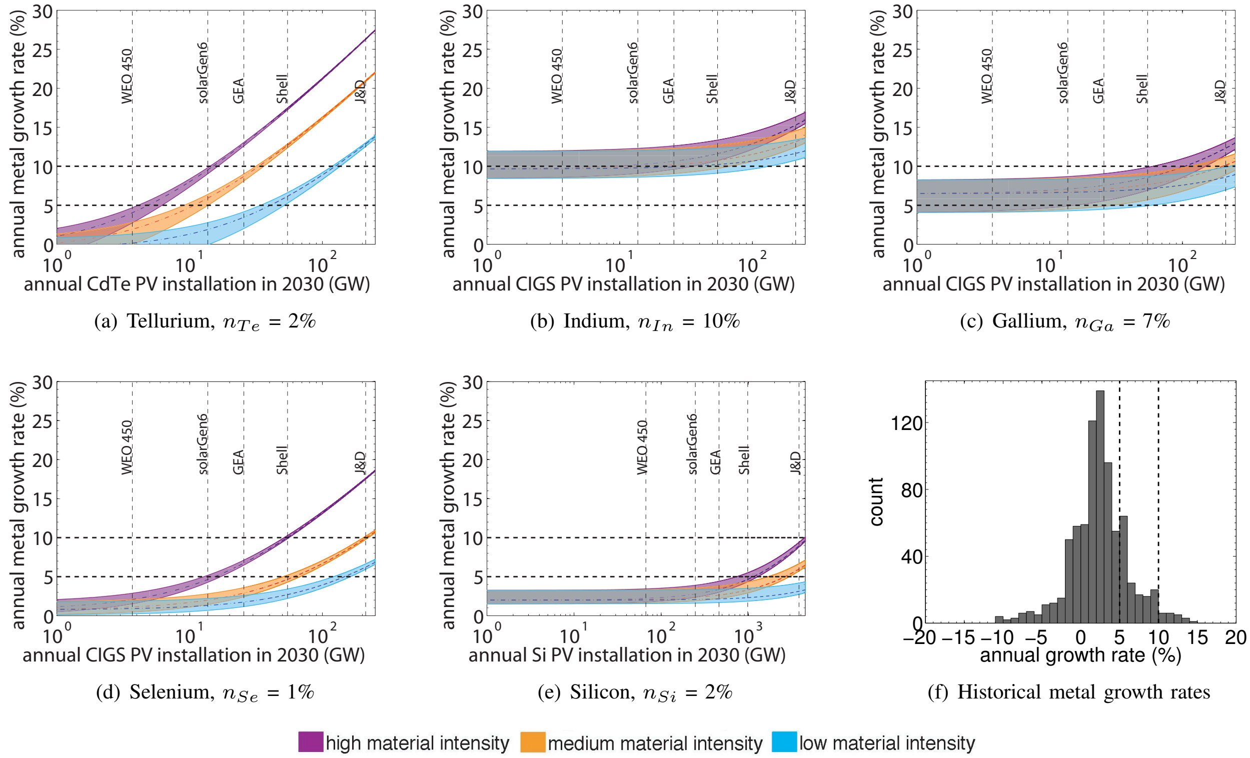


(e) Tellurium



(f) Projected tellurium production

Fig. 1. (a) - (e): 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 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. Note that the goodness of fit varies substantially across the metals and time periods investigated. Reported growth rates are rough estimates of the scale of increase in production. (f): Projected annual tellurium production assuming CdTe provides 25%, 10%, and 5% of the world's electricity generation in 2030. Projections are shown for medium material intensity (70 t/GW). The annual Te production increases at a rate of 32%, 24%, and 18% per year for these installation levels, respectively. The non-PV end-uses of tellurium are assumed to grow at the median historical growth rate of tellurium, which is 2% per year.



(a) Tellurium, n_{Te} = 2%

(b) Indium, n_{In} = 10%

(c) Gallium, n_{Ga} = 7%

(d) Selenium, n_{Se} = 1%

(e) Silicon, n_{Si} = 2%

(f) Historical metal growth rates

Fig. 2. (a) - (e): 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 II. The energy scenarios report only the total PV installations, not the distribution across PV technologies. Here we assume that 90% of the annual installations in 2030 are c-Si, whereas CdTe and CIGS have 5% share each, which are close to the current levels [16]. The bands are obtained by assuming different rates for the non-PV end-uses of the metals. 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 of the historical growth rate distribution of that metal, respectively. The median historical growth rate (n) of each metal is shown below each plot. The vertical lines indicate the assumed annual installation level for the PV technology corresponding to each energy scenario. (f): Histogram shows the distribution of the historical annual growth rates of production of 35 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 annual growth rate is 2.4%. Only 20% of the growth rates are above 5%, and 18 out of 35 metals experienced growth rates that are above 5% in at least one of the 18-year periods in 1972-2012. On the other hand, only 3% of the growth rates are above 10%, and only 4 out of 35 metals experienced growth rates above 10% in at least one of the 18-year periods in 1972-2012.

historical benchmark) for thin-film PV metals. For example, in the GEA scenario [9], if CdTe supplies 5% of the total installations, CdTe installation is 25 GW in 2030. In this case, as Fig. 2(a) shows, the annual Te production needs to grow at a rate of 13% per year for the high material intensity case, 9% for the medium material intensity case, and 2-4% for the low material intensity case over the next eighteen years. The medium and high material intensity cases result in rates that are on the higher end of the historical growth rate distribution for all metals shown in Fig. 2(f). It must be noted that, as Table I shows, in the case of Te, the low material intensity is lower than the high intensity almost by a factor of 10.

As shown in Fig. 2(a), Te must grow at rates higher than 5% per year for 2030 annual CdTe installation levels above around 5 GW for the high material intensity, 10 GW for the medium material intensity, and 40 GW for the low material intensity case. The Te annual growth rates exceed 10% if the 2030 annual CdTe installations exceed 15 GW for the high material intensity, 35 GW for the medium material intensity, and 130 GW for the low material intensity case.

These required growth rates are calculated based on the assumption that they are sustained every year over the next eighteen years. A 10% annual growth rate over an 18-year period means that Te production would have to increase from around 500 t per year today [28] to 2780 t per year, a major increase as compared to historical production levels [29], [30].

The GEA scenario combined with the assumption that CdTe provides 5% of the PV installations projected in this scenario means that CdTe provides less than 1% of the world's electricity generation (0.65%) in 2030. If CdTe PV is to provide a more significant share, the required growth rates in thin-film PV metals exceed the historical growth rates experienced by many metals in the last 40 years. Fig. 1(f) shows one example of a production projection for tellurium using the method described in the Methods section. In this example, CdTe is assumed to provide 5%, 10% and 25% of the world's annual electricity generation in 2030. For these levels of contribution to global electricity generation, the annual CdTe installations in 2030, X_α, are 140, 360, and 1100 GW, respectively. The projections are made for the medium material intensity case and result in required annual growth rates, r_β, of 18%, 24% and 32%. These are unprecedented growth rates.

Fig. 2(b) - Fig. 2(d) show the growth rates required for In, Ga, and Se for various levels of CIGS PV installations. In the GEA scenario [9], if CIGS supplies 5% of the total installations, CIGS installation is 25 GW in 2030. In this case, assuming high material intensity, the required growth rates would be 10-13% for In, 6-9% for Ga, and 6-7% for Se. These growth rates are on the higher end of the historical growth rates. For In, the medium and low material intensity cases still require growth rates above 9%. The medium and low material intensity cases require approximately 4-8% growth rates for Ga and 1-3% for Se.

For In and Ga, the low and medium material intensity cases do not result in much difference in growth rates for the range of PV installation levels shown in Fig. 2 because the growth of non-PV demand for these metals is projected to be high and determine the lower bound of the required future growth rates. The median historical growth rates for these metals are n_{In} = 10% and n_{Ga} = 7%, which are on the higher end of the historical growth rates of all metals. Te growth rates are more directly related to the level of PV installations than CIGS metals are because a larger fraction of Te (40%) is used for PV compared to the CIGS metals that only have 5% of their production dedicated to PV uses.

If CIGS is to provide a higher portion of electricity generation, reaching a quarter of the electricity generation in 2030 (30000 TWh [3]), the required growth rates in CIGS metals must increase significantly. As explained earlier, in this scenario, the cumulative installed PV capacity would be 5700 GW and the annual addition to installed capacity in 2030 would be 1100 GW. If we assume that CIGS provides all of these installations, then the required growth rates would be 18-24% for In, 13-20% for Ga, and 15-28% for Se for the low to high material intensity range. These growth rates far exceed the highest observed annual growth rate of 14%.

Fig. 2(e) shows that for the high intensity case silicon production growth rate needs to exceed 5% only beyond an annual c-Si installation level of 750 GW. The medium intensity case results in a growth rate above 5% per year only after 2000 GW annual c-Si installation is exceeded. In the low material intensity case, the required growth rates stay below 5% per year for the range of annual installation values we explored. We observe that even for the case where c-Si provides a quarter of the electricity generation in 2030 (1100 GW installation in 2030), the required growth rates for Si do not exceed 3%, 4% and 5% for the low, medium, and high material intensity cases, respectively.

In contrast to the thin-film PV metals, Si will require growth rates below 10% almost up to 4000 GW of c-Si projected in 2030 for the high material intensity case. The required growth rates for Si do not go above the historical rates even for the high material intensity case for the range of installation levels we explored.

IV. Summary and Conclusions

A rapidly growing PV sector would require metals supply to grow as well. In this work, we focused on the annual PV installation levels for 2030 projected by energy scenarios and the corresponding annual metals production requirements. We then calculated the annual growth rates needed for the production of absorber materials of CIGS, CdTe and c-Si. We compared these rates to historical growth rates observed for a wide range of metals.

If CdTe (or CIGS) is to provide even 1% of the projected electricity generation in 2030 (30000 TWh [3]), metals production needs to grow at unprecedented rates unless there are dramatic decreases in material intensity. We have shown that even for the GEA scenario, the required growth rates are above 10% for Te and In, and lower than but close to 10% for Ga and Se for today's material intensity levels. If either CdTe or CIGS is to provide 5% of the electricity generation in 2030, the required growth rates for the thin-film PV metals exceed 5% even for the low intensity case and approach 20% for the high intensity case. If thin-film technologies are to provide a higher share of the electricity generation in 2030, such as a quarter, then the growth rates required for thin-film PV metals would be unprecedented.

On the other hand, c-Si utilizes a very abundant element, silicon, and is much less affected by increasing installation rates. One of the most important results to emerge from this analysis is that even for the highest levels of c-Si installations, the growth rate required for Si would not be unprecedented.

The uncertainty about the metal demand by non-PV end-uses is important for this analysis. The required growth rates resulting from our analysis depend on the assumptions about the non-PV uses of the metals. In this paper, we used historical metal growth rates to obtain the growth of non-PV uses. We estimated a median future growth rate for non-PV uses by using the median historical growth rate of the metal and also added an uncertainty band around the median. Despite the uncertainty regarding the future growth of the non-PV uses, the main message of the analysis is robust to the assumptions.

The analysis of historical growth rates provides a benchmark against which we can assess metal needs associated with future energy scenarios. This approach can provide useful information for other technologies that also use these metals.

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