Resources, Conservation & Recycling 190 (2023) 106783

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Dynamic material flow analysis of tantalum in the United States from 2002 to 2020

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ARTICLE INFO

Keywords:
Conflict minerals
Critical minerals
Embedded material flow
Import reliance
Industrial ecology
Substance flow analysis (SFA)

ABSTRACT

Tantalum has received considerable attention due to risks associated with its supply chain. In 2020 ~70% of global tantalum supply originated in Africa, with 40% produced in the Democratic Republic of Congo alone. The United States has relied entirely on imports since the 1950s. However, quantifying total domestic consumption is problematic because refined tantalum compounds do not have unique tariff codes resulting in significant trade volumes not properly documented. Furthermore, tantalum incorporated into finished goods is not tracked as tantalum. Thus, estimates only capture a fraction of total consumption. We performed a material flow analysis to quantify total domestic tantalum consumption from 2002 to 2020. Our results indicate that consumption may be up to 250% more than previously estimated. Our detailed results allow quantification of tantalum stocks in-use as well as coming out of use any year, providing valuable insight to industry and policymakers for addressing potential supply security issues.

1. Introduction

Tantalum, a rare and very hard transition metal, has received a lot of attention in recent years primarily due to its increasing use in modern electronics and the high risks associated with its supply chain. In 2020, approximately 70% of the world's supply of tantalum was sourced from countries in Africa according to the U.S. Geological Survey (Padilla, 2020; Friedline, 2022), with nearly 40% of it thought to have originated in the Democratic Republic of Congo (DRC) where mining is often associated with human rights violations and armed conflict (e.g., Dodgson, 2016). Tantalum-bearing columbite-tantalite (or "coltan") mineral ores mined in the DRC are believed to be a source of funding for rebel militia groups fueling conflict in the eastern DRC, and likely produced by child and/or forced labor (U.S. Department of Labor, 2020; U.S. Government Accountability Office, 2020). As a result, tantalum has come to be known as one of the so-called "conflict" or "3TG" minerals (3TG referring to the "three Ts" of tantalum, tin, and tungsten, plus gold), and various governments have enacted or introduced legislation aiming to increase responsible sourcing of 3TG mineral concentrates and ores (e.g., Dodd-Frank Wall Street Reform and Consumer Protection Act, 2010; European Union, 2017).

The United States is a leading consumer of tantalum materials (Padilla, 2020; Friedline, 2022). Between 2015 and 2020, the United States consumed on average about 800 metric tons of tantalum (t-Ta) per year contained in concentrates, refined metal (including powder, unwrought, and wrought forms), and scrap, which represents roughly 35% of global annual tantalum supply. However, tantalum ores have not been produced in the United States since 1959 and domestic tantalum resources are of low-grade and currently not commercially recoverable (Padilla, 2020). For this reason, the United States relies entirely on imports for its supply of primary tantalum materials (U.S. Geological Survey, 2022). Furthermore, production of tantalum ores is highly concentrated in a few countries, including Brazil, China, DRC, and Rwanda (Bleiwas et al., 2015; Padilla, 2020; Friedline, 2022). Over time, there has been a shift in the supply chain of primary tantalum materials in the United States. Historically, raw materials in the form of tantalum-bearing concentrates were imported by the United States to supply domestic processors (Fig. 1). Australia was a major supplier of tantalum concentrates through the 1990s and 2000s, but in the last decade countries in the Great Lakes region of Africa have become the dominant suppliers. Currently, the majority of imports into the United States are primarily in the form of intermediate and refined tantalum materials (metal, metal powder, and scrap; Fig. 1), and while several domestic operations can produce secondary tantalum via recycling of high-grade tantalum scrap, only one operation has the capability to convert raw material (tantalum concentrate) into refined products.

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https://doi.org/10.1016/j.resconrec.2022.106783
Received 7 September 2022; Received in revised form 11 November 2022; Accepted 18 November 2022
Available online 25 November 2022

Domestic consumption is best quantified when detailed consumption data are available for all domestic consumers at every step of the material flow cycle. However, such level of detail is not readily available for most mineral commodities. In the absence of detailed reported consumption data, as is the case for the tantalum industry in the United States, domestic consumption must be estimated from alternative sources of information. Because the United States is entirely reliant on imports for meeting its domestic tantalum demand, international trade statistics, aggregated at the country-wide level, offer a good first-approximation and can thus be used to estimate an "apparent" consumption for the United States (calculated simply as the difference between domestic production, imports, and exports, plus changes in domestic stockpiles). However, a limited number of tantalum materials are tracked closely in the global economy. These include raw and primary feed materials, such as tantalite mineral concentrates and refined tantalum metal (in unwrought, wrought, and metal powder forms), as well as scrap for recycling. In addition, the international trade of tantalum-based electrolytic capacitors is also tracked closely but is typically reported in number of capacitors rather than tantalum content, and the wide variety of capacitor types and sizes makes it particularly difficult to accurately quantify the total amount of tantalum embedded in their trade. Notably absent from documentation is the trade of tantalum pentoxide (Ta_2O_5) and potassium heptafluorotantalate (K_2TaF_7 or "K-salt"), two of the most important forms of tantalum forming the intermediary link between tantalum-containing concentrates and refined tantalum metal. These tantalum compounds do not have unique international material trade codes. Thus, a potentially significant portion of tantalum material trade is not properly documented. Furthermore, once tantalum materials are incorporated or "embedded" into semi-finished and finished goods, they are no longer tracked as tantalum materials but rather as the manufactured product. These factors combined make it difficult to properly quantify the total volume of tantalum material entering or exiting the U.S. economy in all forms any given year. At present, only those raw and primary tantalum feed materials that can be tracked accurately (mentioned above) are included in estimates of "apparent" consumption, which we hereafter refer to as *primary* consumption.

There are few published studies on the supply chain and flow of tantalum materials, and the temporal, geographic, and material scope of these has generally been limited to either a small geographic focus (e.g., Deetman et al., 2017 [European Union]; Yen et al., 2016 [Taiwan]), a single year timeframe (e.g., Deetman et al., 2017 [2007]; Cunningham, 2004 [1998]; Mancheri et al., 2018 [2014]; Gille and Meier, 2012 [2011]; Achebe, 2016 [2014]), or a limited material form, specific application, or stage of the tantalum life cycle (e.g., Achebe, 2016 [raw materials]; Cunningham, 2004 [recycling]; Hoppe and Korinek, 1995 [recycling]; Gille and Meier, 2012 [recycling]). In addition, some studies have quantified tantalum flows at the global scale (e.g., Nassar, 2017; Mancheri et al., 2018; Hoppe and Korinek, 1995), but only Nassar (2017) has done so for a significant time period (1970-2015) and for the entire life cycle of tantalum (i.e., from primary production through post-consumer end-of-life [EoL]). Notably, only Deetman et al. (2017) included quantification of the flow of tantalum embedded in the trade of finished goods at a high level of detail in their assessment, which requires not only detailed trade data but estimates of the tantalum material content for a large number of end-use products, as well. With the increasing interdependence of world economies and growing scale of international trade of commodities, it has become imperative to include this downstream portion of the material supply chain in assessments of material consumption as it may account for a significant portion of total consumption. This is particularly important for commodities like tantalum for which electronic devices are a primary end-use: in 2019 approximately 51% of global tantalum supply was consumed in the electronics sector (Roskill Information Services Ltd., 2020).

These previous studies have laid a valuable foundation for understanding the tantalum material cycle, but to date there have been no detailed and comprehensive studies of tantalum material flows with a focus on the United States. The aim of this study, therefore, is to perform

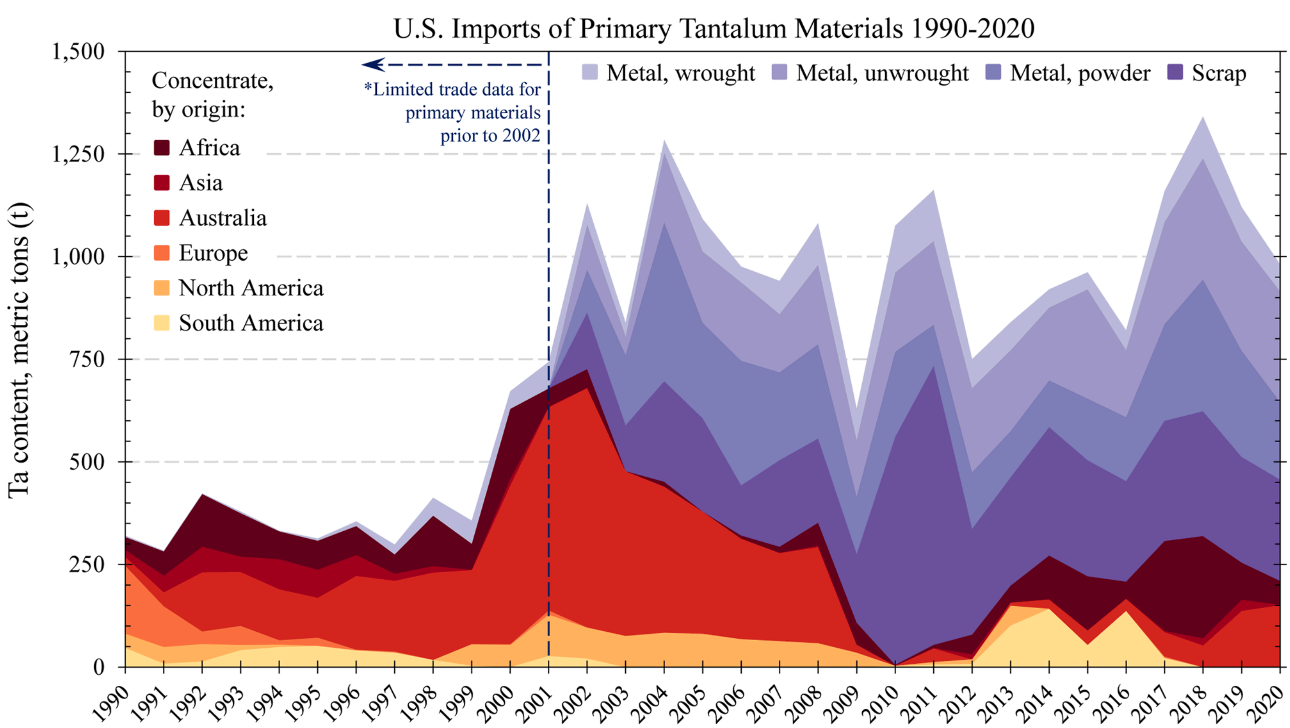

Fig. 1. Imports of primary tantalum materials into the United States from 1990 to 2020, in metric tons of contained tantalum. Imports of tantalum concentrate are further subdivided based on their place of origin (as reported in the trade data) and color-coded using warm colors. *Note that detailed import statistics for tantalum scrap, tantalum metal powder, and unwrought tantalum metal were not available for the years prior to 2002. Data sources: U.S. Geological Survey; U.S. Census Bureau, 2021; IHS Markit Ltd. Global Trade Atlas, 2020.

a comprehensive dynamic material flow analysis (MFA) for the United States using import and export data and tantalum market statistics in order to quantify (1) the annual volume of tantalum consumed domestically between 2002 and 2020; (2) the annual volume of tantalum consumed by end-use for the same period of time; and (3) the total cumulative volume of tantalum that remains in use or in hibernation (no longer in use, but not yet discarded) in the United States. While our model required several simplifying assumptions about the domestic tantalum industry due to the lack of detailed published data, it includes the flow of tantalum embedded in all products for which we were able to identify a relevant trade code as well as an assessment of the stocks of tantalum above ground, every year, and at every step of the tantalum life cycle in our assessed timeframe. Our results provide valuable insight to both industry and policymakers for addressing potential supply chain issues and supply security, as well as identifying the different above-ground tantalum resources that may be potentially available for re-use or recycling as recovery technologies, especially for electronic waste, improve.

2. Background

Tantalum is largely used in a wide variety of applications that require increased chemical, corrosion, and/or heat resistance (Roskill Information Services Ltd., 2020; Tantalum-Niobium International Study Center, 2021a). The electronics industry consumes roughly half of the annual tantalum supply, primarily to manufacture tantalum electrolytic capacitors, semiconductors, surface acoustic wave filters, and resistors for consumer electronic products such as cellular phones and computers (Roskill Information Services Ltd., 2020). Tantalum capacitors are also used in a variety of specialty applications, such as vehicle electronics and aerospace systems. The remainder is consumed by the chemical and metallurgical industries to manufacture tantalum-containing carbide tools (e.g., teeth for excavator buckets and drill bits for the mining industry), corrosion-resistant chemical processing components (e.g., heat exchangers and liners for industrial furnaces), and as an alloying element in superalloys for the aerospace and oil and gas industries (e.g., for aircraft and land-based industrial gas turbine blades). A small share of tantalum is also used in the medical industry (e.g., for surgical tools, medical screws and staples, and prosthetic implants) because of tantalum's inert and biocompatible properties (i.e., tantalum does not react with body fluids) (British Geological Survey, 2011; Roskill Information Services Ltd., 2020; Tantalum-Niobium International Study Center, 2021a).

Most of the global tantalum supply is derived from the mineral tantalite [$(Fe,Mn)(Ta,Nb)_2O_6$], which is primarily produced by artisanal and small-scale mining of tantalite-bearing placer or weathered deposits in the Great Lakes region of Africa. In 2020, production from artisanal and small-scale mining accounted for nearly 70% of total primary tantalum supply (Friedline, 2022; Roskill Information Services Ltd., 2020; Tantalum-Niobium International Study Center, 2021c). Conventional or large-scale mechanized mining of tantalite-bearing ores (e.g., operations in Brazil, China) accounted for approximately 28% of total supply in 2020. In addition to tantalite, other important tantalum minerals that have been traditionally mined by conventional methods include wodginite [$(Ta,Nb,Sn,Mn,Fe)O_2$] in Australia and microlite [$(Na,Ca)_2Ta_2O_6(O,OH,F)$] in Brazil (Linnen et al., 2014). A small portion (approximately 3% in 2020) of tantalum is also produced as a co-product from mining of other tantalum-bearing minerals (e.g., mining of loparite in Russia) or as a byproduct from other mining operations (e.g., from the tailings of hard-rock lithium mining in Australia).

To produce a refined tantalum metal, primary concentrates are mainly processed by chemical digestion in which the material is dissolved in hydrofluoric acid at high temperature to produce a solution containing tantalum heptafluoride ($H_2[TaF_7]$), and then further purified by different methods into either potassium heptafluorotantalate (K_2TaF_7), commonly referred to as "K-salt," or tantalum pentoxide (Ta_2O_5). These two chemical compounds, the primary tantalum chemicals of industrial significance, can then be further refined into either a high-purity tantalum metal powder (by sodium reduction of K_2TaF_7) or tantalum metal (by metallothermic reduction of Ta_2O_5) (Tantalum-Niobium International Study Center, 2021b; Linnen et al., 2014). Two less common processing methods used for non-tantalite concentrates, in which the primary tantalum-bearing mineral(s) is also host to other heavy elements such as titanium or niobium, involve either chlorination of the concentrates, which results in the production of a tantalum pentachloride ($TaCl_5$) that can be further refined into Ta_2O_5, or aluminothermic reduction, which results in a tantalum or mixed ferroalloy (e.g., FeNbTa) that can be crushed and treated with acid to oxidize the tantalum and produce a synthetic concentrate to be refined by the same methods as a primary tantalite concentrate (Tantalum-Niobium International Study Center, 2021b; Linnen et al., 2014). A more thorough description of primary processing methods is presented in Appendix A of the *supporting information* (SI).

Importantly, with the exception of aluminothermic reduction, the path between tantalum contained in the concentrate and a refined high-purity tantalum metal product is inevitably through a chemical compound phase: K-salt (K_2TaF_7), tantalum pentoxide (Ta_2O_5), or to a lesser extent tantalum chloride ($TaCl_5$) (see Fig. S1 in Appendix A of the SI; Tantalum-Niobium International Study Center, 2021b). It is therefore important to emphasize that, at present, there are no dedicated domestic or international standardized trade codes under which the trade of these central intermediate tantalum forms can be tracked, which highlights one of the major obstacles in accurately estimating the total global flows of tantalum: these materials are traded as "other" within broader material categories. Notably, the Japan Ministry of Finance has a dedicated domestic imports tariff code for K-salt, making Japan the only country in the world to explicitly document trade of any tantalum chemical compound (Japan Ministry of Finance, 2021).

3. Methodology

3.1. Material flow analysis (MFA) framework

Material Flow Analysis (MFA) is an industrial ecology tool that provides a framework for examining the structure of a material industry, such as tantalum, and quantifying the movement of material between the different stages of its life cycle within the boundaries of a defined system (Graedel, 2019). The results of a MFA can provide valuable insight to stakeholders, such as industry participants and policymakers, for addressing potential issues with the supply chain, securing future material supply, and identifying the current above-ground resources that could be potentially available for recycling.

In this study we use a top-down MFA approach, in which annual time-series statistics on consumption and trade of materials and products are aggregated at the country-level and combined with lifetime distributions of end-use products, to make a first-order estimate of the stocks and flows of tantalum across the entire U.S. economy through time (e.g., Golev et al., 2016; Deetman et al., 2017), with our study timeframe being 2002 to 2020. We define our system boundary as all tantalum consumed within the United States at all stages of the tantalum material lifecycle, beginning with the processing of tantalum raw materials (i.e., tantalum concentrates) and ending with the disposal of tantalum-containing finished goods at their EoL.

3.2. Data sources

Trade statistics for the United States (imports for consumption and domestic exports) were compiled primarily from the U.S. Census Bureau (USCB) accessed through the USA Trade Online database (U.S. Census Bureau, 2021). Data were extracted by individual HTS tariff line codes (the most detailed level available) for all relevant tantalum-containing categories identified for this study, which are listed in Table S1 in

Appendix B of the SI. In addition, the USCB does not track certain material categories with sufficient detail to allow quantification of the tantalum contained in their trade (e.g., tantalum chemicals). In such instances, we used additional data obtained from other countries' official statistics for their trade with the United States, accessed through the Global Trade Atlas (IHS Markit Ltd., 2020) and Global Trade Tracker (Zen Innovations AG, 2021) online databases, if available, or used alternative methods and sources of information to obtain an estimate of average traded quantities as discussed in detail in Appendix A.

For each material and product category considered in this study, we estimated the tantalum metal content as either the percentage by weight (e.g., tantalum concentrates contain approximately 30.3% tantalum metal by weight) or content by unit (e.g., hard disk drives contain approximately 0.29 grams of tantalum metal per unit). We then applied a market share factor (i.e., the percentage of products in a particular industry category that are likely to contain tantalum) to estimate the total amount of tantalum traded under each tariff code each year. Tantalum content and market share parameters were either obtained from previously published studies or derived from available market information where no other published estimates were found. These parameters are presented in Table S2 of Appendix B along with the source (s) and assumptions associated with each parameter. Using these parameters, we arrived at an estimate of the total amount of tantalum contained within each trade category for the years 2002 through 2020 (Fig. 2; Tables S3–S6). These data, along with annual changes of tantalum-containing materials in the U.S. Government stockpile (Table S8), form the base dataset for our MFA model.

3.3. Elements of the material flow framework

We determined the individual components of the MFA framework based on the market structure of the United States, including processing capabilities. The framework consists of the following elements: (1) transformative processes, in which a tantalum product is consumed in one form to produce a tantalum product in a different form (e.g., processing of primary tantalum concentrates to produce K-salt); (2) material reservoirs, in which the form of tantalum materials remains constant; and (3) distributive processes, which represent the amount of tantalum flowing between transformative processes and/or material reservoirs, as well as the flow of tantalum materials across our defined system boundary (i.e., international trade of tantalum-containing materials). A simplified MFA framework diagram for tantalum is presented in Fig. 3; the complete MFA framework used in our model is presented in Figs. S2–S5 in Appendix A of the SI.

The MFA framework was first mapped in disaggregated form with material reservoirs and transformative processes linked by input and output flows. Processes are organized from left to right, starting with upstream mining and processing of tantalum concentrates. Continuing downstream, tantalum concentrates are consumed by intermediate processes such as the production of K-salt and Ta_2O_5, chemical manufacturing, tantalum metal manufacturing, tantalum carbide manufacturing, and tantalum capacitor manufacturing. The outputs of intermediate processes are then assigned to finished product categories or end-use applications, which together represent the total volume of tantalum put into use. The right end of the framework represents the EoL for all tantalum end-uses, at which point material flows either into the

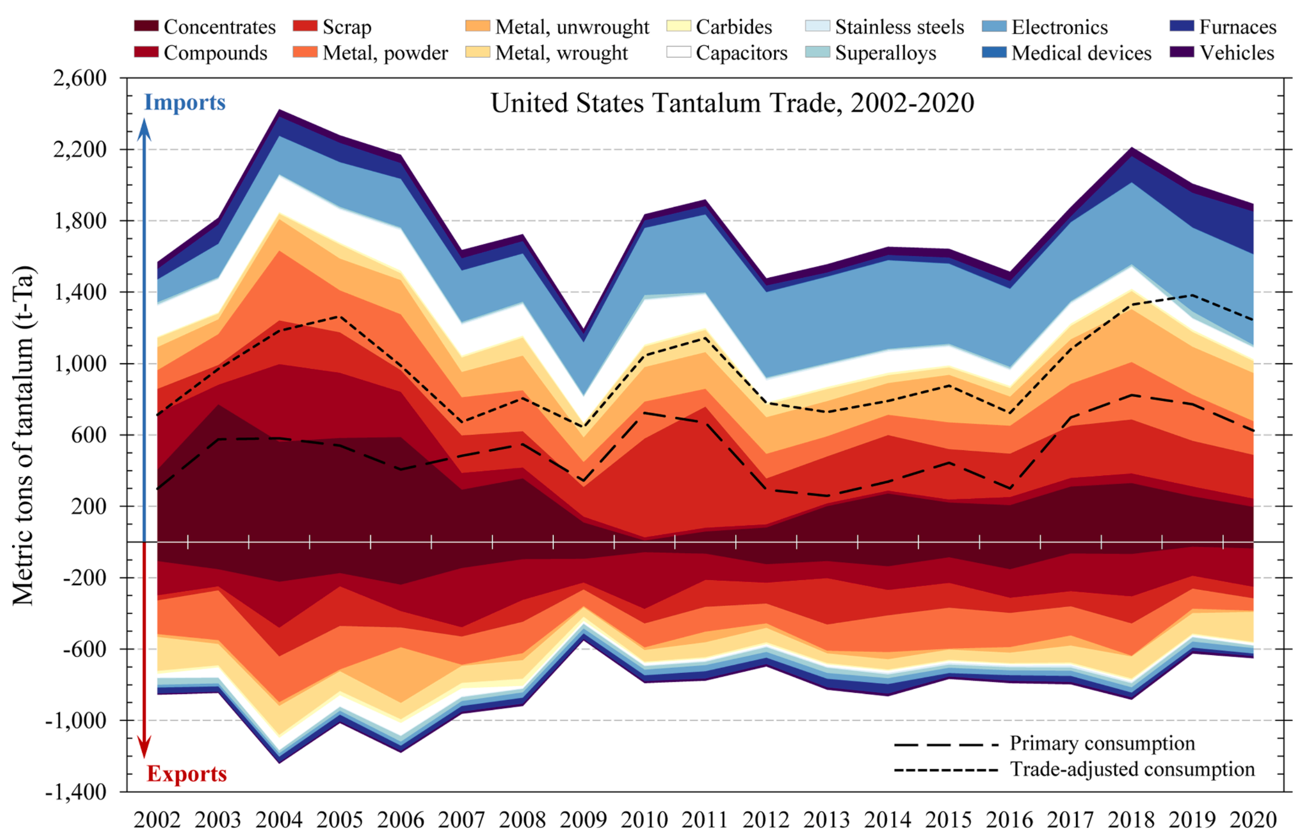

Fig. 2. Trade of tantalum-containing materials in the United States between 2002 and 2020 by material category, after adjusting for changes in material stockpiles. Exports are plotted as negative values for visual purposes. Primary consumption (typically calculated as the net balance of trade plus changes in U.S. Government stockpiles for only the primary tantalum materials: concentrates, unwrought and wrought metal, metal powder, and scrap) is also plotted for reference as a long-dash line, along with "Trade-adjusted" consumption which represents consumption calculated in the same way as primary consumption but adjusted to include tantalum embedded in the trade of all identified tantalum-containing semi-finished and finished goods categories. Trade-adjusted consumption thus provides a first approximation of total aggregated consumption, but it does not incorporate the consumption of upstream refined tantalum materials into their final end-uses. Data sources: U.S. Geological Survey; U.S. Census Bureau, 2021; IHS Markit Ltd. Global Trade Atlas, 2020.

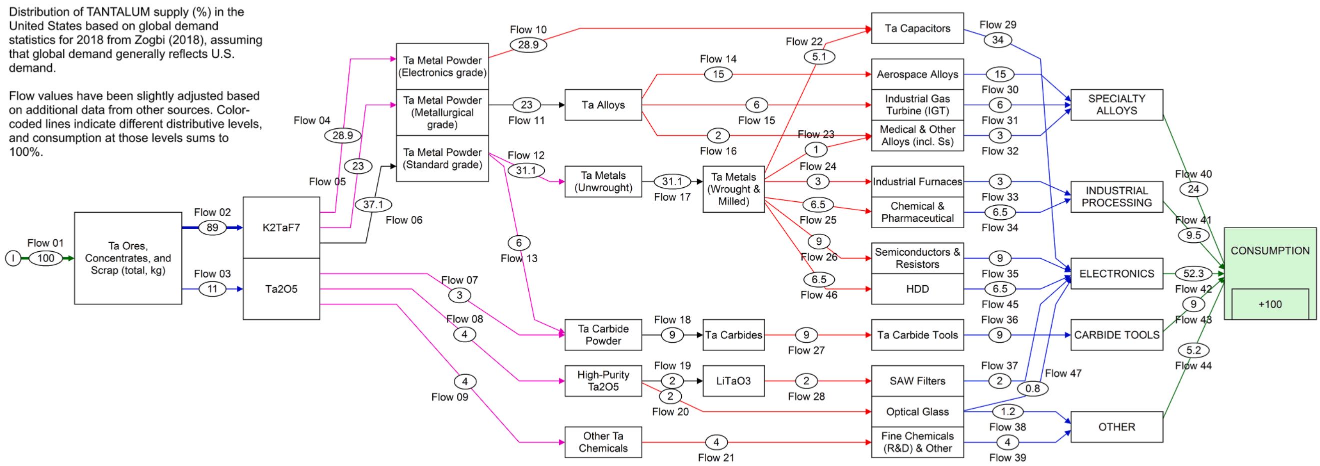

Fig. 3. Generalized material flow analysis (MFA) framework for tantalum in the United States for 2018. The colored arrows represent the different flows within the same stage of the tantalum material lifecycle (e.g., the leftmost blue arrows represent the primary tantalum refining stage; the rightmost green arrows represent the final end-use consumption stage) and sum to 100% of consumption for that material stage. The numbers within the ovals associated with each flow represent the relative consumption of a material form in each application relative to the total of all applications in that material stage (e.g., "Flow 10" in red represents consumption of electronics-grade tantalum metal powder for the production of tantalum electrolytic capacitors, which accounts for 28.9% of total tantalum material consumption in the manufacturing stage of the tantalum material life cycle) and are used as the distribution coefficients for the equivalent processes in our full model. Data sources: U.S. Geological Survey; Zogbi, 2018.

"Losses and Disposals" reservoir at the lower right corner of the diagram or is re-introduced into the system by a recycling flow. The entire MFA framework represents a timeframe of one year. Tantalum stockpiles, such as those contained in the U.S. National Defense Stockpile, are represented as a sub-component *within* material reservoirs and may remain static from year to year (i.e., no change in the amount of tantalum contained in the stockpile).

Building the MFA framework also required the use of distribution parameters in order to determine the relative share of each flow for transformative processes or material reservoirs with a single input but two or more output flows. We used market statistics from published literature to determine domestic parameters for the distribution of primary materials into semi-finished goods (e.g., relative consumption of tantalum metal by the steel and specialty alloy versus electronics industries), as well as the allocation of semi-finished goods into their final applications (e.g., consumption of capacitors by personal computers, vehicle electronics, mobile phone, and other industries). Losses at the different stages of the material cycle were also incorporated into our model using distribution parameters (as % loss within certain transformative processes). A summary of all distribution parameters is presented in Tables S10 and S11 in Appendix B of the SI. We assumed that the breakdown of global tantalum consumption by application available in published literature (e.g., Zogbi, 2018; Roskill Information Services Ltd., 2020) is generally representative of U.S. consumption, though we adjusted distribution and allocation parameters for industries in which the United States has increased capabilities (e.g., specialty alloy manufacturing).

In addition, we used lifetime distribution parameters to estimate the total residence of tantalum in use for each of our final sixteen (16) end-use categories. From these residence times, we estimated the annual accumulation of tantalum in use (i.e., current "in-use" stocks), as well as the annual flow of tantalum out of use, from which we then estimated the cumulative total amount of tantalum that has been disposed from use in the United States within our modeled timeline. This also allowed for a first-order estimate of the total amount of post-consumer tantalum material that may be available for recycling each year. For the consumer electronic devices categories, we included *hibernation* as an additional material life cycle stage – that is, the time following consumer use when a device or product has been removed from active operation (whether or not it has reached its EoL) but has not yet been discarded as waste or disposed of for recycling and remains in the possession of its consumer (e.g., a consumer portable computer that is no longer in use but is kept by the consumer as a back-up device or not disposed of for lack of available pathways for reuse/recycling) (e.g., Thiébaud et al., 2017). There is a lack of data on hibernation and recycling/reuse rates for consumer electronics in the United States. Because of this, we treated all electronics in our model as having a hibernation period after exiting use, followed by final disposal. Our model also takes into account post-consumer EoL recycling rates for each end-use category. Previous studies have estimated an overall tantalum EoL recovery rate of around 18% (e.g., Nassar, 2017; Gille and Meier, 2012), though for some leading applications, such as consumer electronics, it may be <1% (e.g., Ueberschaar et al., 2017). To the extent possible, we used EoL recycling rates derived from published literature specific to each end-use category (Deetman et al., 2017; Nassar, 2017; Thiébaud et al., 2017). For consumer electronics, we assumed that only 1% of the material collected for recycling re-enters the tantalum supply chain at the top as recovered scrap, while the remainder is either discarded as waste to landfills or downgraded during the recycling process (i.e., collected and recycled for the recovery of non-tantalum materials such as gold and silver, with tantalum effectively being lost to waste during the recycling process). All lifetime distribution parameters, hibernation rates, and EoL recycling rates are presented in Table S12 in Appendix B.

3.4. Uncertainty in our model

Building the complete MFA framework for tantalum in the United States required several simplifying assumptions due to the lack of available information, especially in the estimation of distribution parameters (including losses) in transformative processes, material contents of imported materials, and residence time of materials in use. Where no published values or parameters were available, we based our assumptions on as much other information as was available to us and made every effort to document such assumptions thoroughly in our work.

The contents of traded materials assume that stoichiometrically balanced compounds are correctly reported. Most codes report trade in terms of the gross weight of materials (e.g., tantalum concentrates), but some semi-finished and downstream materials are reported as the number of individual units (e.g., number of capacitors, or number of smartphone units). These, along with finished products, required further assumptions to calculate their tantalum material content (see Table S2 in Appendix B).

Highly detailed trade data (organized by individual products) are not readily available. Moreover, processing such data, if it were available, would be time prohibitive. Instead, we take data at an aggregate level and made assumptions about the mean content and market share (fraction of products) that may contain tantalum in them in order to estimate the flow of tantalum embedded in semi-finished and finished goods. For some industries (e.g., consumer electronics), data exist that help in estimating the average amount of contained tantalum on a per unit or per kilogram of product basis, but for others (e.g., industrial furnaces, carbide tools) data are either not easily available or do not exist, and thus we must estimate the amount of contained tantalum based on limited product information.

Domestic raw material processing capabilities are limited to a single processor. However, several secondary (i.e., recycling) processors have been in operation throughout the timeframe considered in our model. The capacities of these operations are not publicly known, typically for reasons of data protection, but based on trade data for both primary and secondary feed materials we assumed an average combined total refined tantalum output of around 350 t-Ta per year. To account for primary processing losses in our model (estimated at ~5%; e.g., Gille and Meier, 2012), we used an average annual tantalum *refining* rate of 368.4 t-Ta and allowed any excess imports of concentrate and scrap to accumulate as processor stocks. In addition, we found a shortage in the availability of these feed materials for the years 2010–2014. To address this shortage and ensure balanced (positive) flow quantities in our model, we assumed that domestic processors operated at reduced levels during some of those years. For 2009–2010, immediately following the global financial crisis of 2007–2008, we assumed processors operated at 10% below typical levels. For 2011–2013, following the rapid increase in the price of tantalum concentrates (a 275% cumulative increase from May 2010 to February 2011, which also marked the highest price in our modeled timeline; CRU Group, 2020), we assumed processors operated at 15% below typical levels. Finally, we assumed all processors returned to their typical operating levels in 2014.

For downstream processes, we assumed non-recoverable losses are around 2% for the reduction of chemical compounds to metal products and 1% for all other further refining and fabrication processes (after Nassar, 2017). Non-recoverable processing losses remain within our system but are collected in a "*Losses and Disposals*" material reservoir and stockpile along with disposals and losses at the material EoL. In addition, certain transformative processes generate "new" or "home" scrap that can be easily recovered and recycled on-site (e.g., cuttings, shavings, and clippings during metal fabrication). This is visually represented in our model but treated as being continually recycled in-house within the same process from which it was generated. As such, it is assigned a flow value of zero in our model for the purpose of the numerical calculations.

We assume that 100% of tantalum metal powder is produced by the reduction of K-salt. Furthermore, we assume 100% of tantalum in semiconductors and resistors is in the form of thin film diffusion layers applied by physical vapor deposition (PVD) using pure tantalum sputtering targets. Thus, we allocate semiconductors to the "Tantalum Metals (Wrought & Milled)" category in our MFA framework. We allocate tantalum raw and intermediate materials to end-uses using the same assumptions and fractions noted by Deetman et al. (2017). Tantalum carbides can be produced by carburization from either tantalum metal powder or Ta_2O_5. We assume that in the United States, approximately two-thirds of carbides are produced from standard tantalum metal powder. In addition to K-salt and Ta_2O_5, some other tantalum chemical compounds can be produced from primary tantalum feed materials and by further processing of Ta_2O_5 (e.g., $LiTaO_3$ crystals produced from high-purity Ta_2O_5). In our process flow, we assumed that the production of these other chemicals in the United States is entirely by downstream processing of Ta_2O_5.

Lastly, incorporating lifetime distributions into our model allows us to estimate the amount of tantalum that is coming out of use at the EoL. However, we acknowledge that the lifespan of some products may differ significantly from one country to another or from year to year (e.g., Golev et al., 2016). In this study, we used average lifetime distribution estimates from various published studies focused on highly industrialized nations (e.g., Japan, Netherlands) and assume that these are generally representative of both the U.S. consumer market and the time period covered in our model (see Table S12 in Appendix B). All data are represented on a one-year basis (i.e., aggregated to the total at end-of-year), and all recoverable scrap generated within year n is assumed to re-enter the system for recycling at the beginning of year n+1.

3.5. Modeling the material flow

We ran our dynamic MFA model for the years 2002 through 2020 using version 2.6.801 of STAN2, a software specifically developed for material flow analysis by the Vienna University of Technology (Cencic and Rechberger, 2008). The software includes the numerical simulation component, which calculated the material balance of each process and flow for every given year in the model including material stockpiles (if any) using the data and parameters described above, as well as a graphical component (Fig. 3) that facilitates building and illustrating the MFA framework for our model.

Our complete model consists of 8 transformative processes, 39 material reservoirs (including 10 reservoirs with material stockpiles), and 132 flows of which 50 are trade flows (Fig. S3 in Appendix A). In addition, two of the material reservoirs include "subsystem" processes. The first subsystem represents the allocation of finished subcomponents into their respective end-use categories (see Section 3.3) and comprises 24 material reservoirs and 58 flows (Fig. S4). The second subsystem represents the EoL stage for all end-use categories and incorporates the "stocks and flows" model described below using a total of 35 material reservoirs (including 16 with material stockpiles representing the volume of tantalum in active use) and 63 flows (Fig. S5).

Lastly, our model also includes a visual representation of the mineral resources as well as mining and beneficiation of tantalum ores, which did not take place in the United States during our modeled timeframe (i.e., they fall outside our system boundary). As such, they were assigned flow values of zero in our model for the purpose of the numerical calculations. A copy of our STAN2 model file is provided in the SI.

3.6. Stocks and flows model

To incorporate the flow of tantalum material out of use at the EoL for each end-use category, we used an Excel-based "stocks and flows" (S&F) numerical model based on lifetime distribution parameters supplied for each material in consideration (see Section 3.3). For each year in our modeled timeline, the input data for the S&F model were the results of annual tantalum material consumption (i.e., the amount of tantalum put into use) from a first iteration of the STAN2 model, which calculated flows within the system up to the final consumption stage [the second subsystem "Tantalum Stocks (In Use)" in Fig. S3]. This allowed us to estimate the tantalum residence time (i.e., time in use), losses in use, and flows out of use for each end-use category. The S&F results were then incorporated back into the STAN2 model (within the second subsystem as described above), which was then run as a second iteration to estimate the amount of material disposed at EoL from each end-use category for each year in the model.

For the consumer electronics categories, the additional life cycle stage of hibernation was also incorporated into our overall MFA model using the results of the second STAN2 iteration and a second S&F model based on published hibernation parameters (see Section 3.3). The results of the second (hibernation) S&F model, representing the aggregated total disposal of tantalum from hibernating stocks, were then incorporated back into the STAN2 model that was run for a third and final iteration to produce the final results for each modeled year. This process is repeated for every subsequent year in our modeled timeline, starting with 2002 and ending with 2020.

4. Results and discussion

Our results suggest that the United States consumed or *put into use* a cumulative total of around 18,000 t-Ta between 2002 and 2020. The quantity consumed was 624 t-Ta in 2002, 932 t-Ta in 2010, and 1,250 t-Ta in 2020 (Fig. 4; Table S13 in the SI). The average annual consumption was 946 ± 194 t-Ta and increased at an annual rate of 5.8% across the entire modeled timeframe. These quantities are on average 103% higher, and for some years as much as 257% higher, than estimates of primary tantalum consumption (e.g., Padilla, 2020; Friedline, 2022) which, as we previously noted, only account for a limited number of properly documented traded materials that are readily identified as primarily tantalum-containing materials.

Non-recoverable losses during all processing stages plus losses during use amounted to an annual average of 47 t-Ta, or around 5% of the annual material put into use, with cumulative losses totaling 898 t-Ta across the entire timeframe. In addition, we estimate that approximately 8,130 t-Ta (or 45% of all tantalum put into use between 2002 and 2020) have been lost as disposals to landfills at the product EoL, including tantalum not recovered during the recycling process, with an average of 428 t-Ta disposed of annually. Post-consumer disposals at the products' EoL accounted for around 84–90% of all tantalum losses, which is in line with the findings of Charpentier Poncelet et al. (2022), a recently-published study on the losses and lifetimes of metals in the economy which found that around 84% of tantalum losses (excluding losses during mine production) are incurred during the EoL waste management and recycling stage of the material life cycle. We also estimate that approximately 1,010 t-Ta have been recovered as recycled scrap since 2002 (an average of 53 t-Ta per year), mainly from the recycling of specialty alloys, tantalum carbide tools, and chemical processing components. As of 2020, a cumulative 8,160 t-Ta remained in-use in the United States and an additional 671 t-Ta in hibernation, which together account for approximately 49% of the total amount put into use since 2002. The cumulative above-ground stocks of tantalum in the United States totaled 18,400 t-Ta at yearend 2020. Above ground stocks are calculated as the sum of all stocks within the model's system boundary, which includes losses and disposals to landfill, processor and government stockpiles, material in use, and material in hibernation.

4.1. Observed changes through time

We observe a shift in the relative proportion of tantalum materials

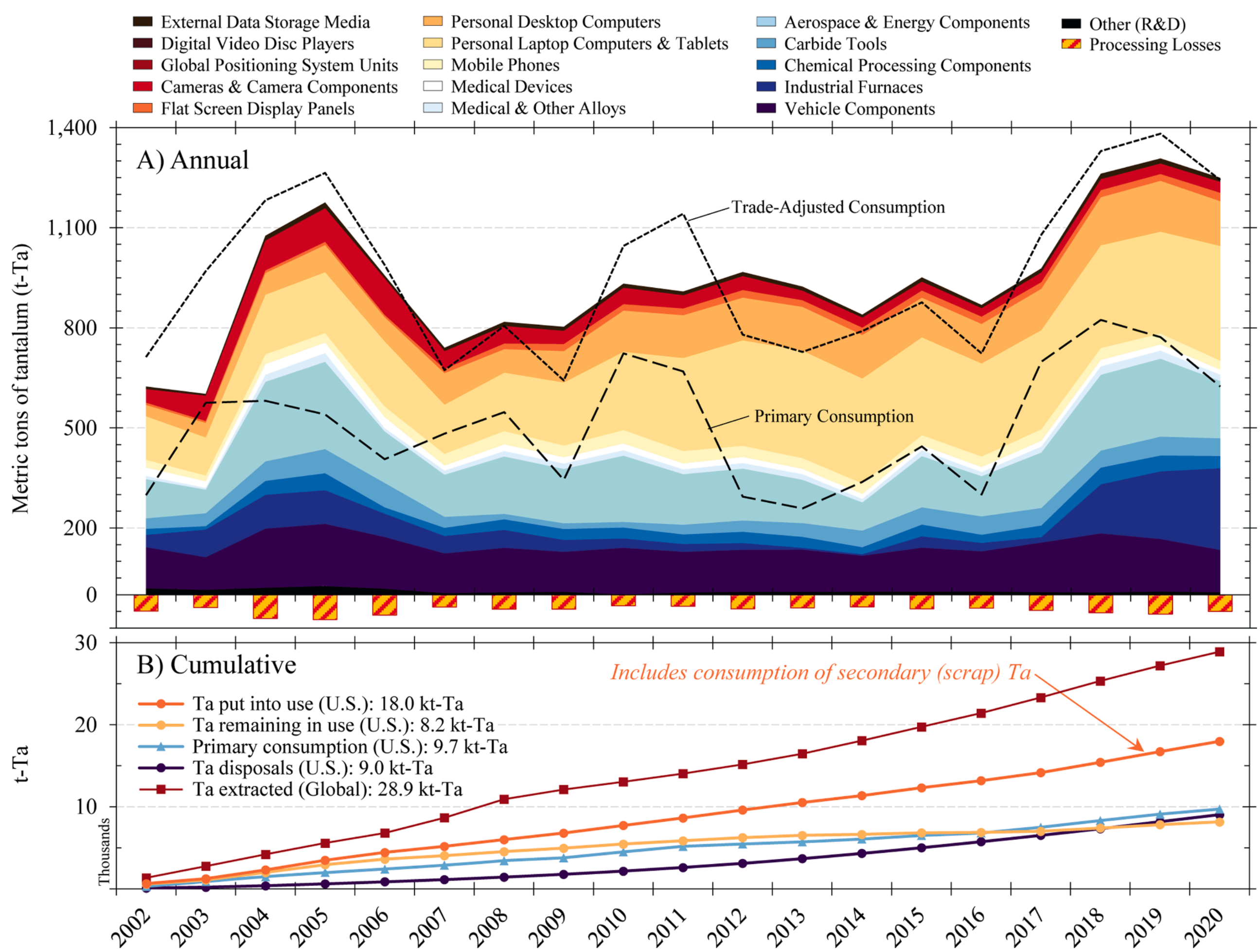

Fig. 4. Results of the STAN2 material flow analysis (MFA) model for tantalum in the United States for the years 2002 through 2020. Top (A): annual consumption (quantity put into use) of tantalum in each of our 16 modeled end-use categories. Estimates of primary and trade-adjusted consumption (calculated as the simple mass balance of trade plus changes in U.S. Government stockpiles as described in greater detail in the Fig. 2 caption) are also plotted as dashed lines for comparison. Bottom (B): total cumulative consumption ("Ta put into use") of tantalum between 2002 and 2020, plotted along with total cumulative stocks of tantalum remaining in use ("Ta remaining in use"), total cumulative tantalum disposals ("Ta disposals" which includes processing losses and losses in use), primary consumption ("Primary consumption" as typically estimated; see Fig. 2 caption), and total cumulative global primary (mining) tantalum production ("Ta extracted") for the same time period.

used in primary processing (smelting/refining) through the years, namely towards decreased consumption of concentrates and increased consumption of tantalum scrap, including some years in which the trade data suggest that the feed material available to primary processors was dominantly tantalum scrap (e.g., for the years 2010–2011; Fig. 2). From the results of our model, we estimate that, on average, domestic processors consumed equal amounts of tantalum concentrates and scrap. This may be, in part, an artifact of the lack of available data for domestic consumer stockpiles of primary feed materials. While our analysis incorporates annual changes in the National Defense Stockpile, which included tantalum concentrates between 2002 and 2006, there are no publicly available data for the stockpiles kept (if any) by private domestic processors, and the movement of primary materials captured in the trade data could very well have been transacted one year but stockpiled and processed in a different year. The time period with the lowest consumption of concentrates in our model (2010–2013) also coincided with the largest increase in the global price of tantalite concentrates in the years following the closure of the world's largest tantalum mining operation (Wodgina Mine, Australia; Papp, 2010) as well as the passage of the Dodd-Frank Act (2010), which resulted in a *de facto* embargo of tantalum concentrates originating in the Great Lakes region of Africa. Thus, it is reasonable to conclude that domestic primary processors used mainly secondary scrap to fulfill their demand. We estimate that scrap accounted for 70–86% of processors' consumption during this period. Importantly, the majority of this scrap material is not "old" scrap, or scrap recovered from EoL recycling of consumer goods, but rather "new" scrap generated either during fabrication processes (e.g., turnings and shavings of tantalum metal; spent tantalum sputtering targets) or as semi-finished materials scrapped due to failure or quality control (e.g., scrapped tantalum anodes and tantalum capacitors). This essentially means that there remains a strong reliance on primary sources of tantalum (i.e., primary concentrates) to generate secondary "recycled" tantalum supply. We discuss the challenges around tantalum recycling in further detail later in this section.

Notably, *direct* consumption of tantalum in the United States, which encompasses the consumption of tantalum in raw, refined, and semi-finished forms (e.g., concentrates; chemicals and compounds; metal; tantalum capacitors) by the domestic manufacturing industry to produce a finished good, has steadily decreased through the years from approximately 82% of total tantalum consumption in 2002 to

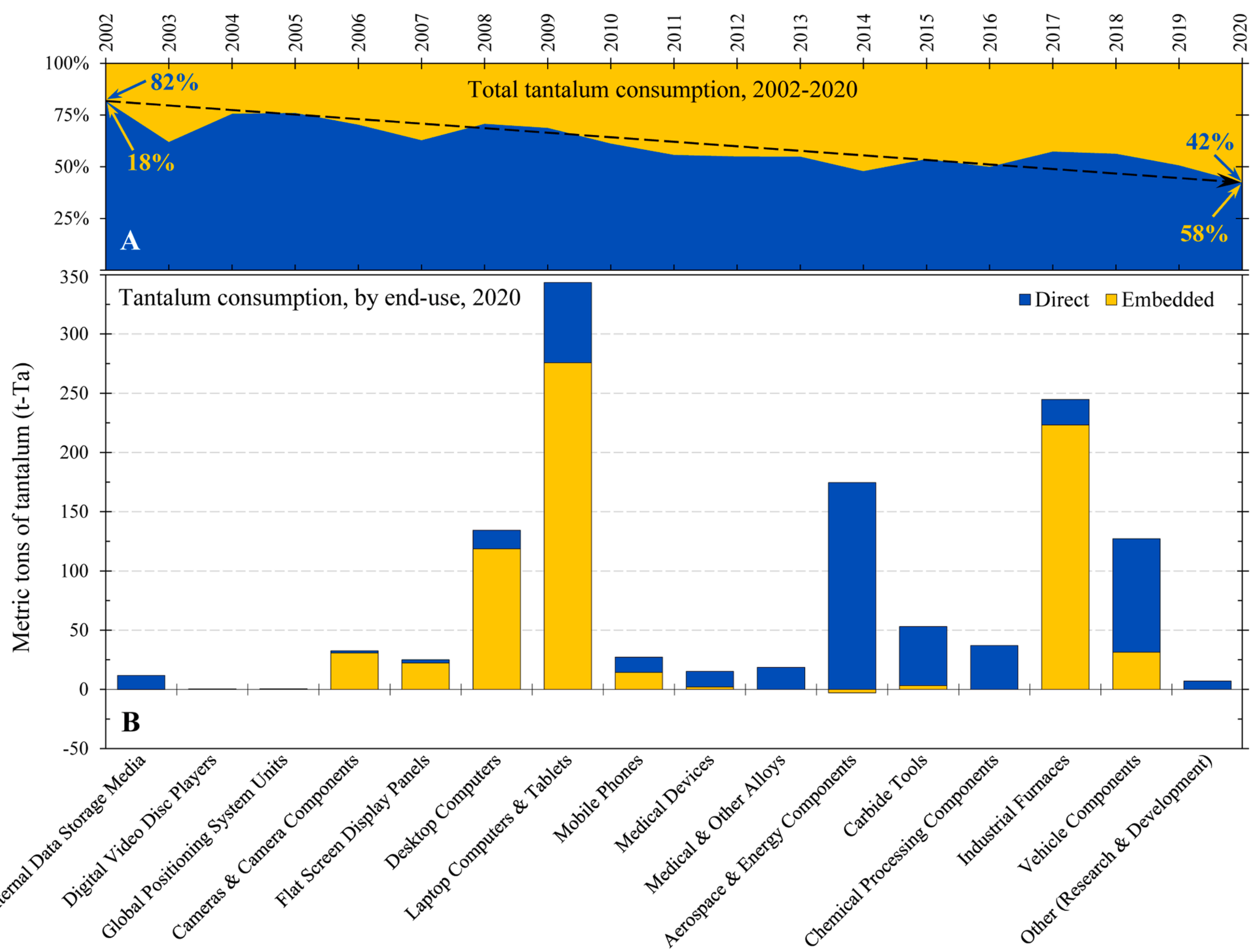

Fig. 5. Top (A): Comparison of direct tantalum consumption (i.e., tantalum consumed by the domestic manufacturing industries in the production of finished goods) and indirect or embedded tantalum consumption (i.e., tantalum contained in finished goods produced abroad and imported for final domestic consumption) in the United States between 2002 and 2020; the black dashed arrow represents the cumulative change in the share of total tantalum consumption for direct versus embedded consumption, and the percentage numbers are color-coded to their respective categories (i.e., percentages in blue correspond to "direct" consumption of tantalum). Direct consumption is represented by flows 35–50 in our STAN2 model (see Fig. S2 in Appendix B of the SI), which is the output from domestic manufacturing; embedded consumption is calculated as the difference between total consumption (flows 51–66 in our model) and direct consumption (flows 35–50). Bottom (B): Comparison of direct and embedded tantalum consumption in the United States within finished goods for the year 2020; negative quantities are net exports.

approximately 42% in 2020 (Fig. 5). This suggests the United States has become increasingly dependent on tantalum embedded in finished goods imported into the United States (i.e., embedded consumption) in order to meet domestic demand due to decreased output from domestic manufacturing.

The percentage breakdown of tantalum consumption by end-use category has been variable but relatively constrained throughout the modeled timeframe, and we note that no significant patterns or consistent changes in the end-use proportions emerged from our results (Fig. 6). Electronic applications, the leading global tantalum application, consistently accounted for a combined 40–65% of total domestic consumption, followed by aerospace and energy components at 10–20%. The only notable exception is tantalum consumption in vehicle electronics, for which we observe a steady decline in the consumption share of roughly 10%, from a high of 20% in 2002 to a low of around 10% in 2020. Interestingly, in terms of absolute quantity, consumption in vehicle electronics appears to have remained relatively steady, around an average of 137 ± 24 t-Ta per year. This may be, in part, an artificial product of the distribution coefficients for direct domestic consumption used in our model, which were constant for all years modeled. However, considering the significant quantity of tantalum consumed in embedded form, including that for vehicle electronics (24% on average), the variability we observe is likely a reflection of changes in consumption as captured by trade data.

4.2. Gap in the global tantalum supply chain

Our analysis suggests that between 2002 and 2020 the United States consumed around half of the total available global tantalum supply. If the results of our model are on the right order of magnitude, this would mean that either previous estimates of global primary production (i.e., available primary supply) are underestimated, the volume of secondary (recycled) tantalum supply is underestimated, or both. This is not a new finding as previous researchers have reached similar conclusions, especially regarding the primary production of tantalum concentrates from artisanal and small-scale mining activities concentrated in the Great Lakes region of Africa. For example, in an analysis of tantalum trade statistics Bleischwitz et al. (2012) found that as much as 20% of the global volume of primary tantalum in 2009 may have been derived from illicit activities in the DRC, likely entering the global market via neighboring countries. In a similar study, Mancheri et al. (2018) documented even larger gaps between the accounted volume of primary tantalum production and final global consumption of tantalum articles. Furthermore, Deetman et al. (2017), in the only other tantalum material flow study to account for embedded trade, estimated that in 2007 a total of 1,690 t-Ta were put into use in Europe alone. Our estimated consumption in the United States for the same year is 740 t-Ta. In contrast, estimates of total available tantalum supply in 2007, including secondary (recycling) supply, range from around 1,300 t-Ta to ~2,000 t-Ta (e.g., British Geological Survey, 2013; Papp, 2013; Roskill Information Services Ltd., 2016). Even considering the high end of that range there remains a supply deficit of around 430 t-Ta (or ~22%) to account for the estimated total consumption between the United States and Europe alone. Undocumented production from the DRC on the order of magnitude that Bleischwitz et al. (2012) found would not be sufficient to close this gap, which suggests that other factors are likely also at play.

Much like our analysis, the analysis by Deetman et al. (2017) does not consider consumer stocks of raw materials, components, or products due to the lack of available data, and such stocks may contribute significantly towards fulfilling domestic demand. It is also likely that some of the tantalum content and domestic market share parameters used in our study are higher than they should be, resulting in inflated consumption estimates. Many of the parameters used in our model are based on a single previous study, and lack of additional data or comparative studies makes it difficult to fully assess the quality of our results.

4.3. Challenges in tantalum recycling

As previously noted, our data suggests tantalum scrap accounts for ≥50% of the domestic primary processing flow. The issue remains that new scrap is generated during the manufacturing of new tantalum materials and parts, which means it is still dominantly derived from the primary processing of concentrates and does not contribute towards diversifying tantalum supply. Trade data for tantalum scrap is not sufficiently detailed to determine either the form of the material or the process from which it was generated, making it nearly impossible to examine the major contributors to secondary tantalum supply. Previous studies have determined there is hardly any EoL recycling of specialty metals like tantalum, primarily because they are used in small quantities as part of complex products like electronics or as minor constituents in multi-component alloys resulting in a high level of dilution in the final products (e.g., Graedel et al., 2011; Gille and Meier, 2012). These products may enter recycling streams at their EoL, but the specialty metals are generally incorporated into base metal scrap, thereby losing their individual functionality. Superalloys are recycled at relatively high rates (~18%; Nassar, 2017), but mostly for the rhenium content, and unless the tantalum content is >5% recycled superalloys are likely to be downgraded, for example, to steel additives (Nassar, 2017; Schütte, 2021). Chancerel et al. (2015) concluded that the best recycling route for the recovery of tantalum from electronic goods at EoL would be from the removal of tantalum capacitors in laptop computers, which we estimate accounted for 27% of U.S. consumption in 2020. Extensive research has been conducted on the recycling potential for tantalum capacitors from electronics at the EoL (Buchert et al., 2012; Niu et al., 2017; Chen et al., 2019). An efficient capacitor recycling method already exists but is limited in practice to only new capacitor scrap (generated during fabrication), which, in the United States, is likely already 100% collected and recycled by the leading, if not all, domestic tantalum capacitor manufacturers (Jayson Young, KEMET Electronics Corp., written communication, September 2019). The gap that remains is in the collection, separation, and processing of electronics specifically for recovery of tantalum at the EoL, the rate of which is estimated to be <1% (e.g., Graedel et al., 2011; Hagelüken, 2014; Ueberschaar et al., 2017).

5. Conclusions

We present results from our dynamic analysis of the flow of tantalum materials in the United States between 2002 and 2020. Our results highlight some of the limitations in the traditional method for estimating "apparent" consumption, which only accounts for primary tantalum materials and excludes the trade of tantalum embedded in semi-finished and finished goods. We estimate that the United States consumed approximately 18,000 t-Ta between 2002 and 2020, 85% more than the estimated cumulative primary consumption (~9,720 t-Ta). Around 45% of that amount (8,160 t-Ta) remained in use in 2020, with an additional 4% (671 t-Ta) in hibernation. Approximately 9,000 t-Ta have been lost to landfills in the same time frame either as non-recoverable losses during processing or within products discarded as waste at the EoL. As of yearend 2020, we estimate that the cumulative above-ground stocks across all the stages of the tantalum material life-cycle in the United States totaled 18,400 t-Ta.

Our results suggest the tantalum contained in materials coming out of use at their EoL could be a potentially significant source of tantalum, but several logistical and technological challenges prevent the recovery of tantalum from discarded materials, namely the extremely diluted tantalum content once tantalum is incorporated into finished goods with complex material compositions, as well as the existing collection, sorting, and recycling pathways in the United States. However, an important starting point in the effort to diversify tantalum supply and improve domestic supply security is the proper quantification of the above-ground tantalum stocks currently residing in the United States, and

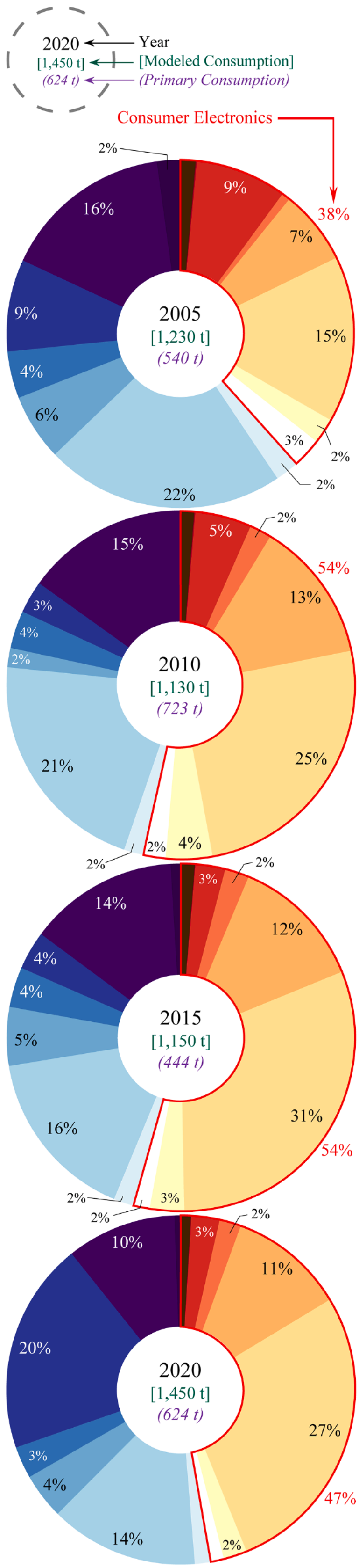

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Fig. 6. Relative consumption of tantalum in the United States, as percent (%) of total consumption, by end-use application for the years 2005, 2010, 2015, and 2020 based on the results of our material flow analysis. Percentages are only labeled for end-uses with ≥2% share. The modeled total consumption (in brackets at the center of each pie chart) and primary consumption (in parentheses) are included with each year for comparison. In addition, the larger red outlines within each pie chart highlight consumption of consumer electronics as a combined category [includes digital video disc players, mobile phones, desktop and laptop computers (including tablets), external data storage media, flat screen display panels, global positioning system units, cameras and camera components, and electronics in medical devices]. End-use categories are presented in the same colors and order as in Fig. 4.

the form in which they are contained, which was a primary goal of this analysis.

It is important to note that our analysis is not without its limitations. As previously noted, building the complete framework for our MFA required many simplifying assumptions due to the lack of available information, which introduced several levels of uncertainty into our model. The material contents and end-use proportions remained constant in our model, but they still provide a good general approximation of the average content and consumption levels throughout the modeled time. We note that consumption in electronics has increased through the years, but at the same time, the tantalum content of capacitors, the single largest application of tantalum, has decreased through the years due to developments in the tantalum powder industry, allowing for higher capacitance powders and resulting in increasing miniaturization of capacitors (Nassar, 2017). While consumption in this application has increased, this is likely offset by the decreased material requirement per unit produced. We also note that for most modeled years, the volume of tantalum consumed embedded in semi-finished and finished goods exceeds that of raw feed materials, and, with the exception of industries that are largely domestic (e.g., specialty alloys, chemical processing components, carbide tools; Fig. 5), trade statistics are likely the bigger contributor to end-use proportions and may better reflect demand by application. In addition, as far as the authors are aware there is currently no reliable data on the quantity of products in use, or the rate at which they are disposed at EoL in the United States, thus preventing a thorough comparison, and much less a “bottom up” verification, of the accuracy of our results. We note, however, that our findings are on the same magnitude as those of Deetman et al. (2017), the only other tantalum MFA study to have incorporated embedded trade of tantalum, which similarly concluded that traditional methods significant underestimate tantalum consumption. Thus, our results still provide a very useful first order estimation of the total flow of tantalum materials within the United States economy that would otherwise not be available.

CRediT authorship contribution statement

Abraham J. Padilla: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Nedal T. Nassar:** Resources, Conceptualization, Writing – review & editing, Supervision, Project administration.

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.

Data availability

Data has been made available as an appendix in the supporting information.

Acknowledgments

The authors are grateful to Graham G. Lederer and Andrew L. Gulley (U.S. Geological Survey [USGS]) as well as other members of the USGS Minerals Intelligence Research Section for their contributions and insightful discussions in the early stages of this work. The authors also thank Chad A. Friedline (USGS), Jean-Paul Meutcheho (Global Advanced Metals), Kurt Habecker (Global Advanced Metals), and two anonymous reviewers for their valuable feedback as well as editor Dr. Keisuke Nansai for guidance during the review process. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The authors declare no conflict of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106783.

References

Achebe, J., 2016. Substance Flow Analysis of Tantalum: Tracking the Conflict−Free Path. University of Waterloo, Waterloo, ON, Canada. Master's Thesis.

Bleischwitz, R., Dittrich, M., Pierdicca, C., 2012. Coltan from Central Africa, international trade and implications for any certification. Resour. Policy 37, 19–29. https://doi.org/10.1016/j.resourpol.2011.12.008.

Bleiwas, D.I., Papp, J.F., Yager, T.R., 2015. Shift in Global Tantalum Mine Production, 2000–2014—Fact Sheet 2015-3079. U.S. Geological Survey, Reston, VA. https://doi.org/10.3133/fs20153079.

British Geological Survey, 2011. Niobium–Tantalum Mineral Profile. British Geological Survey, Nottingham, United Kingdom. Accessed at https://www2.bgs.ac.uk/mineralsuk/statistics/mineralProfiles.html.

British Geological Survey, 2013. World Mineral Production 2007–11. British Geological Survey, Nottingham, United Kingdom. Accessed at https://www2.bgs.ac.uk/mineralsuk/download/world_statistics/2000s/WMP_2007_2011.pdf.

Buchert, M., Manhart, A., Bleher, D., Pingel, D., 2012. Recycling Critical Raw Materials from Waste Electronic Equipment. Öko-Institut e.V., Freiburg, Germany. Accessed at https://www.oeko.de/oekodoc/1375/2012-010-en.pdf.

Chancerel, P., Marwede, M., Nissen, N.F., Lang, K.-D., 2015. Estimating the quantities of critical metals embedded in ICT and consumer equipment. Resour., Conserv. Recycl. 98, 9–18. https://doi.org/10.1016/j.resconrec.2015.03.003.

Charpentier Poncelet, A., Helbig, C., Loubet, P., Beylot, A., Muller, S., Villeneuve, J., Laratte, B., Thorenz, A., Tuma, A., Sonnemann, G., 2022. Losses and lifetimes of metals in the economy. Nat. Sustain. 5, 717–726. https://doi.org/10.1038/s41893-022-00895-8.

Cencic, O., Rechberger, H., 2008. Material flow analysis with software STAN. J. Environ. Eng. Manag. 18 (1), 3–7. https://www.stan2web.net/.

Chen, W.-S., Ho, H.-J., Lin, K.-Y., 2019. Hydrometallurgical process for tantalum recovery from epoxy-coated solid electrolyte tantalum capacitors. Materials 12 (1220). https://doi.org/10.3390/ma12081220.

Cunningham, L.D., 2004. Tantalum recycling in the United States in 1998. In: Sibley, S.F. (Ed.), Flow Studies for Recycling Metal Commodities in the United States—Circular 1196. U.S. Geological Survey, Reston, VA, pp. J1–J10.

CRU Group, 2020. Noble Alloys and Minor Metals Prices. CRU Group, London, United Kingdom. Accessed via http://www.crugroup.com/.

Deetman, S., van Oers, L., van der Voet, E., Tukker, A., 2017. Deriving European tantalum flows using trade and production statistics. J. Ind. Ecol. 22 (1), 166–179. https://doi.org/10.1111/jiec.12533.

Dodd-Frank Wall Street Reform and Consumer Protection Act, 2010. Pub. L. No. 111-203, 124 Stat. 1376. Accessed at https://www.govinfo.gov/content/pkg/PLAW-111publ203/pdf/PLAW-111publ203.pdf.

Dodgson, L., 2016. On the trail of tantalum—tracking a conflict mineral. Mining Technol. Anal. Accessed at https://www.mining-technology.com/features/featureon-the-trail-of-tantalum-4831288/.

European Union, 2017. Regulation 2017/821 of the European Parliament and of the Council of 17 May 2017 laying down supply chain due diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and gold originating from conflict-affected and high-risk areas. Off. J. Eur. Union L 130 60. May 19, ISSN 1977-0677. Accessed at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2017:130:TOC.

Friedline, C.A., 2022. Tantalum—U.S. Geological Survey Mineral Commodity Summaries 2022. Reston, VA, pp. 166–167. Accessed at https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-tantalum.pdf.

Gille, G., Meier, A., 2012. Recycling von refraktärmetallen, band 5 (Recycling of refractory metals, volume 5). In: Thomé-Kozmiensky, K.J., Goldmann, D. (Eds.), Recycling Und Rohstoffe (Recycling and Raw Materials). TK Verlag Karl Thomé-Kozmiensky, Neuruppin, Germany, pp. 537–560.

Golev, A., Werner, T.T., Zhu, X., Matsubae, K., 2016. Product flow analysis using trade statistics and consumer survey data—a case study of mobile phones in Australia. J. Clean. Prod. 133, 262–271. https://doi.org/10.1016/j.jclepro.2016.05.117.

Graedel, T.E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What do we know about recycling rates? J. Ind. Ecol. 15 (3), 355–366. https://doi.org/10.1111/j.1530-9290.2011.00342.x.

Graedel, T.E., 2019. Material flow analysis from origin to evolution. J. Environ. Sci. Technol. 53, 12188–12196. https://doi.org/10.1021/acs.est.9b03413.

Hagelüken, C., 2014. Recycling of (critical) Metals. In: Gunn, G. (Ed.), Critical Metals Handbook. John Wiley & Sons, Ltd, Nottingham, United Kingdom, pp. 41–69. Accessed at https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118755341.

Hoppe, A., Korinek, G., 1995. Recycling of tantalum. In: Queneau, P.B., Peterson, R.D. (Eds.), Proceedings of Third International Symposium on Recycling of Metals and Engineered Materials. The Minerals, Metals and Materials Society, Point Clear, AL, United States, pp. 1013–1025.

IHS Markit Ltd., 2020. Global Trade Atlas [database]. IHS Markit Ltd., London, United Kingdom. Accessed via https://connect.ihsmarkit.com/GTA/home.

Japan Ministry of Finance, 2021. Japan's Tariff Schedule as of January 1, 2020. Japan Ministry of Finance website, Tokyo, Japan. Accessed at https://www.customs.go.jp/english/tariff/2020_1/index.htm.

Linnen, R., Trueman, D.L., Burt, R., 2014. Tantalum and niobiumGunn, G. (Ed.), In: Critical Metals Handbook. John Wiley & Sons, Ltd, Nottingham, United Kingdom, pp. 361–384. Accessed at https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118755341.

Mancheri, N.A., Sprecher, B., Deetman, S., Young, S.B., Bleischwitz, R., Dong, L., Kleijn, R., Tukker, A., 2018. Resilience in the tantalum supply chain. Resour. Conserv. Recycl. 129, 56–69. https://doi.org/10.1016/j.resconrec.2017.10.018.

Nassar, N.T., 2017. Shifts and trends in the global anthropogenic stocks and flows of tantalum. Resour. Conserv. Recycl. 125, 233–250. https://doi.org/10.1016/j.resconrec.2017.06.002.

Niu, B, Chen, Z., Xu, Z., 2017. An integrated and environmental-friendly technology for recovering valuable materials from waste tantalum capacitors. J. Clean. Prod. 166, 512–518. https://doi.org/10.1016/j.jclepro.2017.08.043.

Padilla, A.J., 2020. Tantalum. In: Metals and minerals—U.S. Geological Survey Minerals Yearbook 2017, vol. I. Reston, VA, pp. 76.1–76.7. Accessed at https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2017-tanta.pdf.

Papp, J.F., 2010. Niobium (Columbium) and Tantalum. In: Metals and Minerals—U.S. Geological Survey Minerals Yearbook 2008, I. Reston, VA, pp. 52.1–52.14. Accessed at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/niobium/myb1-2008-niobi.pdf.

Papp, J.F., 2013. Niobium (Columbium) and Tantalum. In: Metals and Minerals—U.S. Geological Survey Minerals Yearbook 2011, I. Reston, VA, pp. 52.1–52.14. Accessed at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/niobium/myb1-2011-niobi.pdf.

Roskill Information Services Ltd., 2016. Tantalum—Global Industry, Markets and Outlook to 2020, 12th ed.;. Roskill Information Services Ltd., London, United Kingdom.

Roskill Information Services Ltd., 2020. Tantalum—Outlook to 2029, 15th ed.;. Roskill Information Services Ltd., London, United Kingdom.

Schütte, P., 2021. Tantalum—sustainability information. Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources, BGR), Hanover, Germany. Accessed at https://www.geozentrum-hannover.de/EN/Gemeinsames/Produkte/Downloads/Informationen_Nachhaltigkeit/tantal_en.html.

Tantalum-Niobium International Study Center (TIC), 2021a. Applications for Tantalum. Tantalum-Niobium International Study Center website, Lasne, Belgium. Accessed at. https://www.tanb.org/about-tantalum/applications-for-tantalum/.

Tantalum-Niobium International Study Center (TIC), 2021b. Processing—Extraction and Refining. Tantalum-Niobium International Study Center website, Lasne, Belgium. Accessed at. https://tanb.org/about-tantalum/processing-extraction-and-refining/.

Tantalum-Niobium International Study Center (TIC), 2021c. Production of Raw Materials. Tantalum-Niobium International Study Center website, Lasne, Belgium. Accessed at. https://tanb.org/about-tantalum/production-of-raw-materials/.

Thiébaud, E.M., Hilty, L.M., Schluep, M., Widmer, R., Faulstich, M., 2017. Service lifetime, storage time, and disposal pathways of electronic equipment—a Swiss case study. J. Ind. Ecol. 22 (1), 196–208. https://doi.org/10.1111/jiec.12551.

Ueberschaar, M., Jalalpoor, D.D., Korf, N., Rotter, V.S., 2017. Potentials and barriers for tantalum recovery from waste electric and electronic equipment. J. Ind. Ecol. 21 (3), 700–714. https://doi.org/10.1111/jiec.12577.

U.S. Census Bureau, 2021. USA Trade Online [database]. U.S. Census Bureau, Washington, D.C. Accessed via https://usatrade.census.gov/.

U.S. Department of Labor, 2020. List of Goods Produced by Child Labor or Forced Labor. U.S. Department of Labor, Washington, D.C. Accessed at https://www.dol.gov/agencies/ilab/reports/child-labor/list-of-goods.

U.S. Geological Survey, 2022. Mineral Commodity Summaries 2022. U.S. Geological Survey, Reston, VA. https://doi.org/10.3133/mcs2022.

U.S. Government Accountability Office, 2020. Conflict Minerals—Actions Needed to Assess Progress Addressing Armed Groups' Exploitation of Minerals. U.S. Government Accountability Office Publication No. GAO-20-595, Washington, D.C. Accessed at https://www.gao.gov/products/gao-20-595/.

Yen, F.-C., Chang, T.-C., Xu, W.-H., 2016. Substance flow analysis of tantalum in Taiwan. Mater. Trans. 57 (5), 613–617. https://doi.org/10.2320/matertrans.M2015420.

Zen Innovations AG, 2021. Global Trade Tracker [database]. Zen Innovations AG, Bern-Kehrsatz, Switzerland. Accessed via https://www.globaltradetracker.com/.

Zogbi, D., 2018. Tantalum—State of the Industry 2018 and Global Market Outlook. Paumanok Publications, Inc., Cary, NC.