Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supplementary Information for

Metals Production Requirements for Rapid Photovoltaics Deployment

Goksin Kavlak, James McNerney, Robert L. Jaffe, Jessika E. Trancik

March 27, 2015

1 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.

2 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 S1.

Metal	Range of purity in production data
In	99.97% – 99.99%
Ga	99.99%- – 99.999999%
Se	90%+
Cd	99.95% – 99.99%
Te	99.99%
Si	55% – 99.99%+
MG-Si	98 – 99%

Table S1: Purity of metals tracked by the US Geological Survey. Source: [1, 2, 3, 4, 5]

3 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 [6, 7, 8], 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 [9].

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 [10, 11, 5] 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.

Most production (around 80%) is used to produce silicones, aluminum alloys, and chemicals, while about 20% is used to produce polycrystalline Si [12]. Of the amount that goes toward polycrystalline Si, around 90-93% is used by the solar industry [13, 5], 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.

4 Historical Year-To-Year Growth Rates

See Figure S3.

5 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 [14]. 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 [15]. The low intensity case is estimated by using a contingency scenario from the literature [16], 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 [15], the low intensity case is estimated at 4 tons/GW.

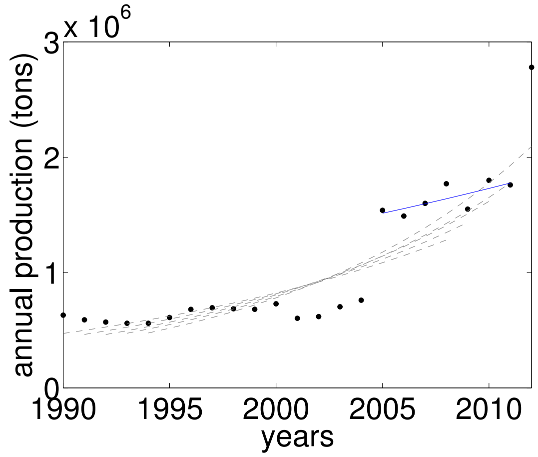

Figure S1: Historical production of MG-Si (gross weight), 1990-2012. Black points show the actual production data obtained from USGS mineral yearbooks from 1994 to 2012. Lines are obtained by fitting a line to the natural logarithm of the production data (using the least squares method) for each 18-year 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).

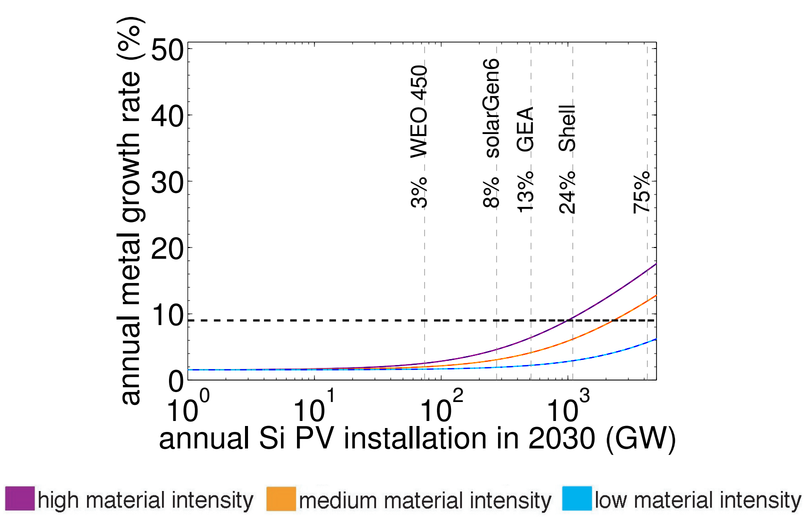

Figure S2: Required growth rates for MG-Si to reach a range of annual PV installation levels in 2030. Non-PV end uses of MG-Si are assumed to grow at the historical growth rate for MG-Si between 2005 and 2011 ($n_{MG-Si} = 2.7\%$). The bands with different colors show the required growth rates for different levels of material intensities given in Table 2 of the main article. See caption of Fig. 4 of the main article for additional detail.

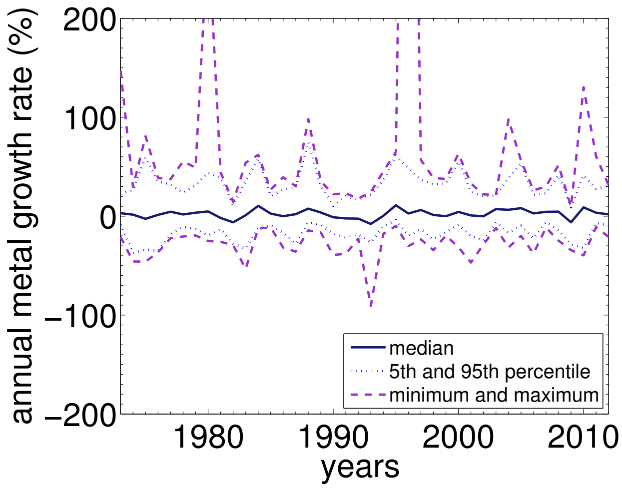

Figure S3: Year-to-year growth rates in metals production have no apparent trend up or down over time. The solid midline is the median of the growth rates of 32 metals for each year. The blue dotted lines show the 5th and 95th percentiles. The dashed purple lines show the minimum and the maximum growth rates observed.

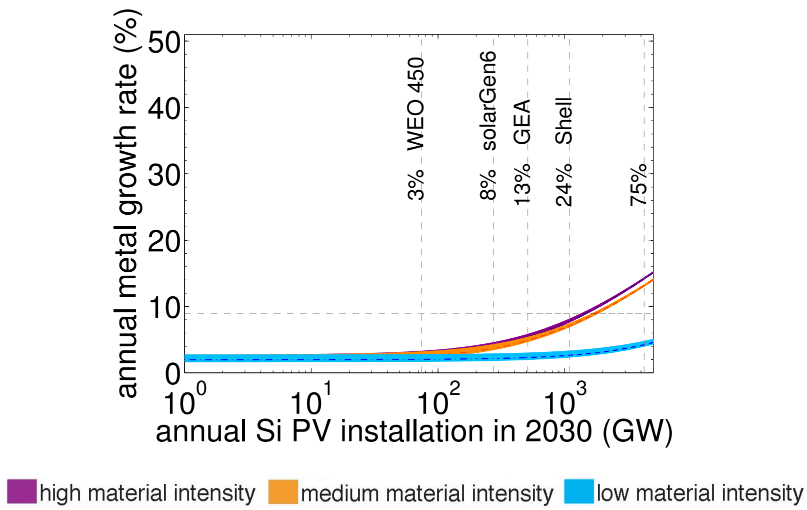

Figure S4: Required growth rates for silver for a range of material intensity estimates and annual c-Si deployment levels in 2030. The lower and upper ends of each band are obtained by assuming that the non-PV end-uses grow at rates equal to the 1st and 3rd quartiles, respectively, of the historical growth rate distribution of that metal over each 18-year period between 1972-2012.

References

[1] U.S. Geological Survey. Indium Minerals Yearbook. Technical report, U.S. Geological Survey, Reston, VA, 2012.

[2] U.S. Geological Survey. Gallium Minerals Yearbook. Technical report, U.S. Geological Survey, Reston, VA, 2012.

[3] U.S. Geological Survey. Selenium and Tellurium Minerals Yearbook. Technical report, U.S. Geological Survey, Reston, VA, 2012.

[4] U.S. Geological Survey. Cadmium Minerals Yearbook. Technical report, U.S. Geological Survey, Reston, VA, 2012.

[5] U.S. Geological Survey. Silicon Minerals Yearbook. Technical report, U.S. Geological Survey, Reston, VA, 2012.

[6] Dajun Yue, Fengqi You, and Seth B. Darling. Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. Solar Energy, 105(0):669 – 678, 2014.

[7] Dajun Yue, Fengqi You, and Seth B. Darling. Corrigendum to "domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis" [solar energy 105 (2014) 669–678]. Solar Energy, 107(0):380 –, 2014.

[8] Jafar Safariana, Gabriella Tranella, and Merete Tangstada. Processes for upgrading metallurgical grade silicon to solar grade silicon. Energy Procedia, 20:88–97, 2012.

[9] Jens Götze and Robert Möckel, editors. Quartz: Deposits, Mineralogy and Analytics. Springer, 2014.

[10] U.S. Geological Survey. Silicon Minerals Yearbook. Technical report, U.S. Geological Survey, Reston, VA, 2010.

[11] U.S. Geological Survey. Silicon Minerals Yearbook. Technical report, U.S. Geological Survey, Reston, VA, 2011.

[12] Meng Tao. Terawatt Solar Photovoltaics. Springer Briefs in Applied Sciences and Technology. Springer London, 2014.

[13] Greentech Media. Polysilicon 2015-2018: Supply, demand, cost and pricing, http://www.greentechmedia.com/research/report/polysilicon-2015-2018.

[14] D. M. Powell, M. T. Winkler, A. Goodrich, and T. Buonassisi. Modeling the cost and minimum sustainable price of crystalline silicon photovoltaic manufacturing in the United States. IEEE Journal of Photovoltaics, 3:662–668, 2013.

[15] D. M. Powell, M. T. Winkler, H. J. Choi, C. B. Simmons, D. B. Needleman, and T. Buonassisi. Crystalline silicon photovoltaics: a cost analysis framework for determining technology pathways to reach baseload electricity costs. Energy and Environmental Science, 5:5874–5883, 2012.

[16] Leena Grandell and Andrea Thorenz. Silver supply risk analysis for the solar sector. Renewable Energy, 69(0):157 – 165, 2014.