October 2020

Introduction

The migration to renewable energy and the evolution of related technologies will increase reliance on many minor metals and elements. In general, these esoteric materials do not adhere to the traditional economic forces that drive larger commodities markets. Often produced as byproducts of more ubiquitous refining processes, these element's and compound's supplies are largely independent of their prices. Additionally, the end products' input costs of these materials constitute a small percentage of overall manufacturing costs, so consumers are unlikely to substitute or curtail their use based on cost. Due to the comparatively low level of speculative participation in these minor metals, they often exhibit a distinct hysteresis versus the equity valuations of corresponding consumers. Tellurium (Te), which is primarily used in cadmium telluride (CdTe) solar cells, provides a classic example of this rare setup. Solar energy buildout is set to lift Te demand considerably, the reduction of solvent extraction electrowinning (SX/EW) copper refining will significantly reduce Te supply, and, due to warranted, optimistic outlooks and expanding orderbooks, the rise in equity valuations of tellurium reliant solar photovoltaic (PV) producers have far outpaced the price of the unique metalloid.

Tellurium Demand

CdTe Solar Panels

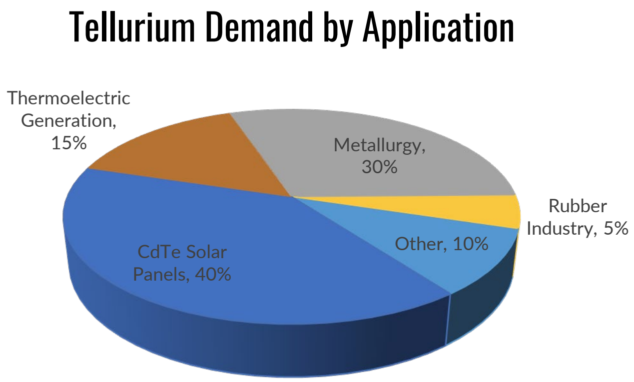

Figure 1: Source: Mahmoudi, A. et. Al

Though constituting only 6% of the installed photovoltaic market, cadmium telluride (CdTe) solar cells consume roughly 40% of tellurium demand per year (Figure 1). Currently, CdTe PVs are the only thin film technology with lower production cost and maintenance than conventional, crystalline silicon PVs. In January of 2020, researchers from the DOE's National Renewable Energy Laboratory (NREL) announced a new manufacturing process to produce CdTe PV panels 45% cheaper than current industry standards[1]. Furthermore, CdTe PVs have the smallest carbon footprint, lowest water use, and shortest energy payback time of any current PV technology. In solid form, tellurium is a deficient heat and electricity conductor. Although the metalloid has many metal-like properties, it is brittle, may degrade quickly, and does not exhibit a particularly high electrical conductance. However, depending on the specific direction of the atomic alignment of its structure and when alloyed to certain metals, it becomes an excellent electrical semiconductor.

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[1] https://www.sciencedaily.com/releases/2020/01/200127134815.htm

Simply, solar cells are a semiconductor diode specifically designed to absorb and convert light energy from the sun into electrical energy. These semiconductors absorb photons and deliver a portion of the energy to electric current carriers: electrons and holes. The semiconductor diode is formed by the combination of a p-type (containing holes) and n-type (containing free electrons) semiconductors, which forms a metallurgical junction (Figure 2). When joined, the free electrons from the n-type semiconductor flow to the holes contained in the p-type semiconductor and create a depletion zone, which contains no free electrons or holes. Because of the electron migration, the n-type side of the junction becomes positively charged and the p-type side of the boundary becomes negatively charged, creating an electrostatic potential difference that will be an essential driving force during operation (Figure 2). When photons contact the depletion layer, their energy liberates the free electrons and the electric field drives them back into the n-type layer (Figure 2). The diode's other electrical contacts are formed by conductive materials on the front and back of the cell, which completes the circuit, allowing the electrons to flow. The energy required to liberate the free electrons in the depletion zone is referred to as the band gap energy and is a significant determinant of solar cell efficiency.

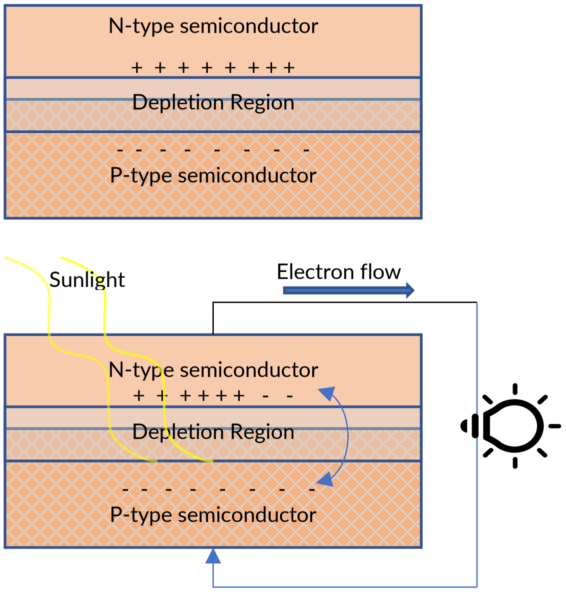

Figure 2: Schematic of CdTe PV junction. When sunlight contacts the depletion layer, the energy from the photos liberates free electrons which are driven to the n-type layer. Source: VAM

Silicon crystals were used in the first photovoltaic cells and are still widely applied in the domestic solar power market.[2] In the polycrystalline process used to produce these cells, silicon is melted then slowly cooled. The produced silicon ingot contains crystalline regions that are separated by grain boundaries, the interface between two crystallites in a polycrystalline material.[3] In the photovoltaic cell, the gaps in these grain boundaries cause this type of cell to have a lower conversion efficiency[4] as compared to CdTe technology. Specifically, thin film crystalline silicon has the optical properties of crystalline silicon, but the grain boundaries alter its electronic properties, causing a lower conversion efficiency. The electronic property alteration caused by grain boundaries also limits the minimum cell thickness for

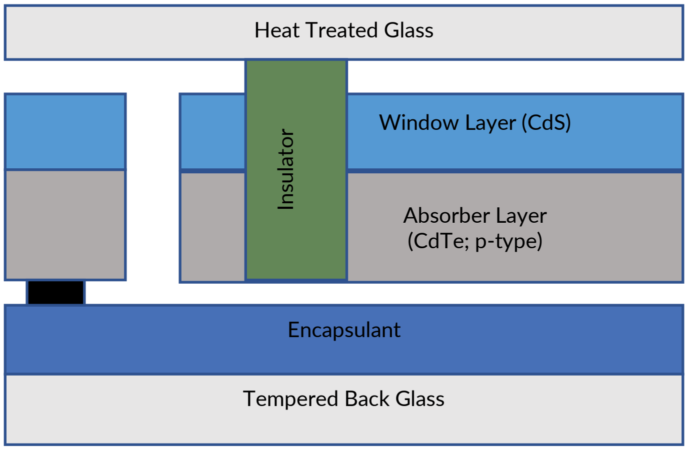

Figure 3: Schematic of CdTe Solar Cell; Source: Lee et al

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[2] Muller, Richard A. (2012-07-30). Energy for Future Presidents: The Science Behind the Headlines, Norton.
[3] Gervorkian, P. (2011). Large Scale Solar Power System Design: An Engineering Guide for Grid-Connected Solar Power Generation. New York: McGraw-Hill Companies.
[4] Conversion efficiency measures the proportion of light converted to energy in a single solar cell.

crystalline silicon to roughly ten microns.[5] Additionally, crystalline silicon has a low absorption coefficient, so a three micron thick cell only absorbs approximately half the energy contained in the electromagnetic radiation available to the photovoltaic cell.

In contrast, CdTe PV modules utilize single junction, polycrystalline, thin film structures that use cadmium sulfide (CaS) as the window layer and cadmium telluride (CdTe) as the absorption layer (Figure 3). This window layer helps to increase absorption by reflecting and absorbing short wavelength light, thereby increasing overall efficiency. CdTe cells exhibit a far lower grain boundary defect density as compared to silicon-based cells[6], allowing them to attain higher efficiency at lower thicknesses. This is achieved by depositing CdTe orthogonally on the solar cell substrate as a tetrahedral zinkblende.[7] In this structure, conductivity may be increased when exposed to light, exhibiting photoconductor behavior that is key to CdTe PV technology. Additionally, CaS/CdTe technology provides a direct-bandgap material with defined bandgap energy of 1.45 (eV), which nearly matches the solar spectrum and is virtually optimal for single junction solar conversion. The advantages of CdTe cells over silicon cells are decreased thickness and increased efficiency: a layer 3 microns thick can produce electricity with a conversion efficiency of 20% or more. Additionally, CdTe compounds can be employed on flexible solar cell substrates, whereas crystalline silicon is too fragile to maintain its structure on flexible cells.

To date, First Solar (FSLR) has been the prominent manufacturer of CdTe PVs, manufacturing over 4 gigawatts in 2019 versus just 25 megawatts in 2005. Company forecasts show that First Solar will consume between 45.5% and 61% of total primary and secondary Te production per year (Figure 4).[8] Additionally, Toledo Solar, a newly launched CdTe PV manufacturer focused on residential applications, started production in Q2'20. Toledo Solar has 100MW/y of manufacturing capacity with aims to expand output to 850MW

by 2025.[9] Thus, Te demand from these two companies alone may constitute 53 – 76% of total primary and secondary Te production by 2025.

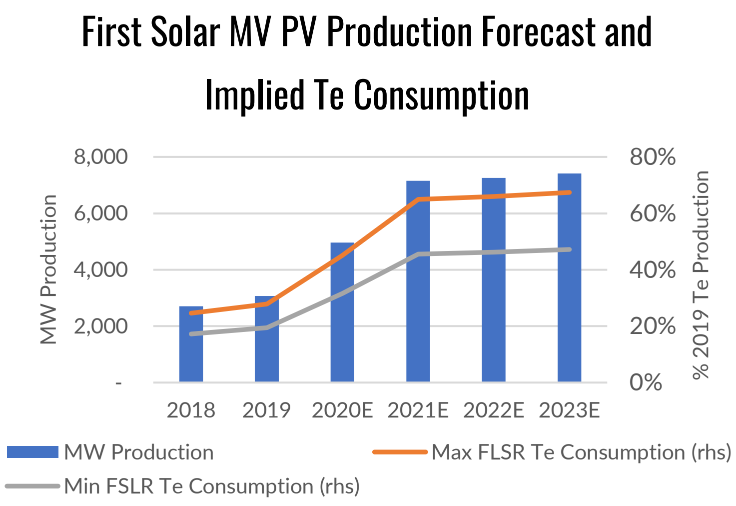

Figure 4: Source: Company Reports; VAM Research

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[5] Nelson, J. (2004). The Physics of Solar Cells. London: Imperial College Press.
[6] Major, J. (2016) *Grain Boundaries in CdTe thin film solar cells: a review.* Semiconductor Science and Technology, 31,9
[7] Karl W. Böer. Handbook of the Physics of Thin-Film Solar Cells. 201310.1007/ 978-3-642-36748-9_36 ©   Springer-Verlag Berlin Heidelberg   2013
[8] VAM calculations
[9] https://pv-magazine-usa.com/2020/05/14/a-new-player-appears-in-american-thin-film-cadmium-telluride-solar-module-manufacturing/

Since 1981, when Kodak proved CdTe PVs could be commercially viable using close-space sublimation manufacturing, skepticism of the technology's proliferation centered on the availability of Te. In 2005, when First Solar began ramping up output of their utility scale CdTe PVs, these concerns became louder. However, First Solar's manufacturing ramp up coincided with a substantial increase in solvent extraction-electrowinning (SX/EW) copper refining, which currently accounts for 80 – 90% of tellurium production (Figure 5). This ramp up in SX/EW copper refining was unrelated to tellurium extraction, occurring rather as a result of copper refining economics. Thus, while demand was steadily increasing, 99.99% Te dropped from \$250/kg in 2008 to the current price of \$65/kg. At current Te price levels, despite significant reductions in manufacturing costs, Te accounts for only 1.2% of the overall cost of First Solar's PV cells, as compared to approximately 8% in 2005, when First Solar determined CdTe PVs were cost competitive enough to significantly ramp up production.

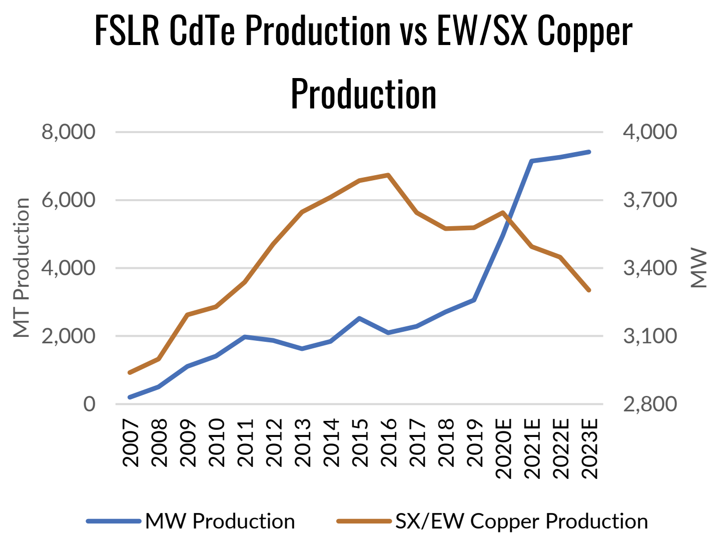

Figure 5: Source: Company reports, CRU; FSLR: First Solar

Data Storage/Electronics

Chalcogenide glass is a glass containing one or more chalcogens (sulfur, selenium or tellurium) and is utilized for digital data encoding. As described previously, chalcogenide glass is distinguished by its low band gaps and resultant optical and electrical properties. Tellurium based chalcogenide glasses are prone to thermally induced amorphous-to-crystalline phase changes, making them well suited for encoding binary information. Examples of this application include rewritable optic disks and non-volatile random access memory (RAM). Specifically, phase-change memory (PRAM) exploits the chalcogenide glass' phase change characteristics to achieve bit rates of up to 35 Mbit/s and up to 10^6 overwrite cycles.[10] Lastly, Te based chalcogenide glasses can be used in infrared detectors, optical fibers and infrared lenses.

In addition to information storage applications, tellurium can be utilized as a specialized semiconductor for use as a highly efficient thermoelectric material, an application which accounts for approximately 15% of tellurium consumption per year. The most prevalent thermoelectric Te-containing alloy is bismuth telluride alloyed with antimony or selenium. Te based thermoelectric cooling devices consist of a series of pairs of semiconducting materials connected to a direct current, which in turn causes one side of the element to heat while the other side cools. These devices are used in infrared detectors, integrated circuits, laser diode and medical instruments.

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[10] Simpson RE, Fons P, Kolobov AV, Fukaya T, Krbal M, Yagi T, Tominaga J (2011) Interfacial phase-change memory. Nat Nanotechnol 6(8):501–505. https://doi.org/10.1038/ nnano.2011.96

Metallurgy

Approximately 30% of tellurium consumption is as an additive for various metallurgical processes. Generally, Te can be alloyed with steel as a free machining additive, copper to improve machinability with no adverse impact on conductivity, lead to enhance resistance to acidic degradation, and cast iron to help control depth of chill. The addition of as little as .04% Te to steel improves various mechanical properties. The use of tellurium in lead acid batteries represents an area of demand that may diminish in the coming years, but this end use currently represents less than 1% of total consumption.

Tellurium Supply

Tellurium is considered an extremely rare element, ranking as the 75th most abundant element at 1 - 4 parts per billion (ppb) in the earth's crust. In comparison, platinum and gold are considered more abundant at 5 ppb and 4.5 ppb, respectively. This low concentration is due to the absence of water and oxygen early in the earth's formation, causing stable elements to be controlled by the reductive capacity of free hydrogen. Tellurium is particularly volatile as a hydride, so much of the element was lost via evaporation. Thus, while tellurium is sometimes found in its native form, it is far more commonly found in tellurides or other chemical compounds (Table 1).

Compound	Formula	Structure	Occurrence
Altaite	$PbTe$	Isometric crystal	Central/East Asia
Hessite	Ag_2Te	Monoclinic crystal	USA
Sylvanite	$AuAgTe_4$	Monoclinic crystal	Romania, Australia, Canada
Calaverite	$AuTe_2$	Monoclinic crystalline	Romania, Australia, USA
Tetradymite	Bi_2Te_2S	Trigonal crystal	Slovakia
Coloradoite	$HgTe$	Cubic crystal	Australia
Empressite	$AgTe$	Orthorhombic crystal	USA
Kostovite	$AuCuTe_4$	Orthorhombic crystal	USA, China, Russia, Bulgaria
Krennerite	$AuTe_2/Au_3AgTe_8$	Orthorhombic crystal	Romania
Melonite	$NiTe_2$	Trigonal crystal	USA
Petzite	Ag_3AuTe_2	Isometric crystal	Romania
Rickardite	Cu_7Te_5	Orthorhombic crystal	USA
Stützite	$Ag_{5-x}Te_3$	Hexagonal crystal	Romania
Tellurobismuthite	Bi_2Te_3	Trigonal crystal	USA
Temagamite	Pd_3HgTe_3	Orthorhombic crystal	USA
Vulcanite	$CuTe$	Orthorhombic crystal	Japan, Russia, USA, Norway
Weissite	$Cu_{2-x}Te$	Hexagonal crystal	USA, Australia, Sweden

Table 1: Naturally occurring tellurium ores

Approximately 90% of tellurium is produced as a byproduct of the solvent extraction-electrowinning (SX/EW) method of copper refining (Figure 6). The SX/EW process involves leaching copper ore with a weak acid solution, producing *pregnant liquor*. The *pregnant liquor* is then treated with an organic solvent, known as an extractant, which extracts the copper away from the aqueous phase. The copper-bearing organic phase is then treated with a strongly acidic aqueous solution, which returns copper to its aqueous phase before advancing to the electrowinning stage of the refining process. In the electrowinning phase, copper is electrochemically reduced from copper sulphate to a metallic copper cathode. Throughout the entire process, anode slime is continuously formed as insoluble elements and compounds fall to the bottom of the electrorefining tank. This anode slime is then refined to extract byproduct elements, including tellurium.[11]

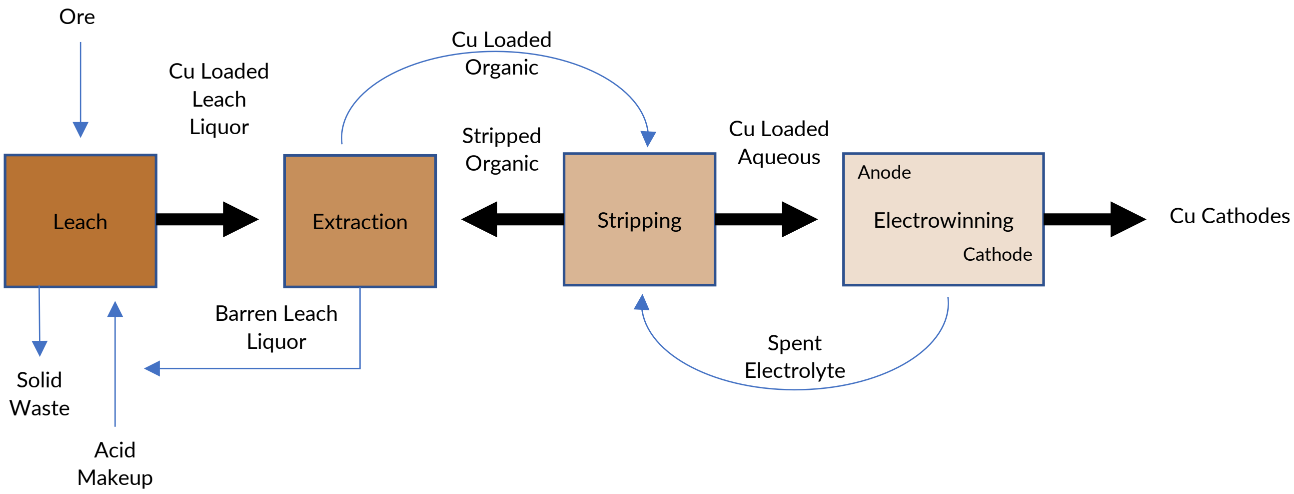

Figure 6: Schematic of SX/EW Process. Reproduced from Mahmoudi, A. et. Al.[10]

Copper anode slime consists of insoluble components or nobler than copper constituents such as silver, selenium, gold, lead, nickel, antimony, arsenic and tellurium. The proportional composition varies based on ore composition and extraction method, so tellurium contained may range from .5 – 4% by weight. However, tellurium does not exist in isolation in the anode slime. Rather, tellurium agglomerates in the copper-selenide matrix phase as copper telluride (Cu_sTe) and must be refined further to obtain pure tellurium. Thus, the anode slime undergoes pyrometallurgical pretreatments and is then leached in an acidic or caustic media. The primarily utilized acidic media is sulfuric acid, which exhibits a maximum recovery rate of 60% tellurium. For caustic leaching, sodium hydroxide is used and tellurium is selectively separated as it is transformed to its hexavalent form. Once tellurium dissolution has occurred, it must be recovered via a precipitation process. This is accomplished by adding either copper powder, sulfur dioxide, or both.

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[11] Mahmoudi, A. *et. Al.* "Tellurium, from Copper Anode Slime to High Purity Product". (2020) *The Minerals, Metals & Materials Society.*

After precipitation, the tellurium must be further treated to reduce impurities. Remaining entrained impurities may include copper, lead and selenium. Electrowinning processes are again utilized to reduce impurities, achieving purity of 99.95%. Ultrasonic cleaning may then be performed to achieve a purity of 99.99%. However, advanced materials such as semiconductors and infrared optics application may require tellurium purity of 99.9999%. The two processes known to achieve this level of elemental concentration are vacuum distillation and zone refining. In vacuum distillation, differences in vapor pressure sensitivity of impurities and tellurium are exploited to isolate tellurium. Zone refining involves constantly moving a heating unit around a bar of target material, ensuring that at any one point, a portion of the material is molten. The difference in solubility of the impurities in a solid state versus in a melted state cause them to accumulate in one end of the bar. This "waste" section is then removed from the high purity tellurium.

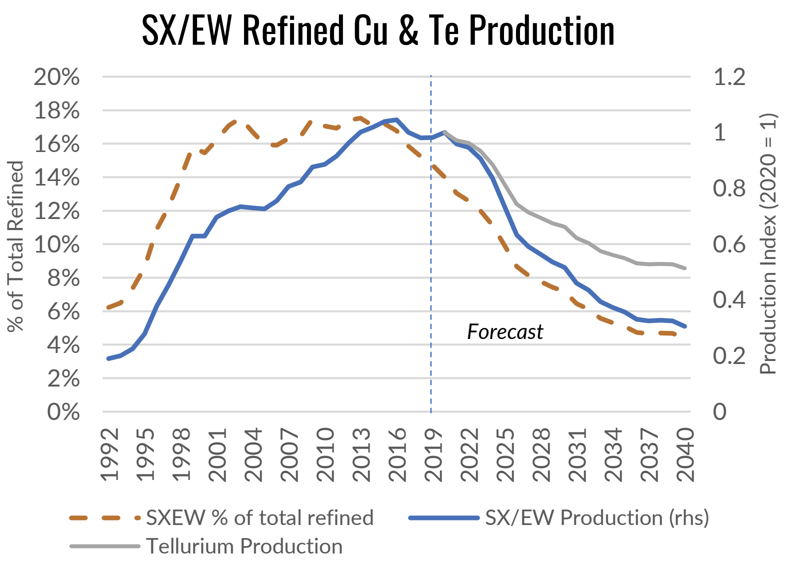

Figure 7: Source: CRU; VAM Research

The supply of copper from SX/EW refining operations peaked in 2014 and is expected to continue declining in the coming years (Figure 7). In general, SX/EW is utilized to refine oxide ores while pyrometallurgical techniques are used to refine high sulfide ores. On average, oxide ore deposits are lower grade than their sulfide counterparts and oxide ore grade decline has accelerated compared to sulfide ores (Figure 8). This has led to producers preferentially developing sulfide ores as the margin on oxide ores and SX/EW has been squeezed, a consequence of which will be a reduction in Te recovery.

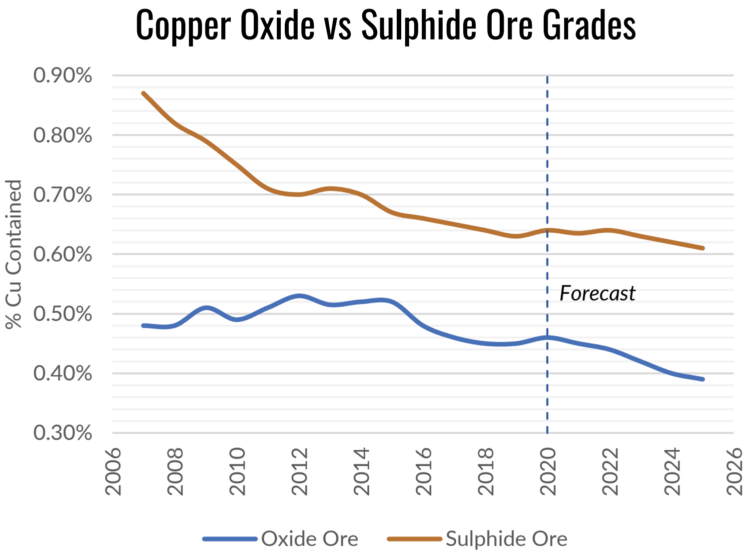

Figure 8: Source: CRU

Importantly, the supply of tellurium is price inelastic as production is dependent on copper refining margins. Tellurium prices have a negligible impact on the profitability of anode slime processing operations that continue to utilize SX/EW processing. For example, in a sample of 12 SX/EW copper refiners, maximum tellurium contribution by weight and by value is 3.90% and

.50%, respectively (Appendix). A full assessment of anode slime components shows that the majority of recovered value is due to gold, the concentration of which has an insignificant correlation to Te concentrations (Figure 9). Thus, impurity recovery from anode slime is unlikely to be dictated by the notional contribution of tellurium.

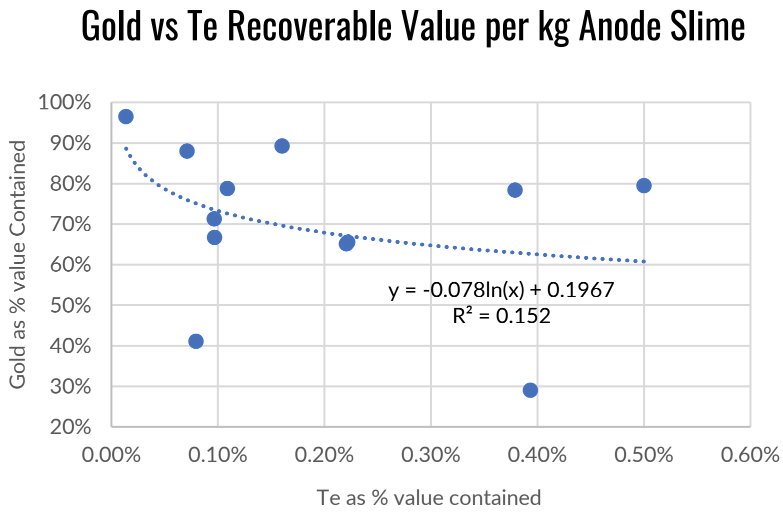

Figure 9: Source: Mahmoudi et al.; Based on October 2020 prices

Conclusion

This analysis elucidates the fact that neither tellurium supply nor demand is likely to respond to even severe price increases. As CdTe photovoltaics began carving their place in commercial applications, coincidental developments in the copper refining industry ensured that sufficient tellurium supply would be available. This dynamic has now reversed. CdTe PV technology has made significant efficiency gains, copper market dynamics have provided CdTe producers with a false sense of Te supply security, and copper oxide ore degradations have made SX/EW copper refining far less economical compared to acid leaching higher grade, sulfide ores. Furthermore, renewable energy oriented fiscal stimulus combined with social support of the same has led to a wholesale buy-in of green technologies, particularly solar generation. Naturally, speculative capital has flowed to the most liquid and readily available points of exposure: renewable energy equities. However, the lofty valuations of these companies have not been followed by the prices of the raw materials essential to deploy their critical technology, even when contracted orderbooks confirm future raw material needs (Figure 4; Figure 10). Low speculative participation leads to the hysteresis exhibited by these raw materials, particularly tellurium, indicating significant price appreciation in the years to come.

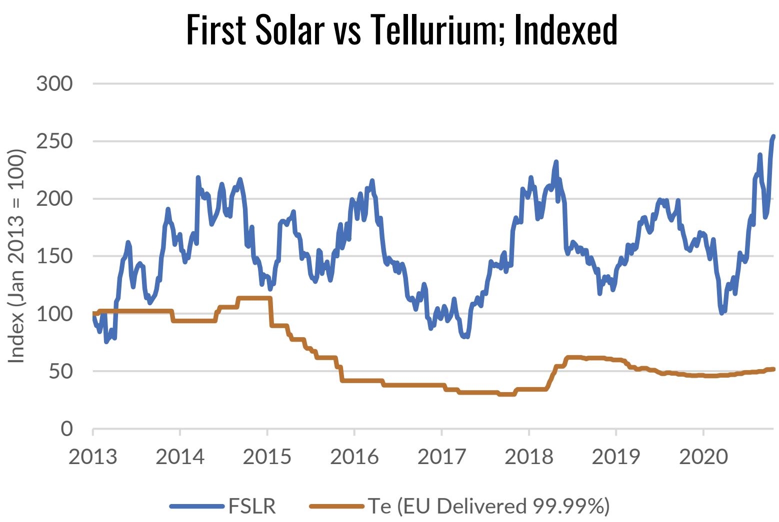

Figure 10: Source: Bloomberg

Appendix

Plant	Country	Cu	Ag	Au	Se	Te	Pb	Ni	As	Sb	Bi	Value ($/kg)*
Saganoseki	Japan	25.20%	19.00%	2.10%	12.10%	3.90%	4.00%	0.40%	3.30%	1.80%	0.70%	$1,578
Bahia	Brazil	4.40%	7.60%	0.40%	11.50%	2.60%	6.70%	0.10%	3.80%	4.10%	0.70%	$337
Montreal	Canada	15.00%	29.00%	1.40%	5.00%	2.00%	16.00%	3.80%	1.50%	4.50%	1.50%	$1,192
Amarillo	USA	19.60%	18.60%	0.10%	14.10%	1.40%	0.10%	0.70%	2.90%	2.90%	0.40%	$231
Boliden	Sweden	15.70%	22.90%	0.60%	5.20%	0.90%	9.70%	5.10%	2.50%	16.00%	0.80%	$603
Las Ventanas	Chile	24.30%	14.80%	5.40%	7.90%	0.80%	8.10%	0.10%	6.20%	5.50%	0.30%	$3,754
Potrerillios	Chile	7.80%	15.40%	0.50%	8.60%	0.70%	1.20%	0.02%	9.20%	10.40%	0.40%	$470
Sarcheshmeh	Iran	7.40%	8.00%	0.20%	15.30%	0.70%	4.30%	0.00%	0.60%	1.90%	0.04%	$206
Lunen	Germany	1.00%	8.00%	0.20%	0.70%	0.70%	30.00%	1.00%	2.50%	9.00%	0.40%	$205
Townsville	Australia	21.00%	6.10%	0.60%	3.00%	0.50%	9.80%	0.30%	3.90%	0.60%	0.70%	$457
Kayseri	Turkey	18.00%	1.50%	0.08%	1.00%	0.40%	16.90%	0.20%	0.30%	0.40%	0.04%	$68
El Paso	USA	1.00%	22.00%	0.20%	20.00%	0.40%	5.00%	0.05%	2.00%	4.00%	0.70%	$326

Table 1A: Source: Mahmoudi, *A.* et. Al; Cu: Copper; Ag: Silver; Au: Gold; Se: Selenium; Te: Tellurium; Pb: Lead; Ni: Nickel; As: Arsenic; Sb; Antimony; Bi: Bismuth. Values based on October 2020 prices.

Glossary

bandgap energy: the energy required to promote a valence electron bound to an atom to become a conduction electron, which is free to move within the crystal lattice and serve as a charge carrier to conduct electric current

close-space sublimation: a method for depositing source material onto a substrate. Both the source material and the substrate to be coated are placed in a vacuum chamber. Both materials are then differentially heated; the source material to just below its melting temperature and the substrate to some lower temperature. This causes sublimation of the source material, which allows vapors to migrate to the substrate where they then condense.

Chalcogenide: a chemical compound consisting of at least one chalcogen anion and at least one more electropositive element.

Depletion zone: an insulating region within a conductive, doped semiconductor material where the mobile charge carriers have been diffused away, or have been forced away by an electric field.

Diode: a semiconductor device with two terminals, allowing the flow of current in one direction

grain boundaries: the interface between two crystallites in a polycrystalline material

n-type semiconductor: an extrinsic semiconductor that incorporates an electron donor doping agent. CdTe PV cells contain a n-doped CdS layer.

p-type semiconductor: an extrinsic semiconductor that incorporates an electron acceptor doping agent. The doping agent accepts an electron, leaving positively charged holes to carry charge. P-type dopants include trivalent elements like boron, aluminum, gallium and indium. CdTe PV cells contain a p-doped CdTe layer.

Semiconductor: a solid substance that has a conductivity between that of an insulator and that of most metals, either due to the addition of an impurity or because of temperature effects

zincblende: cubic array of anions cations occupying one half of the tetrahedral holes