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# Global Tellurium Supply Potential from Electrolytic Copper Refining

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Full length article

# Global tellurium supply potential from electrolytic copper refining

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ABSTRACT

The transition towards renewable energy requires increasing quantities of nonfuel mineral commodities, including tellurium used in certain photovoltaics. While demand for tellurium may increase markedly, the potential to increase tellurium supply is not well-understood. In this analysis, we estimate the quantity of tellurium contained in anode slimes generated by electrolytic copper refining by country between 1986 and 2018, including uncertainties. For 2018, the results indicate that 1930 (1500-2700, 95% confidence interval) metric tons of tellurium were contained in anode slimes globally. This is nearly quadruple the reported tellurium production for that year. China has the greatest potential to increase tellurium supplies. However, most of the tellurium potentially recoverable by Chinese refineries appears to come from copper mined elsewhere. Further research into the business decisions associated with tellurium recovery may help translate the physical availability of tellurium into economic availability. The methodology presented here can be applied to other byproduct elements.

## 1. Introduction

Solar technologies are expected to comprise the largest share of globally installed electricity generation capacity within the next two decades (see Fig. S1, with data from the Energy Information Administration (Energy Information Administration 2019), in the Supporting Information). This is perhaps not surprising given the sustained decline in the levelized cost of electrity of utility-scale solar photovoltaic (PV) plants, the globally weighted average of which has decreased 85% in the decade spanning 2010 to 2020 (IRENA 2021). With an estimated learning rate (i.e., percent decline in total installed cost with every doubling of cumulative production) of 34%, utiliy-scale solar PV technologies have become not only cost competitive with fossil fuels but have significantly undercut even the least expensive existing coal-fired power plants (IRENA 2021). Among the many implications of this transition from fossil fuels to renewable energy technologies will be an increased reliance on nonfuel mineral commodities. This is because, like other renewable energy generation and storage technologies, solar technologies require notable quantities of a wide range of nonfuel mineral commodities including copper (Cu), aluminum (Al), silicon (Si), as well as a variety of minor elements recovered predominantly as byproducts (Hund et al., 2020). The clean energy transition will thus also necessitate a transition from fossil fuels to nonfuel mineral commodities.

Of the currently commercially available solar PV technologies, crystalline silicon (c-Si) technologies are dominant with over 90% of annual solar PV production globally (Fraunhofer Institute for Solar Energy Systems, 2022). Other commercially available solar PV technologies include three thin-film technologies: copper indium gallium selenide (CIGS), cadmium telluride (CdTe), and amorphous silicon (α-Si). Of the thin-film technologies, CdTe has the largest market share in both the United States (24% of all solar PV utility-scale capacity installed in 2020 and also 24% of those cumulatively installed since 2001 and still operating; see Fig. S2) and globally (4% of all solar PV capacity installed in 2020) (Fraunhofer Institute for Solar Energy Systems, 2022). This represents over 98% of the thin-film solar PV technologies installed that year, 96% of those cumulatively installed since 2001 and still operating in the United States, and 79% of the thin-film solar PV technologies produced globally in 2020. This can be partially attributed to several advantages associated with CdTe, including low cost and ease of manufacturing and an optimal band gap for light absorption (Romeo and Artegiani, 2021). As a result, global production of

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CdTe solar cells has increased markedly in the past decade from negligible levels in the mid-2000s to over 6 Gigawatts (GW) in 2020 alone (Fraunhofer Institute for Solar Energy Systems, 2022). This increase in CdTe production has been accompanied by an increase in demand for tellurium (Te), accounting for an estimated 60% of global Te use and its single largest application.[1] How fast the demand for Te in CdTe will grow in the future will depend on the overall demand for solar PV, CdTe's market share, the material intensity of Te in CdTe (i.e., the quantity of material needed per GW of installed capacity), and manufacturing efficiencies (Nassar et al., 2016). It will also depend on the price and availability of Te.

Tellurium is recovered predominantly as a byproduct during the refining of Cu; its supply is thus strongly linked to this metal. Other sources of Te are skimmings from lead (Pb) refineries and deposits enriched in Te minerals, but these sources currently contribute little toward total global Te supply. Indeed, over 90% of the world's Te supply is reportedly recovered from the anode slimes generated during electrolytic Cu refining (U.S. Geological Survey, 2021). During this process, electrical potential is applied to Cu anodes (typically <99% pure Cu) to release $Cu^{2+}$ cations to the electrolyte. The Cu cations migrate to and deposit on the cathode to produce >99.99% pure Cu metal. Insoluble impurities settle to the bottom of the tank and form anode slimes. More than 98% of the Te contained in the anode is insoluble in the electrolyte and thus reports with other insoluble impurities to the anode slimes (Davenport et al., 2002, Ojebuoboh, 2008). The slimes are regularly processed to recover additional Cu (which also liberates some Te) and then to recover precious metals (mainly gold, silver, and sometimes platinum-group metals), as well as minor elements including selenium (Se) and Te. Some refineries recover Te from the slimes and process it on-site. More commonly, refineries recover and sell the slimes or intermediate Te products (e.g., crude Te dioxide or copper-telluride) to a third party for further processing. Importantly, Cu smelters have historically considered Te (and Se) a nuisance and may set penalties if either appear above certain thresholds in the initial ore concentrates entering the smelting process (Ojebuoboh, 2008, Fountain, 2013). This strong dependency on electrolytic Cu production, along with Te's geological scarcity, (Hu and Gao, 2008) has raised questions regarding the reliability and availability of Te supply (Nassar et al., 2016, Houari et al., 2014, Candelise and Winskel, 2012, Davidsson and Höök, 2017, Bustamante and Gaustad, 2014, Marwede and Reller, 2012, Zuser and Rechberger, 2011, Fthenakis, 2009, Fthenakis and Anctil, 2013).

Despite the potential increase in demand and the concerns regarding its availability, there is limited information regarding current Te production and even less on the potential to increase that production should the need arise from CdTe or any other high-demand application. What is known is that contemporary global Te production is on the order of 500 metric tons (t) per year, (Willis et al., 2012, Feng, 2017, Anderson, 2021) with Chinese production from three provinces (Guangdong contributing 27% of total Chinese Te production in 2016; Hunan, 32%; and Jiangxi, 34%; others, 7%) comprising roughly half of the world total (Feng, 2017). In its 2019 Minerals Yearbook, the U.S. Geological Survey estimates that global Te production was at least 503 t in year 2018, (Anderson, 2021) with China accounting for 61% of this total, followed by Japan (11%), Sweden (9%), Russia (8%), and Canada (8%) (Anderson, 2021). It should be noted that these are best estimates and there may be discrepancies from actual production for two major reasons. First, the total production may be greater than the reported total as not all producing countries report their production figures. In addition to withholding the production figure for the United States from this total to avoid disclosing company proprietary data, the U.S. Geological Survey notes that "Australia, Belgium, Chile, Colombia, Germany, Kazakhstan, Mexico, the Philippines, and Poland may have also produced refined tellurium, but available information was inadequate to make reliable estimates of output" (Anderson, 2021). Second, the definition of what constitutes Te production can be ambiguous. For example, Natural Resources Canada defines Te production to include contained Te in exported concentrates as well as refined Te production (Natural Resources Canada, 2020). This could potentially result in double-counting of the production figures where countries report the same Te in various forms along the value chain as their production. A recent analysis noted significant discrepancies in the estimated global production of Te between the U.S. Geological Survey and the British Geological Survey, (McNulty and Jowitt, 2021) illustrating the challenges of estimating global Te production. Firm-level production data are similarly limited, mainly due to confidentiality concerns. However, a report by Oakdene Hollins identified global Te production in year 2011 at the firm-level to sum to 450-470 t of Te in various forms from over 26 operations in at least 19 countries (Willis et al., 2012). An update to that report sums firm-level production in 2015 to 522 t of Te in various forms from over 37 operations in at least 21 countries, with only 70 t being attributable to 4 of the 9 identified producing firms in China (Pfaltzgraff et al., 2015). The U.S. Geological Survey's estimate of Te production for the same year was at least 411 t from 7 countries, excluding the United States.

To determine how much primary Te production can increase, it is important to quantify how much is potentially available from Cu operations in which Te is present but not recovered. A study by Ojebuoboh suggested that the vast majority (~90%) of the Te contained in ores is lost to tailings during the concentration process of the Cu-containing minerals at mine sites (Ojebuoboh, 2008). The same study also identified the likely percentages of Te being lost further downstream and estimated the potential production of Te at 1200 t in 2006 based on the Te content of Cu anodes and anode slimes reported in a survey of electrolytic Cu refineries (Ojebuoboh, 2008). This was the same quantity estimated by the U.S. Geological Survey using the same data source (George, 2012). Similarly, Green (Green, 2013) estimated 1300 t of Te were available in Cu anodes slimes in 2005, while the Öko-Institute estimated that 1500 t of Te were the maximum theoretically available from Cu anode slimes, with another 130 t from Pb refining (Buchert et al., 2009). While these single-point estimates are helpful, they do not provide any context regarding the associated uncertainties. Moreover, while identifying China as the largest potential source, they do not indicate which other countries have large potential to increase their Te production nor do they indicate how this potential may have changed over time. It is important to remember that the country where Te is produced reflects only Te refining capabilities rather than the geologic endowment because Cu concentrates and anodes slimes are shipped globally. The goal of this analysis is thus to address these knowledge gaps and provide a comprehensive assessment of Te's supply potential from Cu refining. To do this, we have combined information from all available surveys of Cu electrolytic refining tankhouse data and information regarding current and historical global Cu electrolytic refining production. These data were used as inputs in a Monte Carlo simulation to allow for a statistically robust assessment of Te's primary supply potential.

## 2. Data

To quantify the physical availability of Te from electrolytic Cu refining, we collected facility-level data on cathode production, anode and anode slime compositions, as well as anode slime generation rates for the years 1986, 1990, 1998, 2002, 2005, 2008, 2012, 2015, and 2018. Cathode production data for individual refineries were obtained from several sources. For the most recent year of the analysis, 2018, data were obtained from company reports. Where facility-level data were not available in company reports, cathode production data were obtained

[1] At 6.1 GW of produced CdTe solar PV capacity, we estimate that Te consumption for CdTe solar PV in 2020 was roughly 350 metric tons, assuming an average module conversion efficiency of 18%, 3 µm absorption layer, and a manufacturing recycling efficiency of 90%. That translates to roughly 60% of world primary production in 2020, which was at least 560 metric tons.

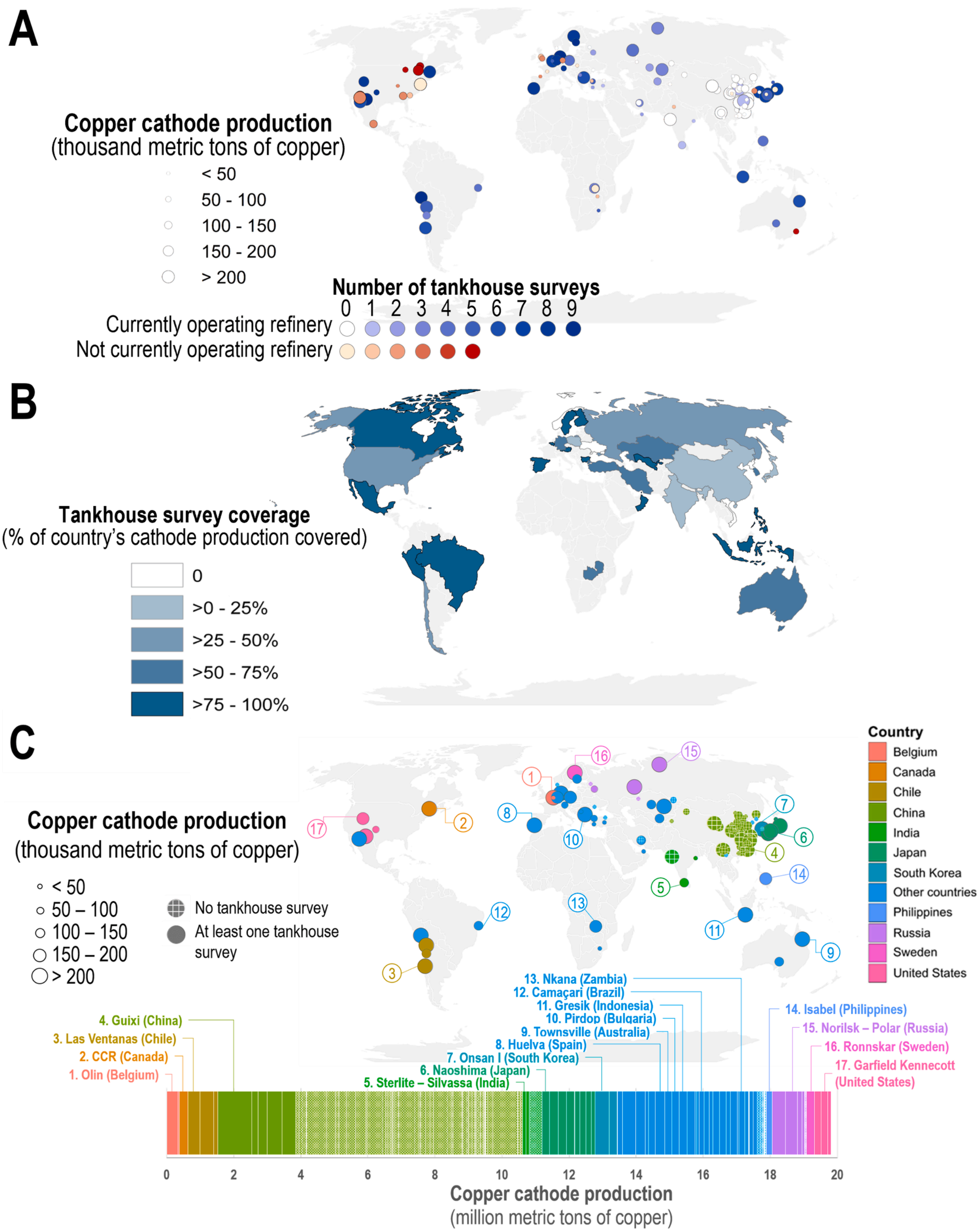
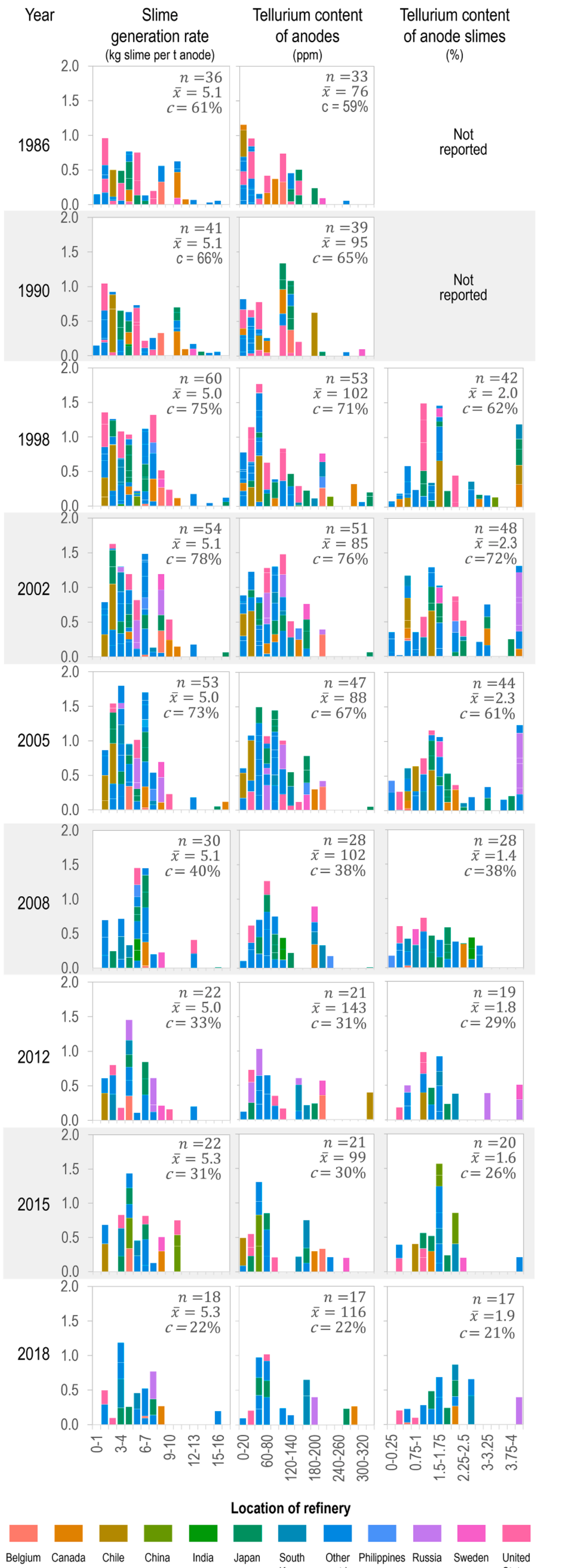



**Fig. 1.** (A) Locations of electrolytic Cu refineries by operating status, cathode production (in 2018 for currently operating facilities, and maximum reported production for not currently operating facilities), and the number of unique tankhouse surveys reporting data for said facilities; (B) Percent of each country's Cu cathode production covered by at least one tankhouse survey across all survey years; (C) Locations of electrolytic Cu refineries that are currently operational (in 2018) by cathode production and tankhouse survey coverage. Selected refineries are identified in panel (C) for reference.

from CRU International Limited (CRU International Limited 2019) or from the International Copper Study Group (International Copper Study Group 2020a, International Copper Study Group 2020b). For years 1998-2015, facility-level cathode production data were obtained exclusively from CRU, (CRU International Limited 2019) as 1998 is the first year for which data were available from CRU. For years prior to 1998, facility-level cathode production data were obtained from a series of global electrolytic Cu refinery tankhouse surveys (Schloen et al., 1987, Schloen, 1991, Schloen and Davenport, 1995, Davenport et al., 1999, Robinson et al., 2003, Moats et al., 2007, Moats et al., 2013, Moats et al., 2016, Moats et al., 2019).

Facility-level data on the Te content of anodes and anode slimes, as well as on anode slime production rates, were also obtained from the global electrolytic Cu refinery tankhouse surveys (Schloen et al., 1987,




*(caption on next column)*

**Fig. 2.** For each survey year, summary histograms for slime generation (in kg per metric ton of anode), Te content of anodes (in parts per million), and Te content of anode slimes (in percent) by refinery, its cathode production (vertical axes, in million metric tons of Cu), and its location (color). Each subfigure also indicates the number of refineries with reported data (n), the cathode production-weighted mean ($\bar{x}$) of these data, and the percentage of global electrolytic Cu cathode production covered (c). All figures share the same vertical axes range, while all figures in the column share the same horizontal axes range. Note that mean values may not be representative of true global production due to missing data in the tankhouse surveys, particularly for later survey years.

Schloen, 1991, Schloen and Davenport, 1995, Davenport et al., 1999, Robinson et al., 2003, Moats et al., 2007, Moats et al., 2013, Moats et al., 2016, Moats et al., 2019). These surveys were conducted in 1987, 1991, 1999, 2003, 2006, 2009, 2013, 2016, and 2019. The data contained in the surveys predominantly pertain to the respective previous years (e.g., 2018 data in the 2019 survey), but in some cases pertain to two or three years prior depending on when the respondents completed the survey and what data they provided. For consistency, the year immediately preceding the survey year was assigned to the tankhouse data used in this analysis. In some cases the same tankhouse data were reported in multiple surveys. These duplicate entries were removed to allow only for unique and up-to-date data entries. In several cases the surveys provide a range of quantities for the various parameters. For such cases, the arithmetic mean or, if the upper bound of the range is at least 3-times the lower bound, the geometric mean of the upper and lower bounds was utilized. In other cases, the surveys note quantities as inequalities (e.g., $<10$). For such cases, the reported quantity without the inequality was utilized.

Information on the electrolytic Cu refineries covered in this analysis are displayed across several maps in Fig. 1. Specifically, Fig. 1A displays the location and Cu production of electrolytic Cu refineries worldwide and provides an indication as to their operating status in 2018. It also indicates the number of surveys for which tankhouse data are available for each refinery. Fig. 1B displays the percentage of each country's electrolytic Cu production covered by at least one tankhouse survey. There are some countries (e.g., North Korea) for which no coverage is available in the tankhouse surveys. However, these countries typically represent only a small percentage of global electrolytic Cu production. As illustrated in Fig. 1C, the largest gap in the tankhouse data exists for China, which is the leading electrolytic Cu producer, but for which only a small number of the operating refineries have responded to any of the tankhouse surveys.

The distributions of the reported tankhouse survey parameters (i.e., anode slime generation rate, Te content of the anodes, and Te content of the anode slimes) are summarized in Fig. 2 by year and country (and in a different format in Fig. S3), with a complete tabulation by refinery provided in Figs. S4-S6. These distributions indicate that the production-weighted means ($\bar{x}$) of the reported anode slime generation rates range from 5.0 to 5.3 kg of anode slime per t of anode across survey years. There is, however, notable variation around these means, with values for individual refineries ranging from 0.7 to 28 kg of anode slime per t of anode. The production-weighted means of the reported Te content of anodes range from 76 to 143 ppm across survey years, while the production-weighted means of the Te content of the anode slimes range from 1.4 to 2.3% across survey years. Again, both parameters have wide distributions around their means, with values for individual refineries ranging from 0 to 700 ppm and 0 to 11% for Te content in the anodes and anode slimes, respectively. In general, because the focus of refineries is on the anodes and cathodes, anode composition is more frequently sampled and thus is more representative and frequently reported than anode slime composition. Therefore, anode composition data were preferred in this work and data on slime compositions were only used when no data on anode compositions were available. In such cases, anode composition was calculated from the slime composition

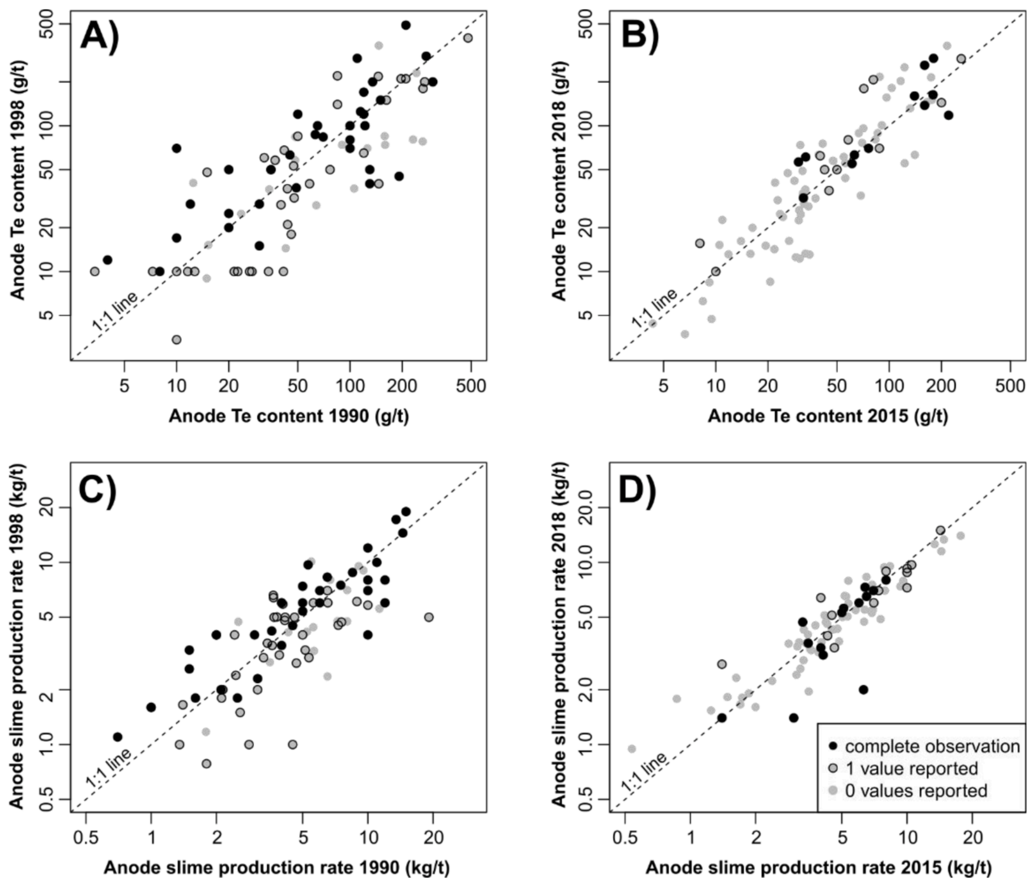



**Fig. 3.** Correlations in reported values for individual refineries across survey years, for different pairs of years: A) anode Te contents reported for 1990 and 1998, B) anode Te contents reported for 2015 and 2018, C) anode slime production rates for 1990 and 1998, and D) anode slime production rates for 2015 and 2018. Imputed values from one of the imputed datasets are also shown. Axes are plotted on logarithmic scales. Note that where a datapoint is described as “0 values reported,” refers to the years shown on the plot. Values are reported for other years in these cases, which were used to infer the values shown.

and anode slime production rate.

While there may seem to be a trend of increased Te content of anodes over time (Fig. S3), it is difficult to draw any conclusions from the dataset due to the large variability among refineries and the decline in the number of refineries ($n$) that have responded to the surveys. This decline in the number of respondents corresponds to a decline in coverage of global Cu electrolytic refining production[2] from a high of approximately 76% in 2002 to 22% in 2018 for Te content of anodes (Fig. S3). Although the global coverage of individual tankhouse parameters in specific surveys has become low in recent surveys, examining the coverage of Cu electrolytic refineries for which at least one tankhouse survey is available indicates that at least 61% (and up to 91%) of global cathode production is covered in any given year (Fig. S7). Moreover, the final dataset contains facility-level cathode production data that covers at least 97% global Cu electrolytic refinery production for all years starting in 1998—the year that CRU data begin. Lower facility-level coverage (61% and 69%) of Cu cathode production was available for years 1986 and 1990, respectively.

[2] Global electrolytic Cu production by year was estimated by multiplying the global electrolytic Cu refining capacity by a calculated capacity utilization for all Cu refineries as reported in the International Copper Study Group’s directory of copper mines and plants (International Copper Study Group 2020) and world copper factbook. (International Copper Study Group, 2021) This calculation assumes that the capacity utilization rate of electrolytic Cu refineries is the same as the overall capacity utilization rate for all Cu refinery production. This assumption is reasonable given that global electrolytic Cu refining capacity typically represents over 80% of all Cu refinery capacity.

## 3. Method

To estimate the total Te content in global Cu anode production, we used two modes of calculation. A direct calculation based on reported Te contents and a Monte Carlo-type simulation method accounting for the uncertainties arising from missing data. Both modes of calculation are based on the following fundamental considerations and are described in more detail in the subsequent subsections. Note that we are estimating Te contents in Cu anode production because most of the available data pertains to Te concentrations in anodes. Since >98% of the Te contained in Cu anodes reports to anode slimes during electrolytic refining, the numbers we obtain are essentially equivalent to the amounts of Te contained in anode slimes.

For any refinery $i$ for which the necessary information is available, the total mass of Te contained in anodes ($m^i_{Te}$) for a given year can be calculated as:

$$m^i_{Te} = \frac{m^i_{Cathode} \cdot c^i_{Te}}{(1 - R^i_{slime})} \quad (1)$$

where $m^i_{Cathode}$ is the mass of cathode production, $c^i_{Te}$ is the Te content in anodes, and $R^i_{slime}$ is the anode slime production rate expressed as the mass of slime produced per unit mass of anode. The total amount of Te contained in global Cu anode production ($M_{Te}$) is then given by the sum:

$$M_{Te} = \sum_i m^i_{Te} \quad (2)$$

where the index $i$ runs over all refineries worldwide. Unfortunately, this sum cannot be calculated from the available dataset due to missing data. Particularly for 2018, data on Te contents in anodes are only available for 17 of the 128 producing Cu refineries included in the dataset.

To address this issue and still provide a realistic estimate of $M_{Te}$, the missing values need to be imputed. Two approaches were used for this purpose:

1) A deterministic approach directly using the most recent values available from the refinery survey to estimate $M_{Te}$ (only for 2018),
2) Monte-Carlo type simulations to assess the probability distribution of $M_{Te}$ given the available data (for all years).

These are described in more detail below.

### 3.1. Direct use of tankhouse data

For 2018, an estimate of $M_{Te}$ was compiled directly from the available data. Assuming that the composition of anodes processed at a given refinery varies little over time, the missing values for anode Te contents and anode slime production rates for 2018 were imputed with reported values from the most recent earlier survey year. For instance, if data for a given refinery were available for 2008 but not 2018 or 2015, then the 2008 values were used in the calculation. This procedure of selecting the most recent data was applied to all operating refineries which appeared in the refinery surveys. The contribution of these refineries to $M_{Te}$was then calculated using Eqs. (1) and (2).

For all other refineries active in 2018 it was assumed that the mean Te/Cu ratio in anodes was the same as for the imputed dataset described in the previous paragraph. That is, a production-weighted average Te/Cu ratio was calculated from the imputed dataset and multiplied by the total cathode production of the remaining refineries to estimate their contribution to $M_{Te}$. At refineries that process primary and secondary Cu, it was assumed that secondary (recycled) Cu did not contain Te, because Te occurring with Cu in ores is removed by primary smelting. Thus, correction factors were applied to account for the proportion of primary Cu treated in each refinery. This assumption was supported by data from three refineries in the refinery survey (Lünen in Germany, Brixlegg in Austria and Beerse in Belgium), all of which reported very low anode Te contents.

It should be noted that this simple calculation was only done as a reference case to yield a more intuitive comparison with the results of the Monte-Carlo simulations. It has clear conceptual disadvantages with respect to the latter approach. Namely, it allows for neither the estimation of the uncertainties on $M_{Te}$ resulting from the imputation procedure, nor the accounting for potential systematic changes in Cu concentrate compositions which may occur over the years. This is a concern given that although the production-weighted average of the Te content of anodes and anodes slimes is relatively stable, there have been significant changes at individual facilities (see Figs S5-S6). Therefore, it cannot support statements about a realistic minimum value of $M_{Te}$, an important consideration in the assessment of by-product availability (cf. Frenzel et al., 2015, Frenzel et al., 2016, Frenzel et al., 2017).

### 3.2. Monte-Carlo simulations

Monte-Carlo simulations were used to assess $M_{Te}$ for the years 1986, 1990, 1998, 2002, 2005, 2008, 2012, 2015 and 2018. These simulations were based on stochastic regression imputation of the missing values for anode Te contents and anode slime production rates in the survey dataset (Amelia II algorithm, Honaker et al., 2021). The method estimates best-fit values and corresponding uncertainties for the missing data based on the available data from other years. Its use was motivated by the observation that anode Te contents and anode slime production rates reported by individual refineries for different years are strongly correlated (Fig. 3). The probable reason for these correlations is the tendency of smelters to keep overall feed material compositions as constant as possible to achieve optimum process conditions compatible with individual plant designs (Pérez et al., 2021, Schlesinger et al., 2011).

To implement the stochastic regression imputation, a data table was

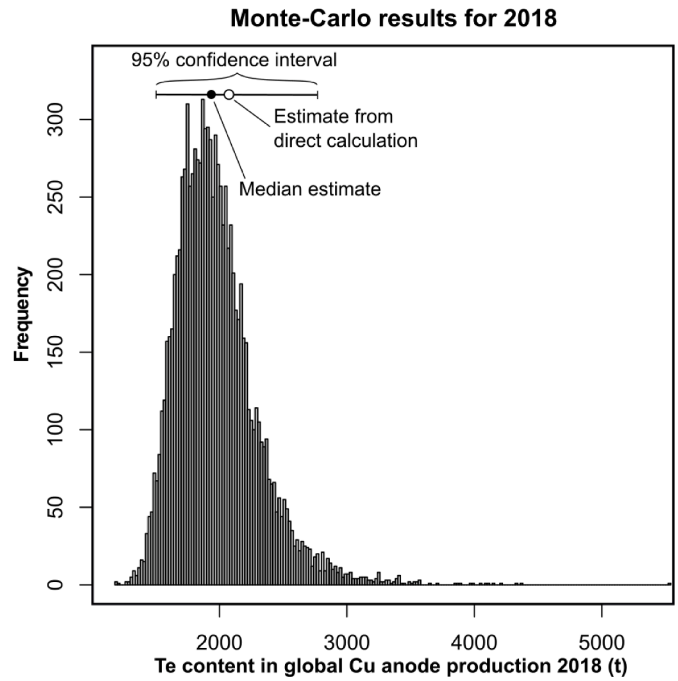



**Fig. 4.** Histogram of the results of the Monte Carlo-type simulations for $M_{Te}$ for 2018. The median estimate and corresponding 95 % confidence interval are also shown. The position of the estimate from direct calculation is also shown for comparison.

prepared containing all available data on anode Te contents and anode slime production rates. Data were then log-transformed to reflect their strictly positive scale of measurement (Gaddum, 1945). Where anode Te contents were reported as below detection limit, they were replaced by the absolute value of the detection limit prior to log-transformation (cf. Frenzel et al., 2015). A total of 10,000 imputed datasets (=simulations) was then generated from the input data. Each of these simulations represents an equally probable realization of the complete dataset given the observed data.

These results were used further to randomly impute the anode Te contents and anode slime production rates for the refineries for which only cathode production data were available (Fig. S7). Here, it was assumed that the distribution of values in any given year is identical to the one for the refineries included in the survey dataset. This is presumed to be a reasonable assumption as most of the relevant refineries are in China and likely process a global mix of Cu concentrates (cf. Fig. 2). The major reason for this is that Cu mining in China only produces a fraction of the Cu concentrates ultimately processed by Chinese refineries (~22% in 2018, cf. Flanagan, 2021), and the remainder must therefore be imported from other countries.

For the cathode-only data, a total of 10,000 datasets again were simulated. For imputation, each of these datasets was paired with one of the 10,000 previous simulations of the survey data. Values for anode Te contents and anode slime production rates for a given year were then drawn randomly (with replacement) from the corresponding simulation of the survey data. This approach was preferred to simulation from fitted probability distributions, since 1) it does not require any assumptions about the shape of the distributions, and 2) it automatically accounts for relevant uncertainties. Finally, correction factors were assigned to each facility according to the estimated proportion of secondary Cu input. These were then used to correct estimated anode Te contents, similar to the procedure used in the direct calculation of Te contents in global Cu anode production for 2018 described above.

Finally, $M_{Te}$ was calculated for each of the 10,000 pairs of imputed datasets, and the individual values were compiled to yield the overall probability distribution of $M_{Te}$ for each year. In addition, data were

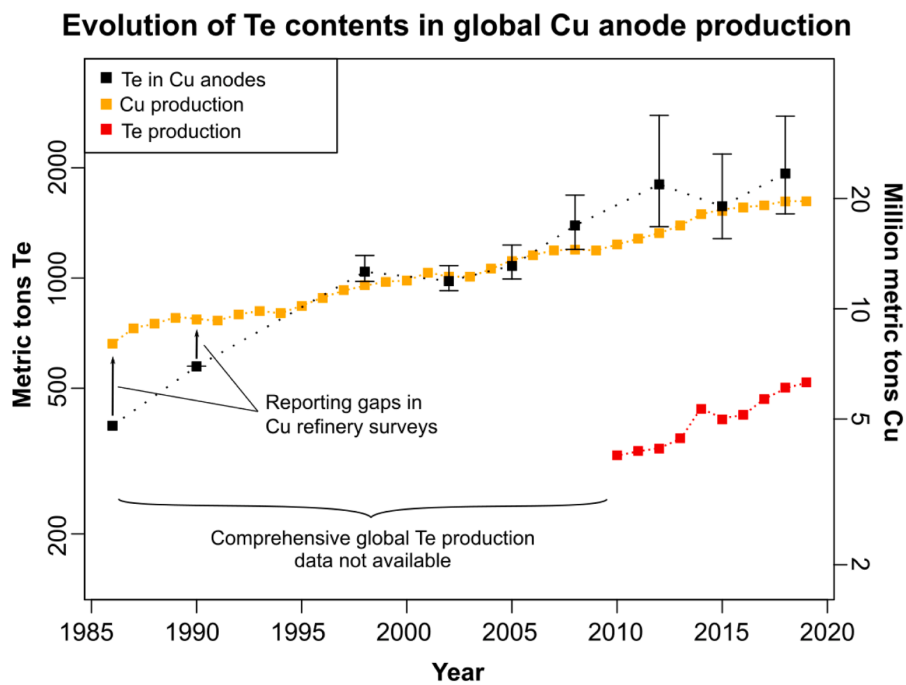



**Fig. 5.** Evolution of Te contents in global Cu anode production relative to primary electrolytic Cu production and reported Te production. Error bars indicate the 95% confidence interval, while plot symbols indicate median estimates (cf. Fig. 4). Note that the vertical axis is plotted on a logarithmic scale.

compiled at the country level to yield insights into the geographic distribution of Te contents in global Cu anode production over time.

## 4. Results

### 4.1. Direct calculation

Using direct calculation from the survey data, the total Te content in global Cu anode production was estimated to be 2055 t in 2018. This total consists of a contribution of 1267 t from the refineries included in the survey database, and 788 t from the remaining refineries for which only cathode production data were available. This estimate provides a rough indication of the overall magnitude of the total Te content in global Cu anode production but does not include any measure of uncertainty.

### 4.2. Monte-Carlo simulations

#### 4.2.1. Results for 2018

Fig. 4 shows the overall distribution of estimates of $M_{Te}$ for 2018 obtained from the Monte-Carlo simulations. The median estimate is 1930 t and the 95% confidence interval ranges from 1500 to 2770 t. The estimate from direct calculation clearly falls well within this interval.

### 4.3. Evolution over time

Fig. 5 summarizes the results of the Monte-Carlo simulations for all survey years and compares them to the evolution of global primary Cu production, as well as reported Te production figures. Median estimates and confidence intervals indicated for Te contents in global Cu anode production in this figure correspond to the ones shown in

Fig. 4 for 2018. Numeric results are presented in Table S1, which also includes estimates of Te recovery for the different survey years, i.e., the fraction of the total Te content in anodes actually converted into Te production for the years where this could be estimated with reasonable certainty. The Te content of global Cu anodes estimate of 1570 t (1280-2180 t; 95% confidence interval) for 2005 is somewhat greater than

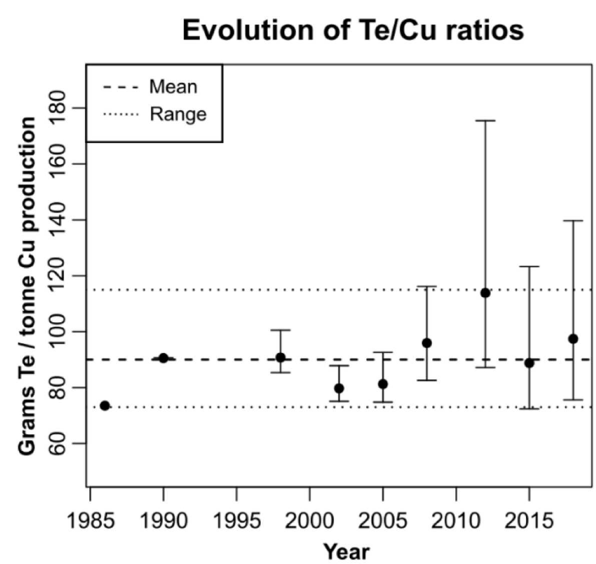



**Fig. 6.** Evolution of Te / Cu ratios over time, as expressed by global Te contents in anodes, divided by reported Cu cathode production. The calculation is based on the refinery data included in this analysis, not global Cu production. Note that median values for 1998 onwards differ from mean values calculated in Fig. 2. In particular, values in Fig. 2 are generally higher. This effect may be due to the omission of unreported values from the calculations in Fig. 2, which were, however, considered in the Monte Carlo-type simulations through imputation.

those previously reported the literature, (Ojebuoboh, 2008, George, 2012, Green, 2013, Buchert et al., 2009) which ranged from 1200 to 1500 t for the same period. The difference is attributable to the utilization of a greater global electrolytic Cu refining production quantity in this analysis than in previous studies.

It is evident from Fig. 5 that Te contents in global Cu anodes have closely tracked global primary Cu production between 1998 and 2018. Only for 1986 and 1990 did this trend fall off . However, this is probably

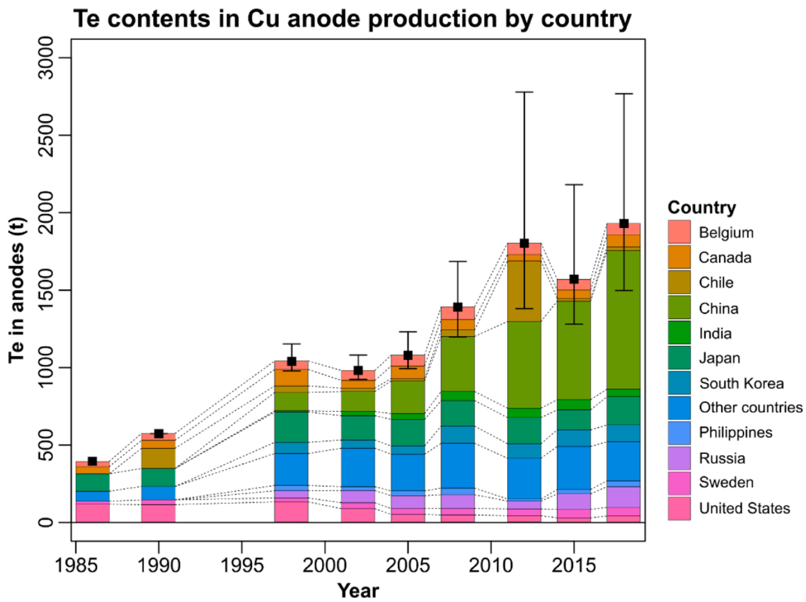



**Fig. 7.** Evolution of Te contents in annual Cu anode production by country. Bar plots indicate median values of the relative contributions (cf. Table S2 for numeric results and corresponding confidence intervals per country). Only the 10 most important potential producers are shown separately here. All remaining countries are included under "Other countries." Note that in contrast to previous figures the vertical axis is plotted on a linear scale such that a meaningful depiction of relative country contributions is possible.

a consequence of the relatively lower data coverage for those years, as indicated in the figure. It is also evident that reported Te production is considerably smaller than overall amounts of Te contained in Cu anodes, with median recoveries of ~19–26% in the years 2012, 2015 and 2018 (Table S1). Furthermore, it is noticeable that the estimated uncertainties for total Te contents increase over time. This reflects a steady increase in the proportion of missing data in the refinery surveys between 1986 to 2018.

Fig. 6 shows the evolution of the estimated global Te/Cu ratio in anodes for the refineries included in this study. There does not appear to be a clear trend in this value over time, with median values fluctuating around a mean of 90 g Te / t Cu (range: 73 – 114 g Te / t Cu). Regressing the median Te/Cu ratios against time yielded a model with a p-value of 0.09 (adjusted $R^2 = 0.25$), indicating that there is no statistically significant relationship between the two variables.

### 4.4. Country balances

Fig. 7 shows the evolution of median Te contents in Cu anode production by country for the different years. The corresponding numeric values and confidence intervals are provided in Table S2, which summarizes the results for all countries covered in this contribution.

Several trends are apparent. Perhaps the most striking feature is the rise of China as the most important potential producer of Te, going from a median Te content in Cu anodes of ~115 t in 1998, to ~870 t in 2018 (Table S2). Thus, China is responsible for virtually the entire increase seen in the total Te contents in global Cu anode production over the past 20 years. The sum of other countries has remained approximately constant. This reflects similar global trends in Cu production.

Another interesting feature is the decline of the United States which, together with Japan, Canada, and Chile, occupied a prominent position as a potential Te producer in the 1990s. However, its potential has decreased nearly by a factor ~3 over the past two decades, mostly due to the closure of several refineries. For many of the other countries listed separately in Fig. 7, Te contents in Cu anode production have remained fairly constant over the past 20 years. Only Russia, Sweden, and India show noticeable increases, while the results for Chile show substantial fluctuations. The latter reflects corresponding fluctuations in the reported anode Te contents for the Las Ventanas (2012) and Chuquicamata (1990) refineries (c.f. Schloen, 1991, Moats et al., 2013).

## 5. Discussion

The results from this analysis indicate that only about 26% (18-33% at the 95% confidence interval; *Table S1*) of the Te contained in anodes was recovered in 2018, although reporting gaps likely exist. Even after taking into account that some Te production is not reported and that the recovery rates of Te from anode slimes may be on the order of 80-90%, (Ojebuoboh, 2008)[3] these results indicate that current Te production could more than triple if all of the current Te content of the anodes is processed for Te recovery. This contemporary overall 26% recovery rate of Te from anodes is notably lower than estimates suggested by others, which have ranged from 33-60% (Bustamante and Gaustad, 2014). It is important to note that those previous estimates seem to be based on anecdotal information rather than detailed analyses.

Importantly, this potential to increase Te production does not incorporate possible future changes to the way Cu is produced nor does it account for possible changes in Te content of anodes. For example, a decline in pyrometallurgical smelting and electrolytic refining of Cu and an increase in solvent extraction-electrowinning (SX-EW) and post-consumer recycling of Cu will decrease the potential for Te production (Bustamante and Gaustad, 2014). While the portion of global Cu supply obtained from SX-EW and recycling has increased notably (with SX-EW increasing from 1% of global refining copper in the late 1960s to 16% in 2020), the absolute quantity (and capacity) of primary electrolytic copper refining has also increased, (International Copper Study Group, 2021) thus suggesting that this will not be the factor that curtails Te supply potential in the foreseeable future.

This analysis further indicates that there is significant variability and uncertainty regarding the median Te production potential—something which had not previously been quantified. Moreover, this analysis indicates that the greatest potential to increase Te production has been (and continues to be) in China. This is mainly due to the increase in China's electrolytic Cu production, which has increased at a greater rate than China's Cu mine production, resulting in China being a notable net importer of Cu concentrates (Renaud et al., 2022). Unless the Cu ores mined in China are markedly more enriched in Te than those of other countries, the majority of Te recovered in China likely comes from Cu

[3] Another study (Cuizon, 2012) suggests that Te recovery at byproducts refinery plant may only be 62%, while lab-scale Te recoveries from cemented Te have been reported to be higher than 95%. (Rhee et al., 1999)

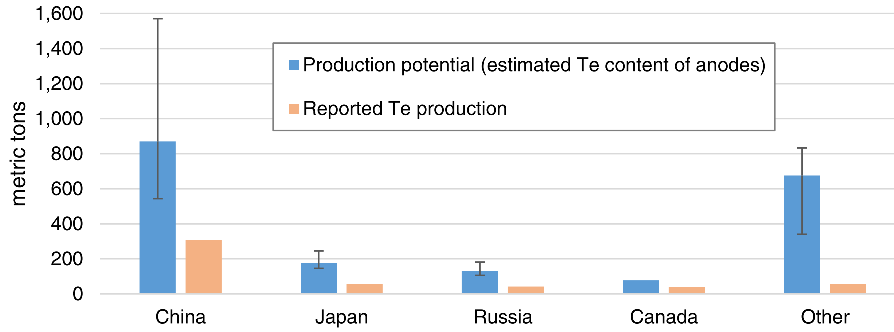



**Fig. 8.** Potential Te production (estimated as the median Te content of anodes with corresponding 95% confidence intervals) compared to Te production as reported by tAnderson (2021) by country for the year 2018.

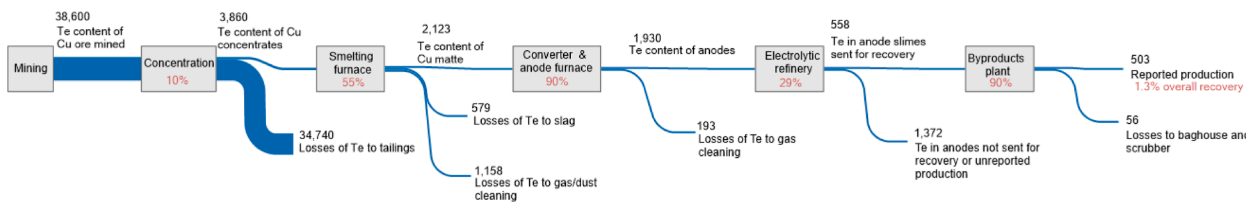



**Fig. 9.** Sankey diagram indicating the flows of Te (metric tons of contained Te) at different stages of the life cycle up to refining for the year 2018. The estimate Te recovery rates (shown in red for each process) are based on those reported by Ojebuoboh (2008) except for those at the electrolytic refinery, which are based on the results of this analysis. Te production is based on what is reported by Anderson (2021).

ores mined elsewhere. Other countries that have notable potential to increase Te production include Japan, Russia, and Canada (see Table S2 and Fig. 8).

A useful extension of this work would be a more detailed examination of the mass flows of Te from ores through concentrators, smelters, and refineries worldwide to better understand the origin and global flows of Te, and the interdependencies of different countries regarding their Te supply. This might be especially useful considering that an estimated 90% of the Te contained in the ores is lost to tailings during concentration (Ojebuoboh, 2008, Josephson, 2016). Although the upstream losses reported by Ojebuoboh (Ojebuoboh, 2008) were based on a single site and these results are a global estimate, when combined they suggests that just over 1% of Te contained in ores is at present ultimately recovered (see Fig. 9). Further research can help advance our understanding of the geological endowments, mineral hosts of Te as a function of deposit type, as well as upstream Te losses using different process technologies, which may point to the potential to recover Te from tailings and other waste streams.

In addition to production from electrolytic copper refining, Te is also recovered from two gold-tellurium epithermal vein deposits in southwestern China and an epithermal-type gold-tellurium mineralization at the Kankberg deposit in Sweden (Goldfarb et al., 2017, Behre Dolbear Asia Inc., 2009, Voigt and Bradley, 2020). Minor quantities of Te are also believed to be recovered from the dust and gases produced during the smelting of sulfide-rich ores and skimmings at Pb refineries (Goldfarb et al., 2017). The potential to increase Te production from these and other alternative sources (Fthenakis and Anctil, 2013) has not been well-quantified and would require further investigation, but is unlikely to be capable of addressing any short-term supply challenges.

Some of the future Te demand will be met via recycling. Up to 90% of the materials in CdTe modules is recovered for reuse by one company (Sinha et al., 2017). However, given that solar PV panels have an expected lifetime of 20-30 years, (Nassar et al., 2016) significant quantities will likely not be available for recycling for some time (Bustamante and Gaustad, 2014). The costs for the recovery of Te from CdTe solar cells may also be considerably greater than the cost to recover Te from primary raw materials (Redlinger et al., 2015). Other uses of Te (for example, in rubber formulations, thermoelectric devices, and metallurgical applications) may be dissipative in nature and, thus, not be directly amenable to Te recovery post-use (Ciacci et al., 2015). As a result, the near- to medium-term demand will thus need to be fulfilled mostly from mined sources.

Whether or not more Te will be recovered from these or other sources will depend on market dynamics. Specifically, it will depend on the Te price, the capital and operating costs associated with Te recovery, technological improvements of the metallurgical recovery of Te, any side effects Te recovery may have on the revenue generated from the recovery of other commodities (e.g., Cu and precious metals), as well as any environmental and health risks associated with Te. (Hayes, 2019, Qin et al., 2017, Missen et al., 2020) Seeing a potential benefit to the recovery of Te, some companies have decided to install new recovery plants. Rio Tinto, for example, recently announced a plan to build a Te recovery plant with planned annual capacity of 20 metric tons at its Cu refinery in Utah (Rio Tinto, 2022). Others may decide to follow if Te prices allow for a positive return on investment or if new government policies are created to incentivize recovery (Bleiwas, 2010). Using the results of this analysis and additional cost data, it may be possible to develop an updated Te supply curve (International Copper Study Group 2020, Moats et al., 2013), which translates the physical availability of Te into economic availability of Te and thereby helps to determine the prices and policies which may be necessary to allow for a significant increase in Te supply.

Nearly all emerging low-carbon technologies depend upon elements that have historically received little attention, are currently recovered as byproducts, (Nassar et al., 2015) and are subject to similar material supply concerns as those outlined here for Te. Moreover, given the severe data limitations associated with byproduct mineral commodity supplies, (Nassar et al., 2015) this approach of imputing missing values in a Monte Carlo type simulation to assess the corresponding uncertainties is directly applicable to other byproducts of Cu, and could potentially be extended to other byproduct critical elements of other target commodities, (Frenzel et al., 2015, Frenzel et al., 2017, Frenzel et al., 2016) if similar datasets existed. This approach is thus a useful evolution to quantifying the potentially recoverable resources of byproduct critical elements.

## Author contributions

NTN conceived the research. NTN and MF designed the research. MSM provided the tankhouse data. HK and NTN collected and organized the copper production and tankhouse data. HK performed the direct-use calculation. MF developed and ran the Monte Carlo simulation. NTN and MF developed the figures and wrote the manuscript with input from the other authors. All authors provided critical input that helped shape the research, analysis, and manuscript.

## Synopsis

Asset-level electrolytic copper refining data reveals that only approximately one-fourth of tellurium contained in copper anode slimes is currently recovered, indicating significant potential to increase supplies for solar PV and other applications.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106434.

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