Tellurium in the Copper Supply Chain

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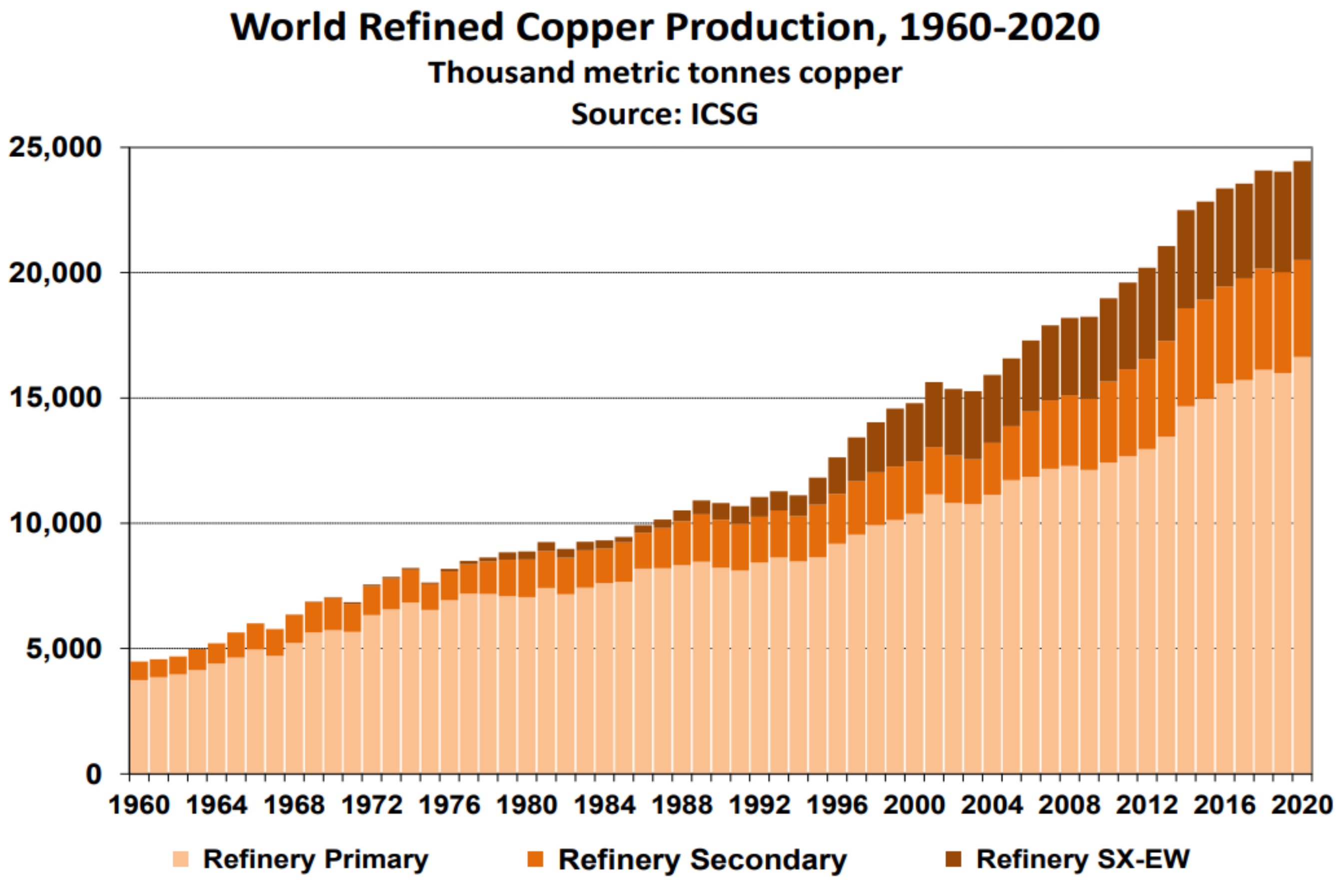
O'KEEFE INSTITUTE SUSTAINABLE SUPPLY OF STRATEGIC MINERALS

MISSOURI S&T

Refined Copper Production

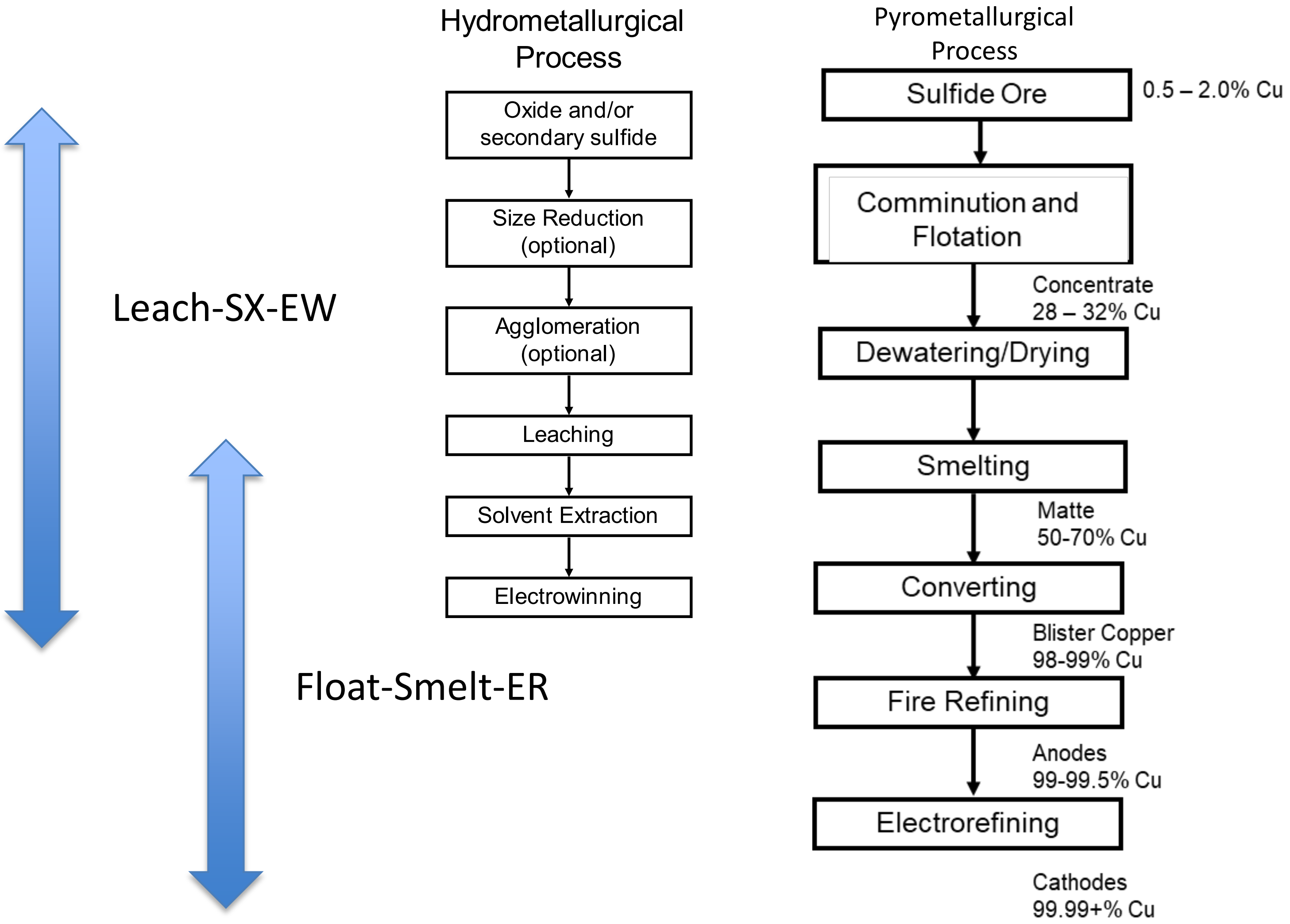
- ~24.5 million tonnes refined copper per annum
  - 20.9M from primary
  - 3.6M from secondary
- ~80% Float-Smelt-ER
- ~20% Leach-SX-EW



Primary Copper Process Determined by Mineralogy

By-products mostly from non-hydrometallurgical processing

- "Oxides"
  - Malachite
  - Chrysocolla
  - Atacamite
- Secondary Sulfides
  - Covellite
  - Chalcocite
- Primary Sulfide
  - Chalcopyrite



Critical Minerals in Float-Smelt-Refine Process

Sulfide Ore

↓

Comminution and Flotation

← Tailings **CM loss**

→ Mo Concentrate **Re** containing

↓

Smelting

↓

Converting

↓

Fire Refining

(Smelting, Converting, Fire Refining) →
Dusts – Recycled
Slags – Treated and Disposed – **In**
Off Gases – Sulfuric Acid
Blow Downs – Treated and Disposed (**Re**)

↓

Electrorefining

→ Slimes – Au, Ag, **PGM, As, Sb, Bi, Se, Te**, Pb, Ni

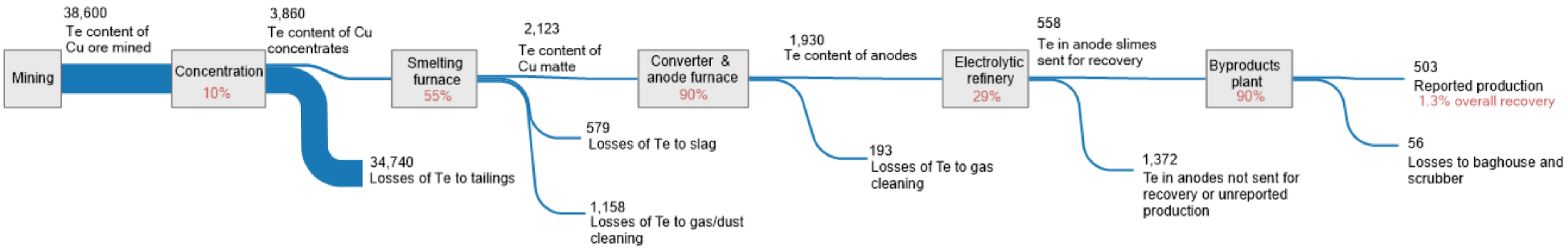
→ Solution Purification – **As, Sb, Bi**, Ni

↓

Cathodes

In North America, copper hydrometallurgical process does not produce by-products

Tellurium Estimate through the Copper Supply Chain



Nassar, N. T., Kim, H., Frenzel, M., Moats, M. S., & Hayes, S. M. (2022). Global tellurium supply potential from electrolytic copper refining. *Resources, Conservation and Recycling*, *184*, 106434.

This is based on two papers!

Mostly comes from ASARCO’s U.S. Supply Chain

Te in Copper Deposits

- Most copper comes from porphyry deposits
  - Large-to-giant in size
  - Low-to-medium Cu grade
  - ~ 60 - 95% of global copper supply
- Deposits can host 1s to 10s ppm of Te
  - Commonly concentrated within sulfide minerals or telluride minerals
    - Pyrite, Chalcopyrite, Bornite
- Generally, lack of information on the distribution behavior of Te within orebodies
  - Inaccurate sampling and assaying due to huge volumes and low grades
  - Potential association with gold and/or PGMs?

Maximum reported concentrations (ppm) of critical elements in chalcopyrite, bornite and pyrite from porphyry and other deposits

Mineral	Deposit Type	Se	Te
Chalcopyrite ($CuFeS_2$)	Porphyry	300	300
	Skarn	538	6.6
	Epithermal	300	0.04
Bornite (Cu_5FeS_4)	Porphyry	277	27.4
	Skarn	1046	148
	Epithermal	299	75
Pyrite (FeS2)	Porphyry	5.46	26.3
	Epithermal	535	343
	Carlin	4284	6600
	Orogenic	199	20823

Moats, M., Alagha, L., & Awuah-Offei, K. (2021). Towards resilient and sustainable supply of critical elements from the copper supply chain: A review. Journal of Cleaner Production, 127207.

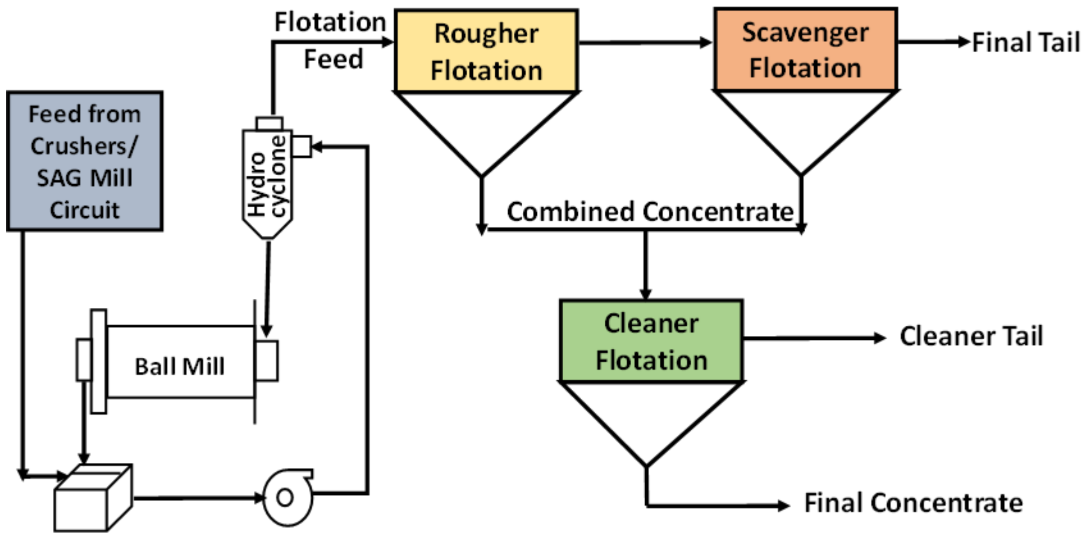
Deportment during Mineral Processing

Concentrations of Se, Te in copper sulfide concentrates from different plants

Element	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Cu (%)	21.7	16-19	25-28	20-26	41-45	28-32	16.6	-	-	-
Se(ppm)	-	8-15	<100	-	23	16	124	58	62	139
Te(ppm)	-	5-8	<100	<50	4.2	1.6	n/a	10	4.9	12

C1: Boliden/Sweden; C2:Hindustan Khetri./India; C3: Hindustan M Malanjkhand/India; C4: Assarel-Medet/Bulgaria; C5: Lumwana Malundwe/Zambia; C6: Lumwana Chimiwungo/Zambia; C7: Copper concentrator North America; C8: Mission Mine Complex-North/AZ-USA; C9: Mission Mine Complex South/AZ-USA; C10: Ray Mine/ AZ-USA

- Lack of information during rougher and scavenger stages of flotation
- Current public data are incomplete or inconsistent
  - Simple mass balance calculations
  - Lack of associated mineralogy for Te
  - Poor fundamental understanding of Te deportment



- Two studies have examined Te deportment
  - ~10% Te reports to concentrate
- Missouri S&T is examining a domestic concentrator for Te deportment

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Smelting and Converting

- Depends on furnace type
  - Most smelters recycle their dust (off gases)
  - Critical minerals eventually deport to anode or slag
- Difficult data to obtain
  - Values reflect grab samples
  - Confidential/proprietary information for custom smelters

Smelting

Furnace	Selenium (wt%)			Tellurium (wt%)		
	Matte	Slag	Gas	Matte	Slag	Gas
Outotec Flash	85	5-15	0-5	60-91	7-30	2-15
ISASMELT	n.d.	n.d.	n.d	71	18	11

Converting

Furnace	Selenium (wt%)			Tellurium (wt%)		
	Blister	Slag	Gas	Blister	Slag	Gas
Pierce-Smith	70-72	5-6	21-25	42	n.d.	58

- **One study has reported Te deportment**

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Flue Dust

Description	Cu(%)	Se(%)	Te(%)
"Flue Dust"	6-30	<0.01	0.2
Outotec Flash	11-30	0.04	0.01
Bottom Blowing	15-28	n.d.	n.d.
Pierce-Smith Converter	3.9-5.5	n.d.	n.d.

- Calculated ~1.2 million tonnes of dust per annum generated during copper smelting
- Dust recycling within a smelter increases concentration of Te
  - Not clear what the sustainable production potential of these elements would be
  - **Te concentration is from one published value**

Value of potential critical elements in smelter flue dusts. Prices reflect average 2015-2019 price for Cu, Se, Te, Sb and Bi metals and As2O3 (USGS, 2020)

Potential in Flue Dusts	Cu	Se	Te	As	Sb	Bi
Dust Grade	18%	0.005%	0.2%	10%	1.5%	1.8%
Price (USD/kg)	5.8	42	134	0.58	8.1	10.6
Tons per year contained in dust	216000	60	2400	120000	18000	21600
Value (millions USD/yr)	1300	3	320	60	150	230
% of total value in flue dusts across these elements	62.1	0.1	15.9	3.3	7.2	11.3

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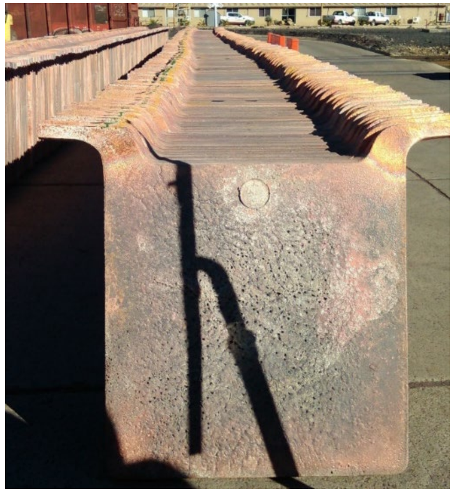
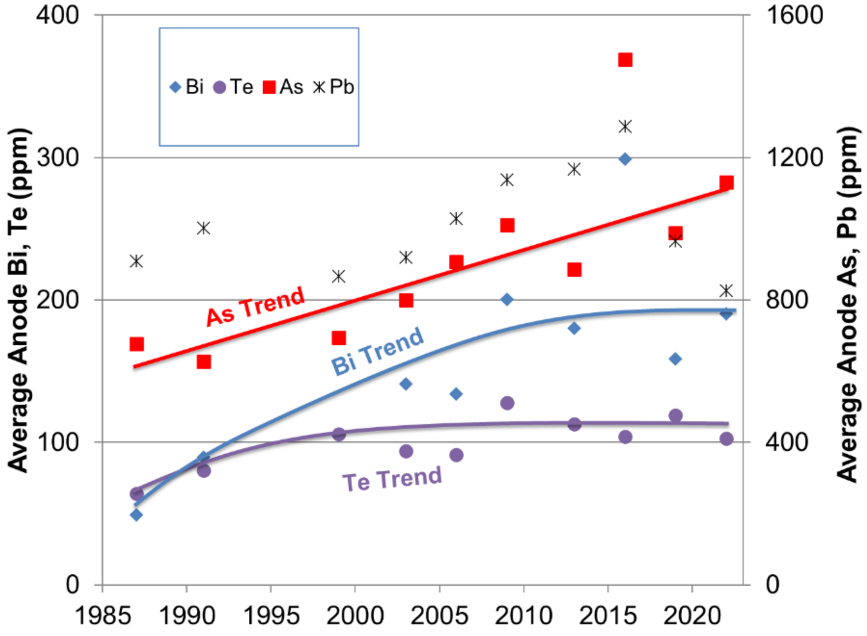
Electrorefining Anodes





Moats et al. (2022) to be presented at Copper 2022 in November, 2022, Santiago, Chile

Slimes

Characteristics		Average Value	
kg per tonne of anode		4.9	
Element	%	Element	%
Cu	22.1	As	3.9
Ag	11.4	Sb	2.1
Au	0.7	Bi	1.4
S	8.6	Pb	10.4
Se	8.0	Fe	0.2
Te	1.7	Ni	3.3

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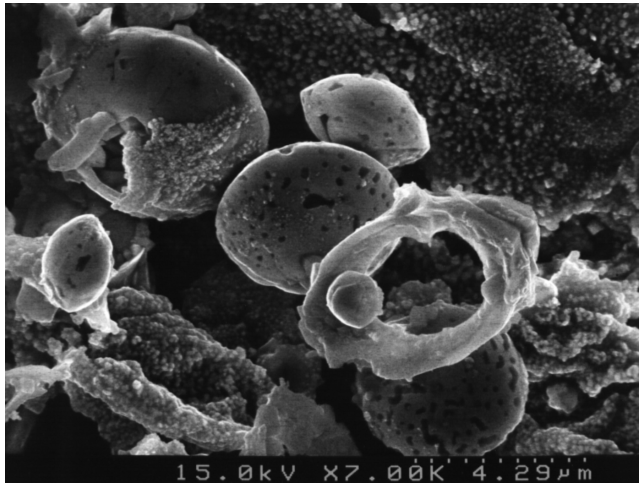
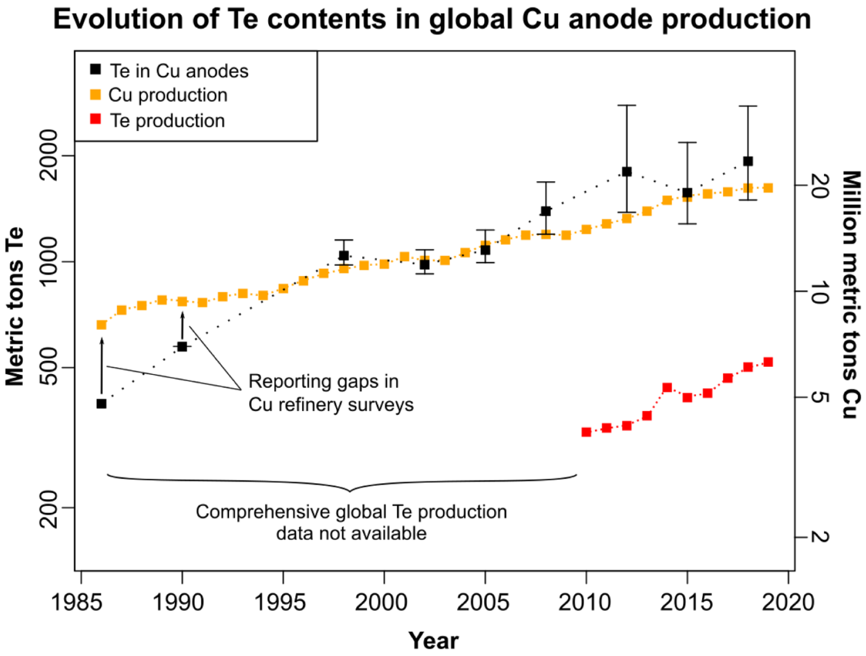
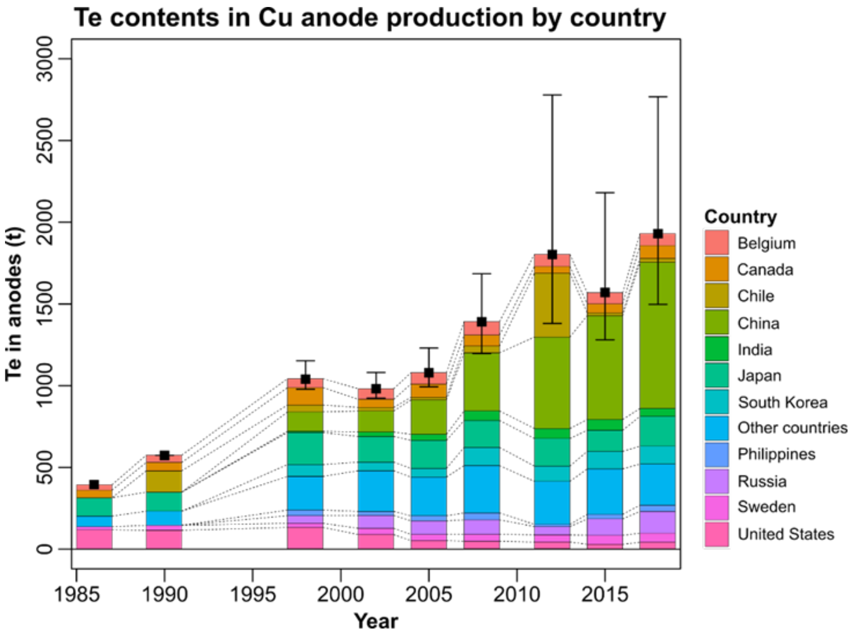
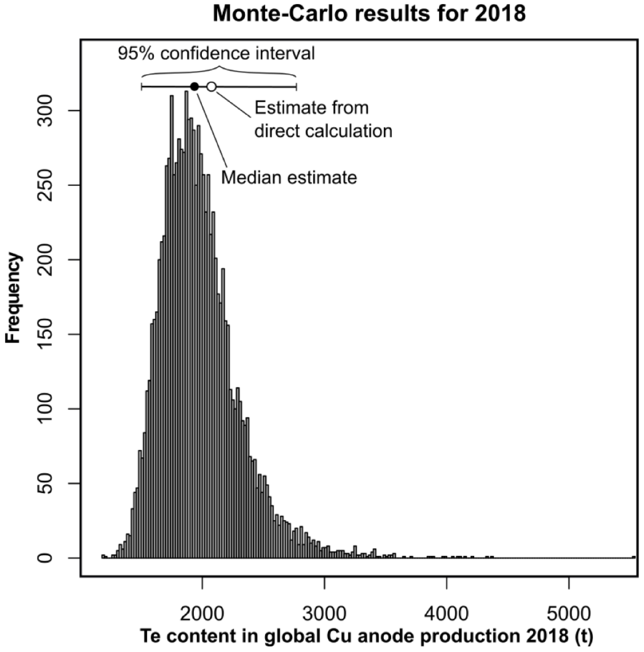


- Significant enrichment of Te
- Facilitates the potential recovery of critical minerals while targeting the recovery of gold and silver

Tellurium in Copper Refineries







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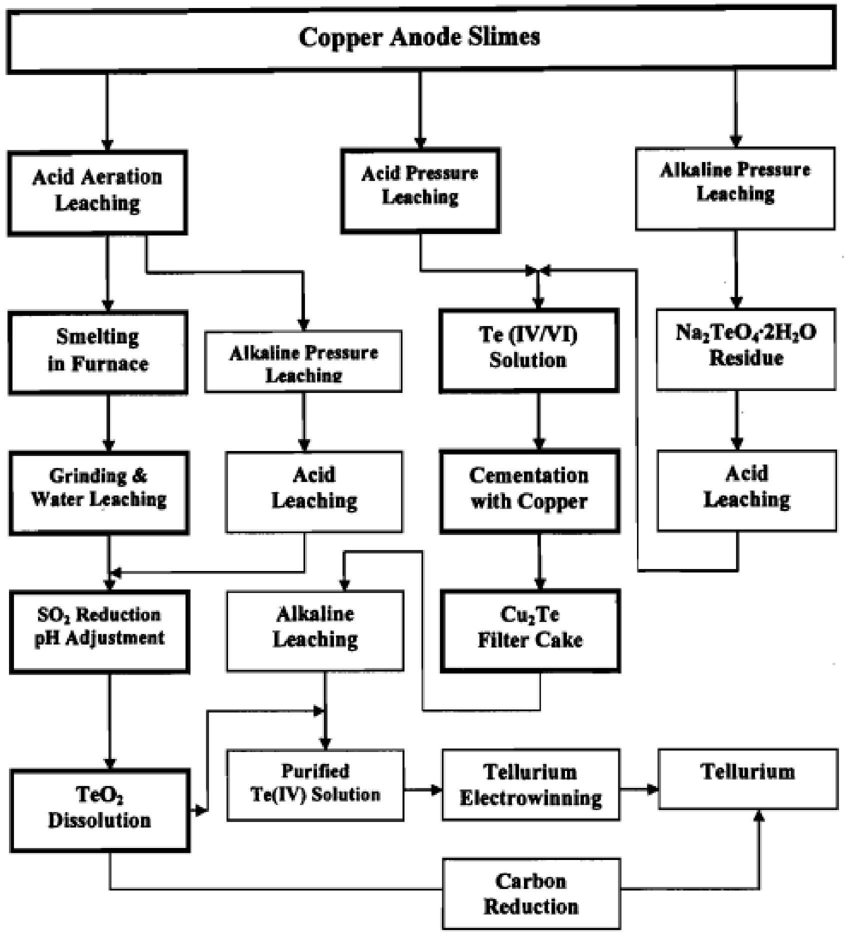
Te Recovery from Slimes



Wang, S., Westrom, B., & Fernandez, J. A. (2003). The recovery of tellurium from copper refinery slimes. COBRE 2003 Volume V, 273-285.

- Te recovery from slides is not widely reported.
- Estimates of worldwide Te recovery from slimes are **25-33%**.
- **Low recovery has been examined in a few papers, but the problem is not well understood.**

Potential value (millions USD/yr) of metals contained in copper anodes at U.S. refineries

Element	Refinery 1	Refinery 2	Refinery 3	Price
Copper	1200	800	1200	$5.8/kg
Gold	290	12	68	$1270/tr.oz.
Silver	47	49	74	$16.4/tr.oz.
Selenium	5.3	3.0	5.1	$42/kg
Tellurium	2.3	1.1	1.5	$134/kg
Arsenic	0.22	0.03	0.04	$0.55/kg
Antimony	0.05	0.09	0.29	$8.1/kg
Bismuth	1.2	0.26	0.24	$10.6/kg

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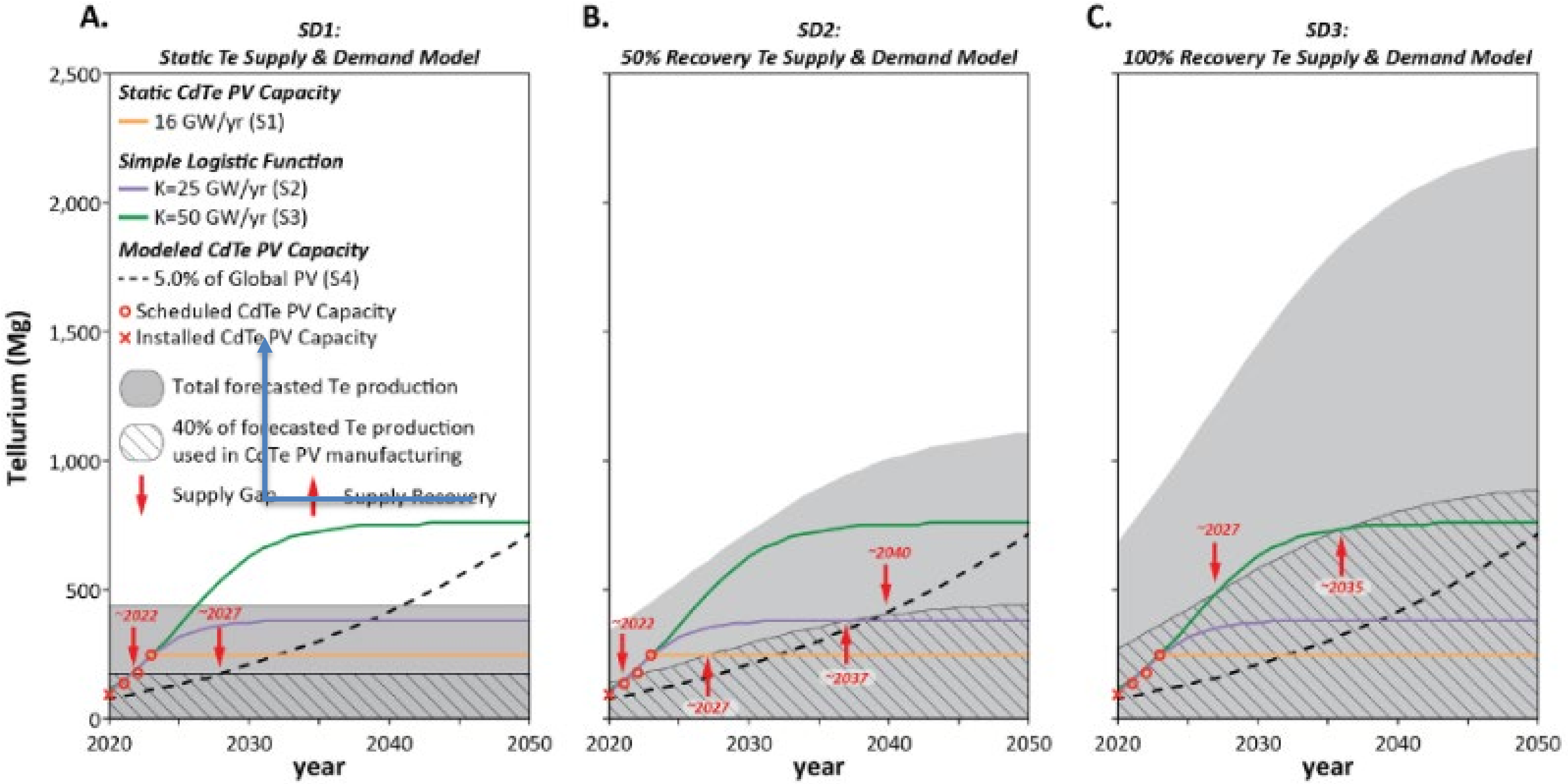
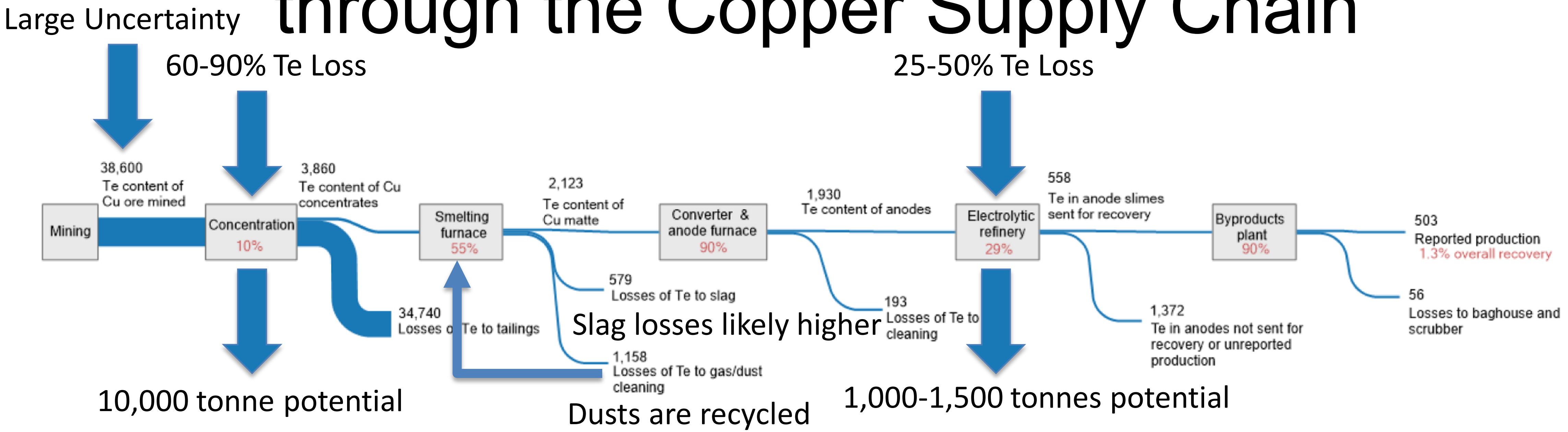
How Much Tellurium is Needed?



McNulty, B. A., & Jowitt, S. M. (2022). Byproduct critical metal supply and demand and implications for the energy transition: A case study of tellurium supply and CdTe PV demand. *Renewable and Sustainable Energy Reviews*, *168*, 112838.

Tellurium Estimate through the Copper Supply Chain



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Stream	Te Concentration (ppm)
Ore	1-5
Concentrate	5-15
Dust	2000*
Anode	0-500
Slimes	5000-50000

This is based on two papers!

Mostly comes from ASARCO's U.S. Supply Chain

* - one published value

Opportunities to Increasing Tellurium from Existing Copper Operations

Determine why 60-90% of Te is loss at the concentrator

Increase Te recovery to smelter by improved flotation

Improve Te recovery during slimes processing

Educate workforce needed to increase tellurium supply

Summary

- The world copper supply chain can supply tellurium needs for the near term
- Without new or bigger U.S. smelters and refineries, Te will be produced elsewhere if sourced from slimes
- Domestic Te supply will only increase if more is captured during mineral processing
- Losses during slimes processing are not understood which impacts allied production