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The Thin Infrared Line: Global Trade in Elements for non-Silicon Solar Cells

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Abstract

Photovoltaic energy production has increased dramatically over the past decade as manufacturing costs have decreased, power conversion efficiencies have increased, and demand for carbon neutral electricity has grown. Silicon-based solar cells represent the largest market share within the photovoltaic industry, with the remainder substantially composed of the thin-film materials cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). The materials used in CdTe and CIGS are less common and their available supply is mediated by a long value chain. This article examines those value chains, including mining, refining, and solar cell manufacturing to discuss potential bottlenecks for future production. While there is enough of these elements to meet current and near-term demand, the production of CdTe and CIGS solar cells will be fundamentally constrained due to limitations when recovering raw materials from parent ores.

Keywords: cadmium telluride, copper indium gallium selenide, thin-film, solar cells, photovoltaics.

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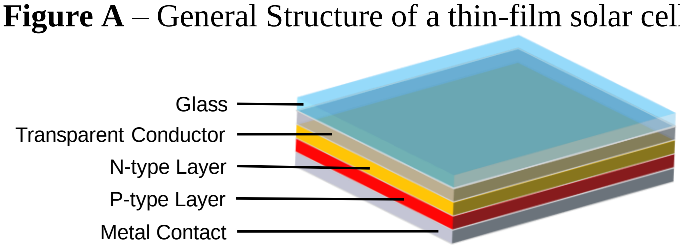
Introduction

Global installations of thin film solar cells substantially increased over the last decade and are likely to continue to grow as producers expand production capacity. The two primary commercially available thin-film technologies, cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS),[1] are reliant on chemical elements (referred to herein as “the elements”) that are relatively rare,[2] which necessitates sourcing from a global trade network (box A). This paper examines the global value chains of the elements necessary for thin-film solar cell manufacturing technology and identifies potential bottlenecks within this industry due to their sourcing.

Box A. Structure of Thin-Film Solar Cells

Thin-film solar cells have a different internal structure than other types of solar cells (see figure A). The first difference is their thickness. The layers in both CdTe and CIGS cells are only one to several micrometers thick (1 micrometer is one 25,400th of an inch), making them an order of magnitude thinner than silicon solar cells, which are most typically 140–200 micrometers thick. Both CdTe and CIGS are typically manufactured as p-type materials in these cells. A p-type material is electron accepting, while an n-type material is electron donating. To form a junction, they need to be paired with an n-type material, such as cadmium sulfide. In contrast, doped silicon is used as both the n-type and p-type materials in silicon solar cells. Doping means adding small amounts of another material, like boron or phosphorous, to create a layer with the desired properties.

Figure A – General Structure of a thin-film solar cell.



Sources: USDOE, “Cadmium Telluride” (accessed April 17, 2019); NREL, “Copper Indium Gallium Diselenide Solar Cells” (accessed April 17, 2019).

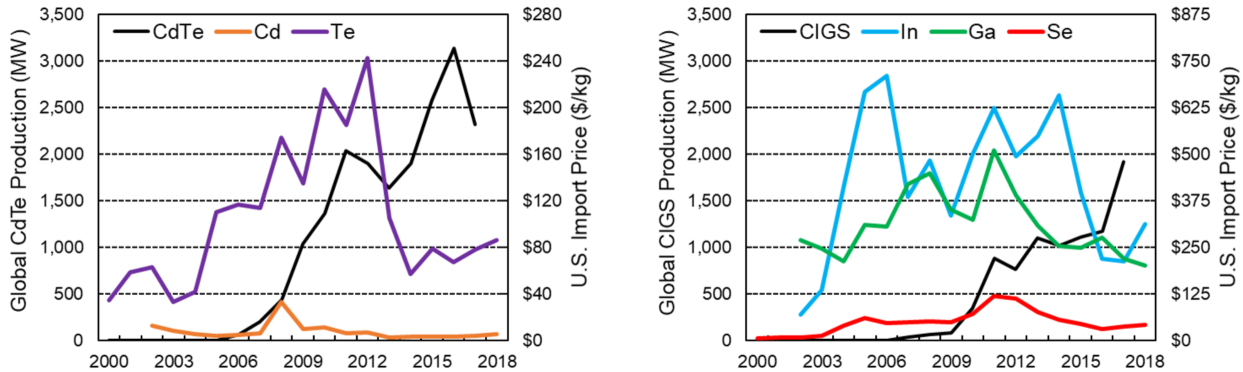
[1] While gallium arsenide is produced for use in high efficiency solar cells in space applications, it is not presently used terrestrially for power generation and is outside of the scope of this paper. Amorphous silicon, another thin-film technology, accounts for just 0.3 percent of the market and will not be discussed further. Also out of scope are the myriad research materials that have yet to find commercial production. Fraunhofer Institute for Solar Energy Systems, “Photovoltaics Report,” March 14, 2019, 22; NREL, “Best Research-Cell Efficiency Chart” (accessed July 1, 2019).

[2] Three of the elements—gallium (Ga), indium (In), and tellurium (Te)—are currently recognized by the U.S. Department of the Interior as critical materials for security and economic prosperity. 83 Fed. Reg. 23295, https://www.govinfo.gov/app/details/FR-2018-05-18/2018-10667https://www.govinfo.gov/app/details/FR-2018-05-18/2018-10667.

Market for Thin-Film Solar Cells

The global demand for both CdTe and CIGS solar cells has continued to increase over the past decade (figure 1) due to increasing light-to-electricity conversion efficiency coinciding with an increased demand for solar cells in general. Both are now being manufactured in sufficient quantities to add more than five gigawatts (GW) of new solar power to the grid every year. The Topaz Solar Farm in San Luis Obispo County, California, is an example of one utility-scale implementation of CdTe: the $2.5 billion project yields 0.55 GW_{AC} of electricity from nine million CdTe modules.[3] Five or six such projects could be completed per year based on 2016–17 global CdTe solar cell production levels. Companies like First Solar Inc. anticipate production to increase beyond that level due to planned capital investments.[4]

Figure 1. Global production of thin-film solar cells and U.S. import price of the elements.



Source: Fraunhofer Institute for Solar Energy Systems, "Photovoltaics Report," March 14, 2019, 23. USITC DataWeb/USDOC, HTS headings 2804.50.00.20, 2804.90, 8107.20, 8112.92.10, and 8112.92.30 (accessed May 23, 2019).

Note: Global production is measured by the nameplate output of the solar cells manufactured in that year in units of megawatts of electric power. Production by this metric will reflect different quantities of solar cells produced and elements used based on increasing efficiencies and decreasing film thicknesses over the period.

Increased production of thin-film solar cells will require more of each element, despite increases in device efficiency, and companies believe that it is crucial to maintain supply lines for certain elements to support growth.[5] Demand for the elements scales with solar cell demand and can be estimated by calculating how much material is required to build a solar power plant.[6] The results are summarized in table 1 (column "1 GW"), which shows that, despite each thin-film being only several ten-thousandths of an inch thick, a solar project the size of Topaz requires tens of tons of

[3] GW_{AC} means gigawatts of alternating current (AC) power. While solar panels are typically rated by their direct current (DC) power output, connecting the solar cells to the power grid requires conversion to AC. That is accomplished using an inverter, which leads to some power loss. First Solar Inc., "Topaz Solar Farm" (accessed July 8, 2019); Penn State College of Earth and Mineral Sciences, "6.5. Efficiency of Inverters" (accessed August 6, 2019); Bromberg, "Inverter Efficiency Curves" (accessed August 6, 2019).
[4] Weaver, "First Solar Sees a Doubling Coming in 2016," December 12, 2018 (accessed July 2, 2019).
[5] First Solar Inc., "2018 Annual Report," 2018, 29.
[6] See annex for calculation details.

each element (column "Topaz").[7] The quantity of material required for further solar cell expansion, regardless of price, indicates that production will be limited by a subset of the elements. For example, if all of the world's tellurium produced in 2018 were used to make CdTe solar cells, modules generating about 8–9 GW_{DC} would be produced. This upper limit (based on current supply) is already being approached by First Solar, which anticipates over 5 GW_{DC} of manufacturing capacity within the coming years.[8]

Table 1. Quantity of thin-film elements required to generate power and the available supply.

		Mass Required		Production		Reserves	
		1 GW (t)	Topaz (t)	U.S. (t/y)	Global (t/y)	U.S. (t)	Global (t)
CdTe	Cd	51	28	***	26,000	--	--
	Te	58	32	***	440	3,500	31,000
CIGS	Cu	21	11	1,200,000	21,000,000	48,000,000	830,000,000
	In	26	14	0	750	--	--
	Ga	7	4	0	350	--	1,400,000
	Se	52	28	***	2,800	10,000	99,000

Source: USGS, "Cadmium," "Copper," "Gallium," "Indium," "Selenium," and "Tellurium," February 2019.
Note: 2018 Data. See Annex I for calculation details. -- Estimates of reserves not currently available. *** Proprietary data. "1 GW" is the mass required for a one gigawatt (alternating current) power plant for each type of thin-film solar cell, while "Topaz" is the quantity estimated to be required by a utility solar project the size of Topaz, though there are wide variations in utility solar projects. All values are in metric tons (t) or metric tons per year (t/y). CdTe: cadmium telluride. CIGS: copper indium gallium diselenide. Cd: cadmium. Te: tellurium. Cu: copper. In: indium. Ga: gallium. Se: selenium.

The price of raw materials has not been a limiting factor for industry growth to date. Based on import prices in 2018, the cost from cadmium and tellurium prices to build a solar project the size of Topaz represents less than one percent of the project's budget.[9] However, at some point the industry will encounter fundamental mass limitations for how many solar cells it can manufacture due to basic constraints in sourcing raw materials. Also shown in Table 1 are the quantities of each element produced and in held in reserves both in the United States and globally. Except for copper, the United States either does not produce them (indium and gallium) or produces them in small quantities relative to the world total (cadmium, tellurium, and selenium). This necessitates a global value chain for material sourcing and production.

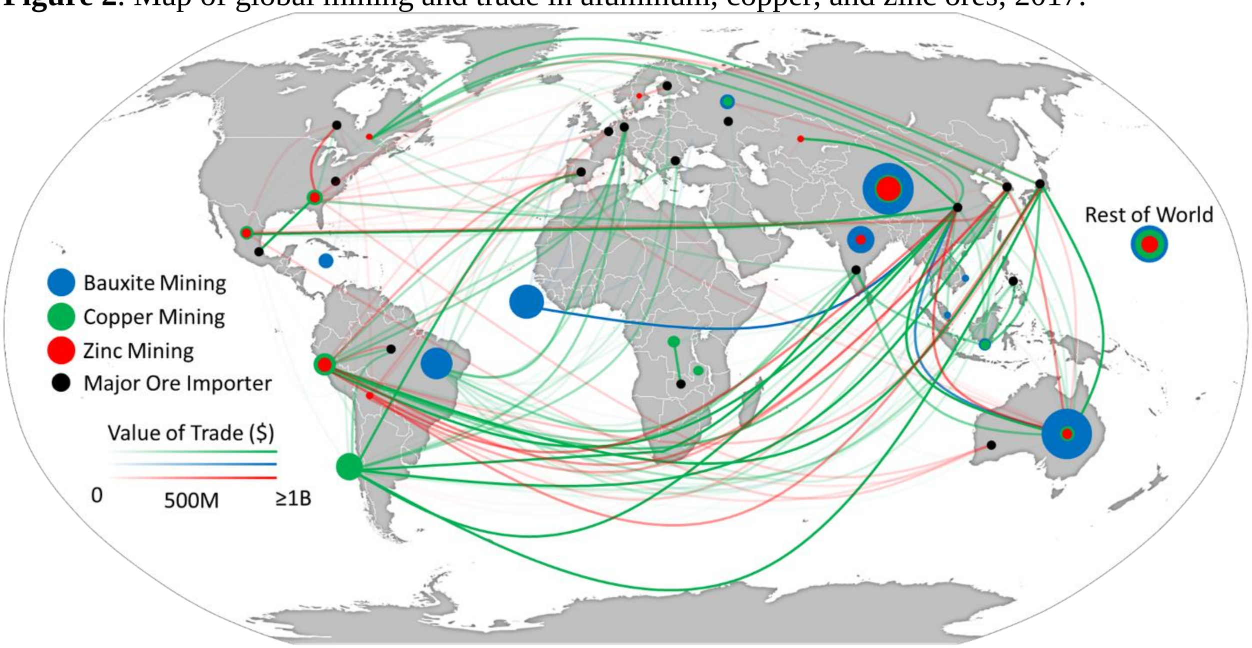
[7] Both "1 GW" and "Topaz" are calculated based on AC power output to the grid.
[8] First Solar Inc., "2018 Annual Report," 2018, 3.
[9] The actual price of highly refined elements is certainly higher than the prices shown on figure 1; however, the statement of less than one percent of total costs holds if the price of refined materials is up to 9 times greater than shown.

Element Value Chains

Identifying potential bottlenecks in the thin-film solar cell value chain involves analyzing the value chain of each constituent element, starting with mineral extraction. The five thin-film elements are all produced as by-products of commodity metal refining. Cadmium and indium are derived from zinc ores, selenium and tellurium are derived from copper ores, and gallium is derived from bauxite, the primary aluminum ore, with minor amounts from zinc refining.[10] This is driven foremost by geology, as the primary minerals of these elements are uncommon and occur in small quantities, which rarely makes direct mining and extraction feasible.

Manufacturing CdTe solar cells requires interacting with zinc and copper ore value chains, while CIGS requires interacting with the value chains of all three ores. The mining locations for each ore are geographically dispersed and not necessarily co-located, since mine placement depends on the presence of natural deposits (figure 2). For example, China has significant bauxite and zinc ore mining, but not copper, meaning CIGS and CdTe produced there would likely require inputs from foreign sources.

Figure 2. Map of global mining and trade in aluminum, copper, and zinc ores, 2017.



Source: USGS, "Copper," "Zinc," and "Bauxite and Alumina," February 2019; IHS Market, Global Trade Atlas database (accessed May 14, 2019); Simoes and Hidalgo, "The Observatory of Economic Complexity" (accessed April 15, 2019).
Note: The area of each circle is proportional to the quantity mined in that country or in all other countries not labeled (Rest of World). Major importers are defined as countries with greater than $500 million combined ore imports (see table A-4 in the annex for additional information). The color of lines corresponds to the type of ore. The transparency of each line is proportional to the trade value of that ore.

[10] See table A-2 in Annex I for a breakdown of concentrations of the elements in each ore. USGS, "Tellurium—The Bright Future of Solar Energy," April 2015; Mindat.org, "Kankberg Mine" (accessed July 5, 2019).

The trade lines for major ores connect producers in the Americas, Africa, and Australia to importers in Europe and East Asia. China is by far the largest importer, with over $31 billion worth of ore imports in 2017, the majority of which are copper to make up for China's relative lack of domestic production. Japan and South Korea have negligible domestic mining of all three ores and rely on high levels of imports to feed their manufacturing sectors. No single European country comes near the levels of Chinese production or East Asian imports, but the European Union as a whole imports over $10 billion worth of ores.[11] For a more granular analysis, the subsequent sections detail the value chains for the elements extracted from each of the parent ores.

Gallium (Bauxite)

Bauxite mining is geographically dispersed, with Australia being the largest overall producer. Mining does not necessarily correlate with further refining or complete refining of a country's output. However, Australia produces, refines, and exports tens of megatons (Mt) of bauxite per year.[12] In contrast, Guinea is working to develop domestic refining capacity but currently exports most of its mined bauxite to other countries, mainly China.[13] Brazil operates two of the world's largest refineries, reflecting its significant mining output.[14] The United States imports all of the bauxite it refines (primarily from Jamaica, Brazil, and Guinea), which is processed at multiple domestic refineries.

The first step of bauxite refining involves extracting the aluminum metal and collecting it as aluminum oxide (alumina) through the Bayer process.[15] Gallium is removed from the ore during this step as well, but only a fraction of the available material is recovered. This is due to the additional energy and equipment costs required to remove it from the rest of the non-aluminum elements.[16] When not extracted, the gallium becomes a minor component of red mud, the Bayer process waste product, which is stored in ponds near the refining location and is available for future use if needed.

China is by far the leading producer of gallium, accounting for over 90 percent of global production.[17] Japan, Russia, and South Korea are also minor producers. The majority of countries that mine and refine bauxite do not produce significant quantities of gallium. This includes the United States, which did not extract any gallium from ores in 2018.

[11] IHS Market, Global Trade Atlas database (accessed May 14, 2019).
[12] Australian Aluminium Council LTD, "Statistics (Trade)," (accessed July 02, 2019).
[13] Guinea has export taxes on bauxite, as of 2017, in order to encourage more domestic refining. Bavier, "Guinea Boosts Power Output to Foster Bauxite Refining," April 26, 2019 (accessed July 2, 2019); OECD, "Trade in Raw Materials" (accessed July 3, 2019).
[14] Al Circle, "Top Five Alumina Refineries in the World by Capacity," December 15, 2018 (accessed July 3, 2019).
[15] Gray, Kramer, and Bliss, "Gallium and Gallium Compounds," April 19, 2013.
[16] The European Commission estimates that only 10 percent of aluminum refining produces gallium. EC, "Report on Critical Raw Materials for the EU Critical Raw Materials Profiles," April 29, 2015, 57.
[17] See table A-4 in Annex I for quantitative data.

Gallium produced from the Bayer Process is in the form of a crude concentrate. However, solar cells require exceptionally pure material, upwards of 99.99999 percent (7N grade).[18] To reach this level of purity, initial refining of crude gallium can be done chemically. For example, gallium is reacted with chlorine to yield the salt gallium chloride, which is sublimated to separate out impurities.[19] The chlorine is subsequently removed by electrolysis to yield an initial purified low-grade (around 4N), and the final, highly refined grade is produced using zone refining.[20]

All of the gallium used in the United States is imported due to the lack of recovery during domestic aluminum refining. The majority of U.S. imports come from China (33 percent) and the EU (40 percent).[21] The gallium from Europe is typically 4N grade (99.99 percent purity), which is subsequently refined to higher grades in the United States.[22] For example, one U.S. firm is reported to refine low-grade, imported gallium powders and scrap in Utah.[23] China and Japan also possess the capacity to produced highly refined gallium.

Solar cells are not the major use for refined gallium, with gallium arsenide and gallium nitride production accounting for about 75 percent of U.S. consumption.[24] Much like silicon microelectronics, gallium arsenide wafers are grown and etched to produce various electronic components such as those used communication devices found in cell phone radios. Substantial amounts of gallium are needed to produce gallium nitride, a key material in light emitting diodes (LEDs), which are now commonly used in energy efficient lightbulbs. These other applications drive the price of gallium, as evidenced by the lack of correlation between the price of gallium and CIGS production (see figure 1).

Cadmium and Indium (Zinc Ore)

Zinc mining occurs across the Americas, Asia, and Australia. Countries that mine zinc typically have some refining capacity, although ore importing countries, like South Korea, possess some of the highest capacity refineries.[25] Unlike bauxite, zinc mining occurs in the United States across half a dozen states at 15 locations, and imports of the ores and concentrates have declined over the past decade.[26] There is only one primary zinc refinery in the United States, Nyrstar in

[18] 7N indicates that the purity contains 7 nines in the percentage. For example, 3N grade is 99.9 percent pure, while 4N grade is 99.99 percent pure. 5N Plus, “Gallium,” (accessed July 23, 2019).
[19] Sublimation is when a solid is heated to become a gas without first becoming a liquid. Dry ice is a common material that exhibits this property.
[20] Electrolysis is the use of electricity to drive reactions, especially for separating chemicals. USGS, “Gallium,” February 2019.
[21] See table A-3 in the annex for additional data.
[22] EC, “Report on Critical Raw Materials for the EU Critical Raw Materials Profiles,” April 29, 2015, 59.
[23] USGS, “Gallium,” February 2019.
[24] USGS, “Gallium,” February 2019.
[25] Bell, “The World’s Biggest Zinc Producers,” June 25, 2019 (accessed July 3, 2019); Wainwright, “$300 Million Zinc Refinery Expansion to Increase Production and Jobs in North Queensland,” December 7, 2018 (accessed July 3, 2019).
[26] USGS, “Zinc,” February 2019. USITC DataWeb/USDOC, HTS heading 2806.

Clarksville, Tennessee, which processes circa 100 kt of zinc metal per year and also produces cadmium.[27]

The refining and production of cadmium and indium is generally co-located, although recovery of each occurs at different stages of zinc processing.[28] Cadmium is removed along with lead during the roasting stage closer to the beginning of zinc refining, while indium is extracted from zinc leach residues near the end. In both cases, the crude cadmium and indium extracts are concentrated and purified using chemical or physical separations and then both are recovered using electrodeposition to reach circa 99 percent purities. Some refineries accept ore concentrates for toll processing from mining firms that do not have those capabilities in-house.[29] Indium is not recovered as often as cadmium, and some estimates cite overall recoveries of mined indium at less than 30 percent.[30] However, models have indicated that an increase in demand for solar cells and a subsequent increase in raw materials prices would increase the recovery rates of elements like indium.[31]

Cadmium recovery occurs in both zinc ore-producing and -importing countries. Canada, China, and Peru all mine significant quantities of ores and furnish a combined 42 percent of global cadmium.[32] South Korea and Japan are exemplars of countries that extract the elements from imports, as they have no domestic mining, but account for 30 percent of cadmium production.[33] Typically, countries that produce cadmium are also the major sources for indium, with the exception of both Mexico and the United States. The zinc refinery in Tennessee, for example, produces cadmium, but not indium.[34]

Like gallium, cadmium and indium used in solar cells needs to be exceptionally pure (99.99999 percent or greater). High purity cadmium can be refined using vacuum distillation due to its relatively low boiling point.[35] Indium refining to high-purities is accomplished through multiple rounds of electrolysis.[36]

[27] There is also a secondary refinery for recycled zinc in the United States, although recycled material would not yield either cadmium or indium. Nyrstar, "Metals Processing" (accessed July 3, 2019). USGS, "Zinc," "Cadmium," and "Indium," February 2019.
[28] Some gallium is recovered from zinc ores, although there is no domestic production from zinc refineries. USGS, "Gallium," February 2019.
[29] Lokanc, Eggert, and Redlinger, "The Availability of Indium: the Present, Medium Term, and Long Term," October 2015, 11.
[30] It is estimated that only 17 percent of zinc refineries produce indium. EC, "Report on Critical Raw Materials for the EU Critical Raw Materials Profiles," April 29, 2015, 78.
[31] This would also mitigate some of the mass limitations explored in the "Market for Thin-Film Solar Cells" section above. Lokanc, Eggert, and Redlinger, "The Availability of Indium: The Present, Medium Term, and Long Term," October 2015.
[32] See table A-4 in the annex for additional data.
[33] USGS, "Cadmium," February 2019.
[34] Nyrstar, "Clarksville Smelter," June 2019.
[35] 767°C (1413°F). Royal Society of Chemistry, "Cadmium" (accessed July 3, 2019).
[36] Alfantazi and Moskalyk, "Processing of Indium: a Review," August 2003; Chagnon, "Indium and Indium Compounds," March 12, 2010.

The United States is wholly reliant on indium imports given the lack of domestic extraction.[37] U.S. imports are approximately 130t per year, primarily from the EU, Canada, and East Asia, with China being the dominant source.[38] There are options for high purity (6N and greater) indium from domestic refineries in addition to similar imported grades.[39] While it does have cadmium refining capacity, the United States imports approximately 350t of refined cadmium per year, mostly in the form of unwrought powders from Germany (77 percent).[40]

Solar cells are not the primary destination for either cadmium or indium. Nickle-cadmium (Ni-Cd) rechargeable batteries are the largest destination for cadmium. Those batteries can be recycled to recover cadmium at their end-of-life, and there is one reported U.S. recycler.[41] Indium is primarily used to manufacture indium-tin-oxide, a transparent and electrically conductive material, which is a component of flat panel displays and screens.

Selenium and Tellurium (Copper Ore)

Like the other two ores, copper production is dispersed geographically. The plurality of copper mining occurs in South America, where Chile and Peru account for 22 percent of the world total.[42] Unlike for zinc and bauxite, China does not account for a double-digit fraction of global production and relies on imported materials, which is processed in several large ore refineries.[43] Japanese and South Korean copper industries mirror zinc, where substantial imports feed domestic refining due to a lack of in-country mining. Despite representing only 5 percent of copper ore production, Europe has significant refining capacity that is also fed by imports.[44] The United States extraction sector includes two dozen operations across the west and mid-west, which feed multiple domestic smelters and refineries.[45]

Both selenium and tellurium are removed from copper at the same point in the refining process. The elements are present in anode slimes that are produced during electrolytic refining. A typical slime is a complex mixture of metals that may contain up to 25 percent selenium and 10 percent tellurium; however, precious metals like silver are the primary focus for enhanced recovery.[46] These are intensive processes whose expansion would not necessarily be economically viable unless downstream prices increased, especially for tellurium.[47] As such, not every copper

[37] See table A-3 in the annex for additional data.
[38] USITC DataWeb/USDOC, HTS heading 8112.92.30 (accessed May 23, 2019).
[39] USGS, "Indium," February 2019. Indium Corporation, "Metals" (accessed July 3, 2019).
[40] USITC DataWeb/USDOC, HTS subheadings 2825.90.75, 2830.90.20, 8107.20, 8107.30, and 8107.90 (accessed May 21, 2019).
[41] Retriev Technologies, "NiCad & NiMH" (accessed July 3, 2019).
[42] See table A-4 in Annex I for additional data.
[43] Bell, "The Largest Copper Smelters," June 25, 2019 (accessed July 3, 2019).
[44] Copper Development Association, "Structure of the EU Copper Industry" (accessed July 3, 2019).
[45] USGS, "Copper," February 2019.
[46] There are multiple approaches for extracting both elements that rely on a series of process steps using heat and caustic reagents to separate each element from the slime mixture. Hoffmann and King, "Selenium and Selenium Compounds," December 17, 2010; Hoffmann et al, "Tellurium and Tellurium Compounds," April 15, 2011.
[47] Redlinger et al, "The Present, Mid-Term, and Long-Term Supply Curves for Tellurium; and Updates in the Results from NREL's CdTe PV Module Manufacturing Cost Model," September 30, 2013.

refining process is capable of producing tellurium, and it is often discarded with the rest of the tailings.[48] Compounding these existing economics, there is now an additional risk that tellurium recovery will be negatively impacted by a switch to lower grade copper ores that are less economical for tellurium recovery.[49]

The extraction of selenium and tellurium is more common among countries that import copper ore rather than mine it domestically. China, Japan, and Germany are the largest global producers of selenium, accounting for a combined 72 percent of production. Tellurium production is more consolidated, with 62 percent of output coming from China. The United States only has one firm that reports producing selenium and one that reports producing tellurium from copper anode slimes.[50]

The initial streams of selenium and tellurium are typically technical grade, requiring further purification for use in electronics. Tellurium can be zone refined using the Czochralski method to achieve high purities, while Selenium requires wet chemical processing to remove lingering impurities.[51] The same companies that provide the other extremely pure elements often offer selenium and tellurium products.

The United States relies on imports for the majority of its selenium and tellurium needs.[52] On a yearly basis, approximately 450 t of selenium and 160 t of tellurium enter the country. The largest sources of tellurium imported by the United States, by order of magnitude, are Canada and China (table 4), accounting for 66 and 23 percent, respectively of total U.S. imports. Selenium imports are more widely sourced, given the larger global extraction base, including substantial imports from the EU and Japan. There is one domestic tellurium producer in the United States, but it is foreign-owned.[53]

CIGS and CdTe solar cell production are in competition with other end-uses for the limited supplies of selenium and tellurium. Tellurium is unique among the elements discussed here, as solar cell production is its primary end-use. Conversely selenium is used in glassmaking, electronics, and, unique for the elements discussed here, it is as an essential nutrient in human and animal supplements.

Solar Cell Manufacturing

Both CdTe and CIGS thin-film solar cell production uses similar processes that are highly automated. Each layer is deposited in a sequence, along with selective removal between certain

[48] Tailings refers to the residual materials left over after ore processing.
[49] Pickerel, "As Copper Recovery Declines, So Does the Tellurium Supply for Thin-Film Solar Panels," July 3, 2018 (accessed May 24, 2019).
[50] USGS, "Selenium" and "Tellurium," February 2019.
[51] Hoffmann et al, "Tellurium and Tellurium Compounds," April 15, 2011; Hoffmann and King, "Selenium and Selenium Compounds," December 17, 2010.
[52] See table A-3 in the annex for additional data.
[53] Asarco LLC, part of Grupo México, located in Amarillo, Texas. Asarco, "Tellurium" (accessed April 19, 2019).

steps to electrically connect the cells (see box A). The specific steps and layout of the cell are dependent upon the manufacturer and ultimately determine capital costs and overall device performance of the process.[54] Other design choices can include whether or not the manufacturer wants to handle toxic materials. For example, cadmium sulfide is used as the n-type layer in a subset of CIGS cells, but some manufacturers use a different material, such as zinc sulfide, and highlight that choice to market their product.[55] Because the films are so thin, the performance of the solar cells will also depend heavily on impurities in the raw materials used to manufacture them, necessitating the use of the highly refined grades of each element.[56] While the purified elements are shipped worldwide, the manufacturing of thin-film solar cells is concentrated in a smaller number of countries.

Thin film PV companies have also chosen to focus on different market segments; for example, First Solar (CdTe) only serves utility projects to maintain high production levels for a given project, while Solar Frontier (CIGS) is marketed towards residential, commercial, and utility users. Some manufacturers differentiate certain CIGS products by advertising them as lightweight and flexible alternatives to traditional PV modules.[57]

Cadmium Telluride

The largest CdTe solar cell producer in the world is First Solar Inc., which is headquartered in Arizona.[58] In addition to its manufacturing capabilities in the United States, the company operates factories in Malaysia and Vietnam.[59] The sum total capacity of these facilities is predicted by the firm to exceed 5 GW_{DC} by the end of 2019.[60] However, First Solar is not the only player in the sector and there are a handful of other manufacturers. The German firm Calyxo GmbH produces CdTe solar cells at a rate of 85 MW per year at a plant in Germany, and Reel Solar produced CdTe solar modules at pilot scale in California.[61] Another company, CTF Solar, manufactures cells in Chengdu, China with a yearly capacity of 100 MW.[62] First Solar

[54] First Solar Inc., "First Solar's Module Manufacturing Process" (accessed April 17, 2019); USDOE, "Copper Indium Gallium Diselenide" (accessed April 17, 2019).
[55] Solar cells consist of n (negative)- and p (positive)- type materials in a junction. N-type materials are electron donating, while p-type materials are electron accepting. CIGS also offers a greater range of options in general than CdTe as the ratio of indium to gallium also can be changed to alter the light absorbing properties of the active layer. A representative manufacturer that advertises non-toxic materials is Solar Frontier. Solar Frontier, "Light Soaking Effect" (accessed August 21, 2019).
[56] Impurities can cause disrupt the film's structure or create recombination points where energy is lost as heat.
[57] Sunflare, "Commercial and Industrial" (accessed July 3, 2019).
[58] First Solar Inc., "Locations" (accessed July 3, 2019).
[59] First Solar Inc., "Investor Overview," February 21, 2019.
[60] First Solar Inc., "2018 Annual Report," 2018, 5.
[61] Calyxo is owned by a U.S. company. Calyxo, "About Calyxo" (accessed July 3, 2019); Reel Solar, "Technology" (accessed August 21, 2019).
[62] CTF Solar is wholly owned by a Chinese state-owned enterprise, but its research and development arm is based in Dresden, Germany. CTF Solar, "CdTe Factory" (accessed July 3, 2019).

currently produces the most efficient CdTe solar cells, advertised at 17 percent, while German manufacturer Calyxo recently reached 15.4 percent.[63]

CIGS

Manufacturers of CIGS solar cells are located in a number of countries, including the United States, Japan, China, and Europe. The largest producer is Solar Frontier KK of Japan, which manufactures on the GW per year scale at several locations across Japan. Other companies ship modules on the hundreds of MW per year scale, similar to the smaller CdTe producers. While there are companies in the United States that produce CIGS solar cells, some are foreign-owned. For example, Arizona-based Global Solar operates a 50 MW per year plant in the United States, but is wholly owned by the Chinese company Hanergy.[64] Hanergy also owns Miasolé in the United States and the German company Solibro, another CIGS producer with manufacturing and research operations in Europe.[65] The most efficient CIGS cells have comparable performance to CdTe, with products offering 16–17 percent efficiencies.[66]

Recycling

Solar cells are typically designed to have an active lifespan of 25 years. Thin-film modules after that point can cause concern for several reasons: (1) as highlighted above, the elements are rare and expensive to extract and (2) some of the materials are toxic and have to be disposed of properly. Instead of disposal, there are some options for recycling the modules once existing installations begin to retire. Recycling will play an important role for sustaining material availability.

CdTe represents the greatest risk for environmental contamination as it contains cadmium. Recycling operations to recover cadmium already exist due to its use in batteries, and major processors are located in the United States, Japan, and the European Union, yielding several thousand tons per year.[67] There also already exists some capacity for recycling CdTe from solar cell manufacturing. First Solar operates a recycling line for production scrap with high recovery rates, and they anticipate being able to recycle solar cells with 90 percent recovery for both cadmium and tellurium at their end of life.[68]

While the recycling of the CIGS elements from manufacturing scrap is common, recycling from electronics is rarely done. It is difficult to recycle elements like gallium from finished products

[63] Efficiency for solar cells is defined as the percentage of sunlight that is converted into electricity. Pickerel, "Calyxo Reaches 15.4% Efficiency with its CdTe Thin-Film Module," January 10, 2019 (accessed April 17, 2019).
[64] Global Solar, "About" (accessed July 3, 2019).
[65] Solibro GmbH, "About Us" (accessed July 3, 2019); ENF Solar, "Hanergy Breaks Solar Efficiency World Record for CIGS Modules," February 7, 2018 (accessed July 3, 2019).
[66] Solibro GmbH, "Powerful Performance: the Solibro SL2 Module" (accessed April 17, 2019); The Building Integrated Photovoltaics Company, "Metektron Datasheet." 2016.
[67] Bleiwas, "Byproduct Mineral Commodities Used for the Production of Photovoltaic Cells," 2010; International Cadmium Association, "Collection and Recycling of Nickel-Cadmium (NiCd) Batteries)," (accessed July 8, 2019).
[68] First Solar Inc., "Recycling" (accessed June 10, 2019).

due to the small amounts that are used in these manufactured goods.[69] The relevant materials would have to be concentrated as part of a larger electronics recycling program, for example, by gathering large quantities of flat panel displays to recover indium. However, that does not yet appear to be economical given the high separations costs for the low quantities used per device.[70] CIGS solar cell recycling is complicated by the need to separate four elements instead of two, increasing potential costs.

Conclusions and Outlook

The expansion of thin-film solar cell production is not threatened by the availability of the elements in the short term. The total mass recovered of each per year is sufficient to allow several additional GW-per-year increases in solar cell manufacturing. This is reflected in the current prices of elements like tellurium, which has remained flat since 2014 despite increased demand for CdTe modules. However, increasing capacity has substantial limits due to bottlenecks at several stages of the elements' value chains.

- *Recovery*. The primary bottleneck occurs at the initial ore processing stage. Most operations are either not set-up to recover the elements or only recover a fraction of them. Overcoming this bottleneck would require additional capital and energy resources dedicated to element recovery. Recycling will help mitigate this bottleneck in the long-term. Increased demand and pricing may motivate higher recovery rates.

- *Mining*. While not the first bottleneck that would be encountered, the elements are always mined as a byproduct of other ores, and their global supplies have to rely on the demand for copper, zinc, and aluminum given their orders of magnitude-larger markets. Thus, a downturn in demand for one or more of those ores could negatively affect the ability to expand solar cell production.

- *Competition*. The production of thin-film solar cells does not exist in a vacuum, as they are competing for the elements with other high-value products. Primary competition is with other electronics applications that require the exceptionally pure grades of each element. Gallium and indium prices reflect this, as they are not correlated with demand for CIGS modules given the markets for cell phones, displays, and other devices. Similar to mining, this will likely be a secondary bottleneck to recovery.

Looking forward, production in the United States will also be subject to additional bottlenecks, as domestic industry requires imports for the elements going into both CdTe and CIGS. The same will be true for several other major solar cell producing countries, including Malaysia, Vietnam, and Japan. It is likely that the future state of CdTe and CIGS will resemble the broader semiconductor industry, with an interconnected global supply chain with different nodes

[69] Umicore, "Gallium" (accessed April 16, 2019).
[70] Swiss Federal Laboratories for Materials Science and Technology, "Rare Metals from E-Waste" (accessed April 16, 2019).

occurring on separate continents. For example, First Solar manufactures CdTe modules in Southeast Asia, where there is neither substantial mining nor refining of the constituent metals. The present situation for South Korea's semiconductor industry highlights the primary risks for those countries dependent on imports for raw or refined materials.[71] If those supplies were cut off, for whatever reason, solar cell manufacturing would be at a standstill until alternative imports are located or domestic capacity is brought on-line. For the United States, which has the available natural resources but not the required infrastructure, that downtime could pose a significant challenge in a commodity industry that competes on price and availability.

[71] Goodman, Kim, and VerWey, "The South Korea-Japan Trade Dispute in Context," October 2019.

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Abbreviations and Acronyms

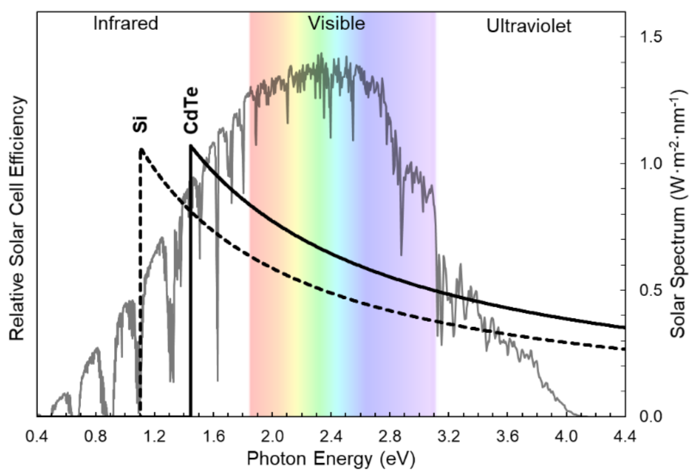
Al	aluminum
Cd	cadmium
CdTe	cadmium telluride
CIGS	copper indium gallium diselenide
Cu	copper
DRC	Democratic Republic of the Congo
EC	European Commission
EU	European Union
Ga	gallium
GaAs	gallium arsenide
GW	gigawatt
HTS	Harmonized Tariff Schedule of the United States
In	indium
Mt	megaton (one million metric tons)
NREL	National Renewable Energy Laboratory
Se	selenium
t	metric ton
t/y	metric tons per year
Te	tellurium
UK	United Kingdom
U.S.	United States
USDOE	U.S. Department of Energy
USGS	U.S. Geological Survey
Zn	zinc

Annex I

Solar Cell Efficiency

The primary concern for any solar cell is how much light it can transform into usable electric power. The efficiency of that conversion is fundamentally limited by the bandgap of the material, which determines what wavelengths of light the cell will absorb and how well each wavelength is used. While a discussion of semiconductor physics is beyond the scope of this paper, the University of Cambridge provides a good introduction to bandgaps on their website and NREL hosts a book that provide additional information on photovoltaic basics.[72] Figure A-1 shows the solar spectrum at Earth's surface compared to the absorbing behavior of silicon (Si) and CdTe solar cells. Si can absorb light with lower energy than CdTe because of its lower bandgap, meaning it can make greater use of the entire spectrum. However, CdTe will use the visible part of spectrum, where the solar spectrum peaks, more efficiently than Si. Combined, these effects render Si and CdTe cells the same theoretical efficiency (table A-1).

Figure A-1. Solar spectrum and the regions utilized by Si and CdTe solar cells.



Source: NREL, "Reference Solar Spectral Irradiance: Air Mass 1.5" (accessed May 14, 2019).
Note: Relative efficiency is defined as the ratio of the photon energy to the material's bandgap. The color gradient reflects the visible parts of the spectrum for reference.

Taking both effects into consideration, the theoretical maximum efficiently of both materials is about the same, and all three of the thin-film materials currently produced are designed to have bandgaps in this region to maximize their potential power output (table A-1). The actual efficiency of each material in a commercial solar cell depends heavily on how it was manufactured, the device structure, and the module in which it is ultimately housed. GaAs, in the laboratory, has come the closest to its theoretic limit.

[72] University of Cambridge, "Introduction to Semiconductors," November 2007 (accessed July 23, 2019).

Table A-1. Comparison of highest solar cell material efficiencies.

	Bandgap (eV)	Theoretical Efficiency %	Research Efficiency %	Commercial Efficiency %
Si	1.1	32	26.1	22.2
GaAs	1.42	33	29.1	26
CdTe	1.45	32	22.1	17
CIGS	1.0-1.7	29-31	22.9	17

Source: NREL, "Best Research-Cell Efficiencies" (accessed May 14, 2019); Rühle, "Tabulated values of the Shockley-Queisser limit for single junction solar cells," June 2016; The Building Integrated Photovoltaics Company, "Metektron Datasheet." 2016; First Solar Inc., "First Solar Series 6 Module Data Sheet," 2019; Energy Sage, "What are the best solar panels on the market? Complete panel ranking table" (accessed May 14, 2019); Alta Devices, "Technology Brief - Single Junction (Preliminary)," April 2018.
Note: all efficiencies are reported as percent. * Alta Devices quotes the research efficiency value on their website, but it is unclear if this value is matches the produced cells for the applications they advertise.

In addition to the position of the bandgap, the type of bandgap will have a significant impact on the cell's performance and cost as well. CdTe, CIGS, and GaAs are all direct bandgap materials while Si has an indirect bandgap, meaning it absorbs light much less efficiently. Si requires an active layer that is about 200 microns (μm) thick, in comparison to the 3 μm required by the thin-film materials because of this. A thicker cell will have higher raw material costs than a thin cell made of the same material, making it unlikely that the thin-films would be able to compete with silicon if they didn't have a direct bandgap.

Estimating Demand

Estimating the total amount of each element required per gigawatt (GW) of power is accomplished using equation 1, which compares the dimensions of the thin-film to the energy it is able to convert into electricity. m_x is mass of element x required per power generated (kg/W) and is summarized in column "1 GW" of table 1. ρ_c is the density of thin-film, which was taken to be 5,850 and 5,700 kg/m^3 for CdTe, and CIGS, respectively. d_c is the film thickness, assumed to be 3 μm for both materials.[73] f_x is the mass fraction of element x in the thin-film; a Ga:In ratio of 7:3 was used for the CIGS calculation. η_c is the solar cell efficiency of the best commercially available modules (table A-1). η_I is the DC to AC inverter efficiency, which is taken to be 95 percent. I is the AM 1.5 solar spectrum intensity of 1000.4 W/m^2.

Equation 1:

$$m_x = \frac{\rho_c d_c f_x}{\eta_c \eta_I I} \tag{1}$$

[73] Bleiwas, "Byproduct Mineral Commodities Used for the Production of Photovoltaic Cells," 2010.

Table A-2. Typical ore concentrations of the thin-film elements (mg/kg).

	Copper	Zinc	Aluminum
Cd		2,000-3,000	
Ga		25-100	40-80
In		70-300	
Se	20-80		
Te	10-100		

Source: Schulz et al, "Chapter H: Gallium," "Chapter I: Germanium and Indium," "Chapter Q: Selenium," and "Chapter R: Tellurium," December 19, 2017; Butterman and Plachy, "Mineral Commodity Profiles Cadmium," 2004.
Note: mg/kg is equivalent to parts per million (ppm). Other ores contain these elements, but copper, zinc, and bauxite are the primary parents. For example, tellurium is often found alongside gold deposits, although the absolute tonnage is small in comparison.

Table A-3. Countries with over $1 million in exports of elements to the United States, 2017.

	U.S. Imports (thousand $)					
	Cd	**In**	**Se**	**Te**	**Ga**	**Total**
Belgium	830	845	1,304	61		3,041
Canada	202	4,683	1,169	8,351		14,406
China	465	11,401	3,245	2,945	956	19,013
France		551			1,609	2,160
Germany	115	9	2,397	989		3,510
Japan	10	4,706	1,878	84	263	6,940
Mexico	33		1,981			2,015
Philippines			3,730	122		3,852
South Korea		2,731	1,081		135	3,947
Taiwan		1,044				1,044
UK	32	239	45	14	809	1,139
Other	365	674	608	112	640	2,399
Total	2,053	26,883	17,440	12,679	4,412	63,466

Source: USITC DataWeb/USDOC, HTS headings 2804.50.00.20 (tellurium), 2804.90 (selenium metal), 2811.29.20 (selenium dioxide), 2825.90.75 (cadmium oxide), 2830.90.20 (cadmium sulfide), 8107.20 (cadmium powders), 8107.30 (cadmium waste and scrap), 8107.90 (wrought cadmium), 8112.92.10 (gallium), and 8112.92.30 (indium) (accessed May 23, 2019).
Note: Cd: cadmium. In: indium. Se: selenium. Te: tellurium. Ga: gallium.

Table A-4. Production and trade in ores and thin-film elements for selected countries, 2017.

	Ore Production† (Mt)			**Ore Import Value (Billion $)**			**Element Production (t)**				
	Zn	**Cu**	**Al**	**Zn**	**Cu**	**Al**	**Cd**	**In**	**Se**	**Te**	**Ga**
United States	0.8	1.3	***		0.1	0.2	***		***	***	
Australia	0.8	0.9	17.6								
Belgium				1.1				20	200		
Brazil			7.7	0.2	0.9						
Bulgaria				0.1	1.7					5	
Canada	0.3			0.8	0.4	0.1	1,800	67	49	49	
Chile		5.5									
China	4.4	1.7	14.0	2.2	26.0	3.5	8,200	287	930	290	300
DRC		1.1									
Finland				0.6	0.7				105		
Germany				0.3	2.2	0.1			300		
Guinea			9.2								
India	0.8		4.6		3.9	0.1					
Indonesia		0.6	0.6								
Jamaica			1.7								
Japan				0.9	8.3		2,100	70	729	38	3
Mexico	0.7	0.7			0.2		1,160				
Poland				0.1	0.4						
Peru	1.5	2.5					797	10	45		
Russia		0.7	1.1				1,200	5	150	44	7
South Korea				2.1	3.6		5,600	225			3
Spain				1.0	3.1	0.1					
Sweden	0.3				0.4				20	35	
Taiwan					0.6						
Zambia		0.8			0.8						
Other	13.3	20.0	5.4	0.9	1.0	0.8	4,500	30	185	7	7
Total	22.9	35.8	61.9	10.5	53.4	4.8	25,357	714	2,713	468	320

Source: USGS, "Bauxite," "Cadmium," "Copper," "Gallium," "Indium," "Selenium," "Tellurium," and "Zinc," February 2019; IHS Market, Global Trade Atlas database (accessed May 14, 2019); Simoes and Hidalgo, "The Observatory of Economic Complexity" (accessed April 15, 2019).

Note: 2017 Data. Countries included if combined ore production is greater than one megaton (Mt), combined ore imports are greater than $500 million, or if one element production is greater than 5 percent of the global total. Imports below $100 million not shown. † Metal content equivalent. DRC: Democratic Republic of the Congo. *** Proprietary data. Zn: zinc. Cu: copper. Al: aluminum. Cd: cadmium. In: indium. Se: selenium. Te: tellurium. Ga: gallium.