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Conflict Minerals in the Compute Sector: Estimating Extent of Tin, Tantalum, Tungsten, and Gold Use in ICT Products

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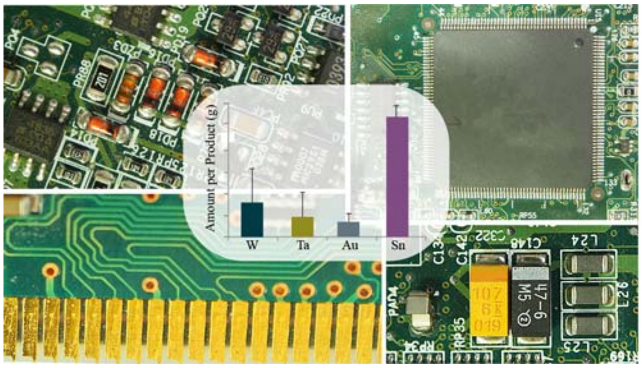


ABSTRACT

Recent legislation has focused attention on the supply chains of tin, tungsten, tantalum and gold (3TG), specifically those originating from the eastern part of the Democratic Republic of Congo. The unique properties of these so-called "conflict minerals" lead to their use in many products, ranging from medical devices to industrial cutting tools. This paper calculates per product use of 3TG in several information, communication, and technology (ICT) products such as desktops, servers, laptops, smart phones and tablets. By scaling up individual product estimates to global shipment figures, this work estimates the influence of the ICT sector on 3TG mining in covered countries. The model estimates the upper bound of tin, tungsten, tantalum and gold use within ICT products to be 2%, 0.1%, 15% and 3% of the 2013 market share, respectively. This result is projected into the future (2018) based on the anticipated increase in ICT device production.

INTRODUCTION

Throughout history, natural resources have often played a role in conflict. That role has come under increasing scrutiny over the last two decades when natural resources have provided the revenues to fuel conflict in developing countries.[1] Although media attention has frequently focused on the role of drugs, oil, and diamonds, a broader array of resources can play a role in funding conflict. In response to public concern, a number of schemes have emerged to create economic disincentives for the use of conflict-related resources; however, the effectiveness of such market-based schemes depends on significant market participation. To better understand this potential effectiveness, this paper describes and applies a method to estimate the flow of "conflict minerals" within the information, communication and technology (ICT) sector.

Within the broader context of conflict resources, the term "conflict minerals" has developed a narrow formal definition (see note at end of document). Specifically, the term conflict minerals is used to describe minerals that originate from the Democratic Republic of Congo (DRC) or adjoining states that are processed into tin, tungsten, tantalum and gold (3TG) and associated with financing severe, ongoing civil conflict in the region.[2, 3] These conflicts lie in mineral rich areas and are perpetuated by poverty, corruption, land right disputes, regional tensions and revenues from mining.[4-6] In 2001, a United Nations panel reported on the connection between the exploitation of mineral resources and armed conflicts in the region.[7] More recently, Non-

Governmental Organizations (NGOs) linked the demand for conflict minerals specifically to consumer goods such as electronics.[8-10] In 2010, the Dodd-Frank Act was adopted requiring companies that report to the United States Securities and Exchange Commission (SEC) to disclose their use of conflict minerals in products .[11] However, a number of sources have claimed that the Act has become a *de facto* ban, reducing economic activity and affecting the livelihoods of 1 to 2 million artisan miners in the conflict regions as a result.[12-15] A subsequent review of the impact of Dodd-Frank found that it has significantly reduced the involvement of armed groups in the production of tin, tungsten and tantalum.[16]

Operationally, manufacturers curtail use either by substituting to other materials or by minimizing the amount acquired in affected regions. Efforts to realize the latter generally support one of two goals: 1) unambiguously identifying the source of a mineral (auditing) or 2) increasing the number of (or at least clearly identifying) those sources that do not support conflict (market segmentation). Significant efforts have emerged to establish certifiable auditing processes to provide assurances on the sources of minerals used.[17-20] To support those processes, the German Federal Institute for Geosciences and Natural Resources has initiated pilot projects to develop certified trading chains and to enhance traceability of the minerals through methods that map characteristic features of the ore to samples of known origin.[21] In the US, the ICT industry responded in 2008 with the Conflict Free Smelter Program (CFSP), which is now part of a broader industry initiative called the Conflict-Free Sourcing Initiative.[22, 23]

Consumer electronics, particularly the cell phone, have been highlighted as connected to the demand for these minerals from within the conflict areas of the DRC.[4, 6] Therefore, this work explores global production of conflict minerals linked to the ICT industry to understand the ability of this sector to send an economic signal to smelters and refiners. To achieve this goal, we estimate and assess the quantity of these metals contained within a subset of consumer electronic products including smart phones, tablets, notebooks and desktop computers, servers and displays. This work develops **upper-bound** assessments of per product use of 3TG. Per product use is then scaled with data for global sales and production of equipment, including projections of future product sales. Upper-bound estimates capture a conservative approximation of 3TG content given the wide variation across ICT products and the significant challenges in tracing the quantities of these materials purchased by ICT brand companies. As many as nine tiers separate the miners and smelters from the final manufacturers, which is often still not the original equipment manufacturer (OEM).[24] Generally a supplier loses visibility beyond the first few tiers, as the quantity of suppliers explodes exponentially (EICC & D. Martin, e-mail communication, July 2014). Previous studies have commented on the challenge of estimating materials content due to lack of data.[25]

Previous work to quantify materials use in electronics has done so for several primary reasons, including 1) environmental evaluation through life cycle assessment (LCA), 2) assessment of toxicity potential, 3) determination of value of materials recovery for waste management, 4) understanding the overall flows of materials through society through materials flow analysis (MFA), or combinations of the above. In the case of LCA, a few studies have reported quantities for a subset of 3TG either at the component or whole product level. These are often based on visual assessment of disassembly data and may be drawn from just a few product tear downs.[26-29] For example, in the work of Deng *et al.*, authors report a number for gold based on a study from 1998 and tin based on a study from 2007.[27] For toxicity potential or materials recovery, materials of value or perceived toxicity, such as gold and tin, are quantified through leaching treatments.[30-34] For MFA, end use sectors are used to estimate the amount of material produced, fabricated, used and disposed of across particularly geographic regions over particular time scales.[35-37] In the case of 3TG, materials flows have been characterized for tungsten[38] and tin[39]; however, these examples do not emphasize the electronics end use, thus do not provide estimates to compare to the work presented here. A recent study has quantified the amount of copper, gold, palladium, silver, nickel, lead, antimony and tin to determine the energy consumed to recover metals from mobile phones.[40] Extensions of MFA based on input-output models (WIO-MFA) have also been developed to estimate flows of substances within commodities, with particular emphasis on trade.[41, 42] The current contribution provides a way of estimating metal content not previously undertaken for these materials within these product categories. A recent review article on a related topic has commented on the lack of such bottom up approaches based on product attributes, such as area of components or pin count.[43]

First, this paper describes the current supply status and application for each of the metals. Then the paper describes the method for estimation of per product concentration and scales this estimate according to total global shipments.

MATERIALS OVERVIEW

This section provides an overview of each of the focus materials. The primary uses of **tungsten** include cemented carbides, mill products, steels alloys, and chemicals.[44, 45] Tungsten's favorable combination of properties (e.g., high melting point, low coefficient of expansion, and high hardness) limits options for substitution, especially cost effective substitutions where performance at high temperatures is desired. As shown in Figure 1, China dominates world production of tungsten, accounting for over 84 percent of the roughly 73,000 tons of tungsten produced worldwide in 2011.[46] Canada and Russia account for roughly 8 percent of the worldwide production, or half of the remaining production that is not from China.[46]

Corrosion resistance, ductility and durability make **tin** a favorable choice for alloying with other metals and for coating harder metals (e.g. with steel to form tin cans or tinplate). The primary uses of tin include solders, tinplate, chemicals, brass, and float glass.[47-49] Solder is the application relevant to the ICT industry, but solder is used extensively in all electrical and electronic products. Tin solders generally have tin concentrations between 5% and 98% by weight, and the greater the tin concentration, the greater the solder's tensile and sheer strengths. Unlike tungsten, there are substitutions for tin including epoxy resins for tin solder, and aluminum alloys, copper-based alloys, and plastics for tin bronze.[50] Roughly 60% of the global mine output comes from China and Indonesia, with China leading with close to 50% of global mine output and 30% of global reserves.[47]

Tantalum is a refractory metal that is ductile, easily fabricated, highly resistant to corrosion by acids, a good conductor of heat and electricity, as well as possessing a high melting point. The primary uses of tantalum are capacitors (the relevant end use for electronic products), mill products, chemicals, sputtering targets, powders, and carbides.[51, 52] Tantalum became desirable in electronics based on the discovery of directional conductivity in tantalum oxide leading to the development of the tantalum capacitor. Brazil and Mozambique have been the leading tantalum producers, followed by Rwanda and DRC.[53]

Gold is the most malleable of metals; it is unaffected by air, moisture, and most corrosive reagents, making it a good protective coating on more reactive metals. The primary uses of gold include jewelry, electronics, and bars and coins.[54] The top 10 gold producing countries are responsible for two-thirds of global gold production, yet no one country produces more than 14% of the global production as demonstrated by the multitude of bars in Figure 1.[55, 56] China currently leads global production and consumption, followed by Australia and the United States on the production side, and India and the United States on the consumption side. Gold originating from the conflict countries is a small minority of the volume, less than 1%, and the large scale of miners and refiners have contributed to responsible sourcing.[54]

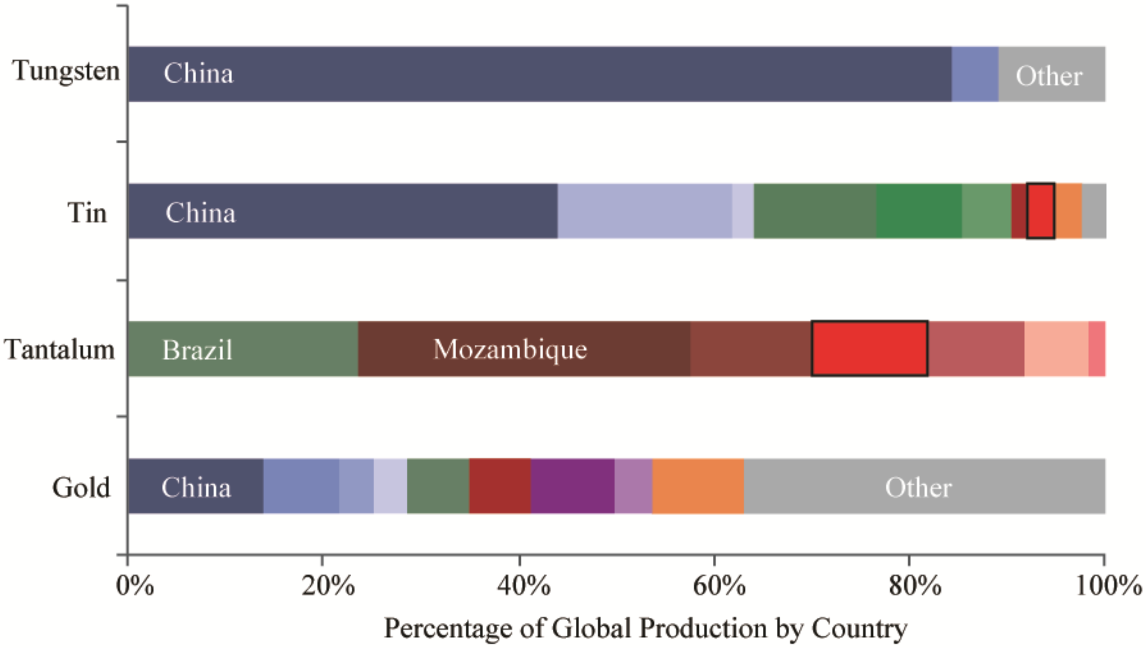


Figure 1. Percentage of production for tungsten, tin, tantalum, and gold by country for the top producing countries.[46, 49, 53, 54] Regions are grouped by color: Asia (blue), South America (green), Africa (red), North America (purple), Oceania (orange), and Other (grey). The two red bars outlined with black shown in tin and tantalum are for the covered countries: the DRC and Rwanda, respectively.

METHOD

To establish the percentage of global consumption of conflict minerals attributable to typical consumer electronics, we estimated the material per component (or attribute), which was then scaled with the number of such components per product. The model used to estimate content was a mechanistic, physical model rather than an empirical model due to limited product-specific data availability and the challenge with measuring metal content directly. We focused on attributes that were reported in product teardown reports.

Each model establishing the quantities of conflict minerals relies on comprehensive product teardown reports of the products in question. These reports provide complete details of all of the electronic, electromechanical, and mechanical components employed in a product. Tear down data were used from several industry sources as well as third party companies.[57] Emphasis was placed on more recent models with at least one, if not all, of the tear downs from products made from 2011 onwards. Because of the expense of obtaining these reports and their selective availability, two tear downs per product type were used in most cases, with the exception of tablets, where 25 tear down reports were available. Wherever possible, more commonly sold products within a category were used for the estimation. Given the large range of configurations of electronic products, significant uncertainty exists in these estimates. Uncertainty was estimated by generating a range in metal content per attribute for each conflict mineral based on the data within the 25 tablet reports. This range was increased by 50% to provide uncertainty range for the products where more tear down reports were not available. Also, as described for each material below, upper bound assumptions were made to deliberately overestimate the conflict minerals content within ICT, including scrap loss in production. A summary of the relevant detail provided is shown in the supporting information and described below. The mechanistic models for each material are described below in text and equation form. The supporting information also provides example images of the components of interest.

The modeled 'per product' figure was then scaled by global sales data to estimate global usage by this product group.[58-61] Finally, this number was represented as a percentage of global production for each metal. The accuracy of these estimates has been gauged based on their congruence with related estimates, where possible, and through interviews with relevant materials-based industry associations.

TUNGSTEN ESTIMATE

The following paragraphs describe the assumptions used to develop the mechanistic, physical model for tungsten content in ICT products. Tungsten has two primary uses in consumer electronics, smart phone vibration motors (a small electric motor used to notify the user of an incoming connection) and vias (opening in an oxide layer that allows conductive connection between layers) in integrated circuits (ICs). Due to its high density, tungsten enclosed in the vibration motor of a cell phone enables large vibration within a small form factor.[45] For IC vias, tungsten is deposited between the metal tracks used to connect components. Tungsten's conductivity, thermal expansion properties and suitability for chemical vapor deposition promotes its use in IC vias.[62]

The quantity of tungsten in a typical vibration motor was found by removing the tungsten piece from a number of typical motors in smart phones, weighing them directly and calculating the average figure. This was determined to be 1 g, though industry feedback we received indicated a tungsten–heavy alloy is used with weight slightly higher than 1 g.

The estimates for tungsten used in ICs were calculated for the quantity of tungsten deposited during the fabrication of the vias, much of which is lost during chemical and mechanical polishing. As such, the calculated figures for tungsten include not only the tungsten present in the product but also tungsten that is consumed during fabrication.

The quantity of tungsten consumed for an IC is related to the number of metal layers that must be connected, L, the volume of the tungsten layer that is deposited, $R_H * T_L * A$, the process yield, S, and the density of tungsten, ρ_W. The data from the teardown reports only supplied the packaged IC area, A, thus several assumptions were necessary. The IC die area (the area of the silicon chip itself) was estimated from the package dimensions and an upper bound die to package area ratio, R_H, of 0.8:1. This ratio is based on an upper bound of previously reported and measured figures.[63] The other main assumptions were that all ICs contained eight metal layers (L), and that layer thickness, T_L, equaled 0.5μm, (based on multiplying an assumed a via size of 0.08 μm by an assumed aspect ratio of 6.2 in line with the current generation of technology).[64] A safety factor, S, of three was added to account for the metal yield of the chemical vapor deposition process used to deposit tungsten on the IC. Equation 1 shows the physical description underlying the model and the equation used.

	Tungsten in vibration motor	Tungsten in ICs
Physical description	Quantity * Weight	Number of metal layers * Volume of tungsten layers * Tungsten density
Equation	$W\ (g) = (N * w) + (L * R_H * T_L * S * \rho_W) \sum_{n=1}^{x} A_n \quad Eqn. 1$	

Where N is the number of vibration motors, w is the weight of tungsten in a motor (in g), L is the number of layers, R_H is the ratio of die area to package area, T_L is the layer thickness (in mm), S is the process yield, ρ_W is the density of tungsten (in g/mm^3), x is the number of ICs, and A is the IC package area (in mm^2). The latter part of this calculation was summed for all ICs to achieve a total for the tungsten due to ICs in the product.

TIN

The dominant use of tin in electronics is solder, providing a mechanical and electrical connection between components and the printed circuit board. The vast majority of components used in consumer electronics are surface mounted, which are soldered used a technique known as reflow soldering. Tin is also present in Indium Tin Oxide (ITO), used as an electrode on flat panel displays. We found this latter application to be trivial in magnitude compared to that of solder, thus we focused solely on solder in the physical model for tin.

The quantity of tin was estimated from the volume of solder paste applied, $T_S * A_C$, the tin content of that paste, ς, and the paste density, ρ_{Sn}. The volume of the solder paste was computed as the product of the surface area of the footprint (or land pattern), A_C, of the components to be soldered and the thickness of the stencil employed, T_S. The land pattern is the outline of the pads that a component will be soldered on. The stencil is the patterned template for the metal deposition on a printed circuit board and an image is shown in the supporting information. The stencil thickness is the same as the solder paste height and so serves as a reasonable proxy to estimate solder thickness. The area for each component was available from component datasheets (specific to each type of component) and the thickness of the stencil, T_S, was chosen as 0.16 mm, a high estimate, based on the fine pitch nature of the components used.[65] The values for solder paste density, ρ_{Sn}, and tin content, ς, by volume were taken from a typical solder paste data sheet. This is expressed in equation 2.

	Tin in solder
Physical description	Volume of solder applied per component * Solder tin content * Tin density

Equation

$$Sn\,(g) = (T_S * \varsigma * \rho_{Sn}) \sum_{n=1}^{c} A_{cn} \qquad Eqn.\,2$$

Where T_S is the stencil thickness (in mm), ς is the tin content of the solder paste, ρ_{Sn} is the density of tin (in g/mm^3), A_c is the area of the component land pattern (in mm^2), and c is the number of components. This calculation was repeated for every component to achieve a total quantity for the tin.

Tantalum

In electronics, tantalum has two main applications. Firstly, it is used in the production of certain capacitors due to its volumetric efficiency and reliability.[66] Volumetric efficiency, *E*, is increased by creating tantalum powders with very high surface area per unit of mass. A measure of the volumetric efficiency is CV/g describing the product of the capacitance (C in μF) and the voltage (V) that is possible per gram of material (g). Capacitance and voltage are either included directly in product teardowns or can be deduced from form factors provided, in addition to the capacitor dimensions.

The volumetric efficiency of capacitor grade tantalum powders has increased from about 2,000 CV/g to over 100,000 CV/g making capacitors with small footprints possible.[52] A value, *E*, of 52,750 CV/g was used, representing the weighted average volumetric efficiency of capacitor grade tantalum powder sales across the industry (Tantalum and Niobium Center, email communication, February 2014). To determine the quantity of tantalum in the wire, a relationship between the length, l_t, and diameter, w_t, of the wire was made based on published cross sections and schematic diagrams. Tantalum wire was determined to be approximately 0.5 the length of the capacitor package (f_l) and the diameter is approximately 0.15 of its width, (f_w).[66]

Thus, knowing the voltage rating, capacitance and dimensions of each tantalum capacitor used in a product in conjunction with the volumetric efficiency of current tantalum powders enabled the calculation of the quantity of tantalum used as shown in equation 3.

Tantalum in capacitors

Physical description — Relative volumetric efficiency — wire volume * tantalum density

Equation

$$Ta_{caps}(g) = \sum_{n=1}^{t} \frac{C_{tn} * V_{tn}}{E} + \pi * \rho_{Ta}(f_w * w_{tn})^2 * (f_l * l_{tn})$$

$$Eqn.\,3$$

where t is the total number of tantalum capacitors, C_t is the capacitance (in μF), V_t is the voltage rating (in V), E is the volumetric efficiency of the tantalum powder used (in μFV/g), w_t is the width of each capacitor (in mm), f_w is the fraction of that width that is wire, l_t is the length of each capacitor (in mm), f_l is the fraction of that length that is wire, and ρ_{Ta} is the density of tantalum (in g/mm^3). This calculation was repeated for every tantalum capacitor in the product to find the total.

The second application of tantalum in electronics is as thin film Ta(Si)N barrier layers for preventing interdiffusion in ICs with copper interconnects.[62]

The quantity of tantalum used in IC fabrication is related to the number of metal layers, L, which must be connected, the area of the die, A, and the thickness of the barrier layer, R_H * T_F. The teardown reports supplied the IC package dimensions, requiring a number of assumptions to estimate tantalum quantity. The main assumptions were that all of the ICs have eight metal layers and the die to package relationship is 0.8:1, as stated previously.[6] Also, a layer thickness, T_F, of 65 nm has been assumed based on industry data that reports the Ta use in sputtering targets is approximately one third of that employed in capacitor grade powders and wire.[67] These terms are combined in equation 4.

Tantalum in ICs

Physical description Number of metal layers * Volume of layers * Tantalum density

Equation

$$Ta_{film} = (R_H * L * T_F * \rho_{Ta}) \sum_{n=1}^{x} A_n \qquad Eqn. 4$$

Where T_F is the film layer thickness (in mm), ρ_{Ta} is the density of tantalum (in g/mm^3), x is the total number of ICs, and A is the IC package area (in mm^2). This was repeated for all ICs to achieve a total quantity of tantalum in the IC for the product.

GOLD

Gold's desirability in electronics is due to a combination of its conductance, malleability and corrosion resistance. It is used extensively to create durable, consistently-conductive connections for card-to-board interfaces. Gold wire is also used to bond silicon die pads to IC package leads. Currently a trend to substitute copper for gold is underway due to copper's lower cost, superior conductivity and recent advances in manufacturing capabilities.[52] Despite this trend, in the spirit of generating upper bound estimates, we assume wire bonding is done with gold. In general there is a lack of information regarding where in an electronic device, outside of the printed circuit board, gold may be found.[68]

For the card-to-board interfaces, each gold contact was measured to assign an area, A_s. To map the area to volume we assumed a coating thickness, T_s, based on market survey data and information on contact reliability as a function of the number of expected mating cycles (i.e., the number of times components are connected and disconnected). For this estimate, we approximated a coating thickness of 0.76 μm based on parts requiring a higher number of mating cycles (10,000), such as USB ports.[69] With this established volume of gold, the total quantity of gold was calculated using its density as shown in equation 5.

Gold in connectors

Physical description Number of contacts * Volume of contacts * Gold density

Equation $$Au_{connectors} = \rho_{Au} \sum_{n=1}^{s} N_n * A_{sn} * T_{sn} \qquad Eqn. 5$$

Where s is the total number of connectors, N is the number of contacts per connector, A_s is the area of the contacts (in mm^2), T_s is the thickness of the contacts (in mm) and ρ_{Au} is the density of gold (in g/mm^3).

The mass of gold in bonding wires is estimated from the number of IC to package interconnections required, N_I, the length of those connections (described below), and the area of the wire, $\pi*(d/2)^2$. The number of interconnections is estimated directly as the number of IO pins reported for the IC in the teardown reports. The length of the wire was estimated based on the distance between the outer edge of the die and the IO pins. This gap was calculated by subtracting the square root of the chip area, $(A * R_H)$ from the length of the die, L_I, as shown below in equation 6. A wire diameter, d, of 15µm is used, typical for the fine pitch chips employed in ICT products. This is shown in equation 6.

Gold in bonding wire

Physical description Volume of Bonding Wire * Number of Pins * Density of Gold

Equation $$Au_{wire} = \pi * \left(\frac{d}{2}\right)^2 * \rho_{Au} \sum_{n=1}^{x} \left[N_{In} * \left(\frac{L_{In} - \sqrt{A * R_H}}{2} \right) \right] \qquad Eqn\ 6$$

Where x is the total number of ICs, d is the diameter of the bonding wire (in mm), L_I is the length of the IC (in mm), N_I is the number of IO pins, and ρ_{Au} is the density of gold (in g/mm^3).

Finally, on a printed circuit board, the conductor surface of the landing pad forms the critical interface between the components and the board. The primary purpose of the final finish is to create a protective coating in order to preserve solderability by preventing oxidation on the landing pad that could result in a bad joint. Several different materials and approaches may be used to create this final finish, with an estimated 12% of printed circuit boards by surface area employing electroless nickel immersion gold (ENIG).[65] However, mobile devices usually do not employ ENIG solder joints as they have been demonstrated to be less tolerant of physical shock. For this reason, a gold surface finish has only been assumed for the non-mobile products under investigation including desktops, servers and displays. For each of these a finish thickness, F, of 0.15 µm has been assumed at the upper limit of what is advised.[65] The expression is shown in equation 7.

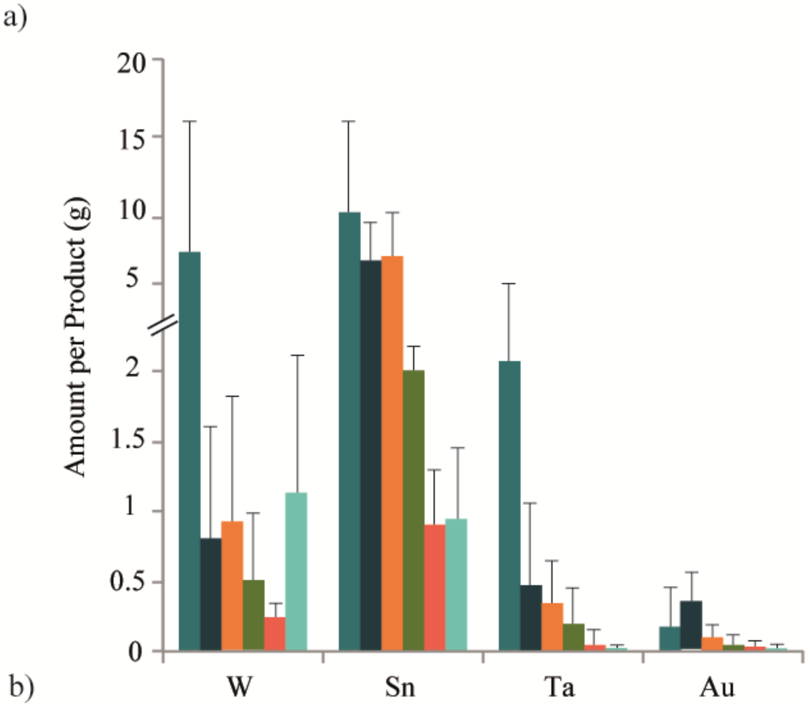
$$Au_{coating} = (\rho_{Au} * F) \sum_{n=1}^{c} A_{cn} \qquad Eqn\ 7$$

Where ρ_{Au} is the density of gold (in g/mm^3), F is the finish thickness (in µm), c is the number of components, A_c is the area of the component land pattern (in mm^2).

Further consideration was made for the scrap generated for each of these materials as a function of their processing conditions. Details of this are provided in the discussion section.

RESULTS

An estimate was made of the per product use by product type for each focal material, essentially providing a technology-based content assessment. The result of these estimates, based on an average for each of the investigated products examined, is shown in Figure 2. As mentioned previously, the aims of the modeling approach were to overestimate the total content of each material to achieve a theoretical upper bound of tungsten, tin, tantalum, and gold in ICT.



b)

	W	Sn	Ta	Au
Server	7.8	10.6	2.1	0.2
Desktop	0.8	6.7	0.4	0.3
Display	0.9	7.2	0.3	0.1
Laptop	0.5	2.01	0.2	0.04
Tablet	0.2	0.9	0.06	0.03
Smart Phone	1.1	1.0	0.02	0.02

Figure 2. Estimated amount of tungsten, tin, tantalum and gold contained in servers, desktops, displays, laptops, tablets and smart phones a) graphically and b) in table form. The maximum whisker shows one standard deviation above the mean.

The estimates show that the amount of each of these materials varies by product, as would be expected. Tungsten is high in the server relative to the other products, and the levels of tin are similar for servers, desktops and displays. Technology forecasting indicates that vibrate functions might be added to additional products (such as tablets). This might increase the amount of tungsten in ICT products. While the overall number of tantalum containing capacitors is high for mobile products, the amount of tantalum within each capacitor has been decreasing over time so this amount may be high for tantalum in the next five years.[58] The ratio of tantalum in the capacitor versus film was found to be three to one. The amount of gold estimated by this study in mobile products is lower than previous estimates, but on the same order of magnitude (see below), possibly reflecting efforts to reduce gold content in these products based on cost. The majority of gold was found to be in the connectors as opposed to bond wire or board surface finishing.

To compare these results with previous analyses we look to the papers mentioned above that assess materials content for environmental evaluation, waste recovery value or materials flow. The quantities of gold, tantalum, and tin found in a mobile phone has been previously estimated at 0.024–0.044 g, 0.1g and 0.625–1 g, respectively, for PCs the amount of gold was 0.2 g. [28, 32, 40] These per product estimates are close to what has been estimated using the model presented here. The individual product estimates were scaled by global shipments of these products, as shown in Table 1. The percentage of the market for each material across all the products investigated is also shown based on the total production in 2013 and forecasted production in 2018. For the forecasted percentages, the number of displays, tablets, and smart phones is expected to increase as well as total number of product shipments. Both factors drive up the market share for 3TG in electronics across all of the materials. Metals industry associations for tungsten, tantalum and gold estimate the use of these metals in electronics generally to be 1400, 1000, and 270 t/y, respectively.[45, 54] Given the different modeling approaches between these estimates and our calculation, the numbers are of similar magnitude. In the case of tantalum and gold the numbers represent all of electronics, while we quantify a subset of this category.

Table 1. Scaled results for each material within each product category. Scaled by 2013 global shipments. The forecasted shipments are provided below pulled from the same references. [58-61]

	2013 Global shipments (millions)	Product total W (tons)	Product total Sn (tons)	Product Total Ta (tons)	Product total Au (tons)
Server[60]	9	70	95	19	2
Desktop[61]	130	100	870	57	40
Display[58]	450	400	3240	120	50
Laptop[61]	180	90	360	35	8
Tablet[59]	195	30	170	12	6
Smart phone[58]	910	1040	870	18	14
Total mass for evaluated products (tons)		**1730**	**5600**	**260**	**120**
Total metal consumption (tons)[45, 50, 54, 55]		95000	359500	1750	4362
Estimated percent of material consumption used by IT		**2%**	**0.1%**	**15%**	**3%**

products based on global shipments (2013)				
Estimated percent of material consumption used by IT products based on forecasted shipments(2018)	**4%**	**0.3%**	**27%**	**5%**

DISCUSSION

This work developed a model to estimate the amount of tin, tantalum, tungsten, and gold in ICT products. One limitation of the approach used here stems from the potential for underestimating the material associated with scrap or chemicals used in the processing and manufacture of components. To that end, we describe the potential for scrap across 3TG. For tungsten, scrap has already been considered in the model because every metal layer was estimated to be completely coated with tungsten rather than what is contained in the vias. Tungsten was estimated using an "as consumed" approach along with a factor of three to account for wafer yields, edges and other losses. Communications with the industry have indicated that waste solder paste is between 10 and 20% because the paste used in the solder may adhere to the containers leaving residue in the cartridges holding the material (personal communication, electronics facility, February 2014). Typically this tin is not reclaimed, so adding the upper bound of 20% to the tin estimates brings that total to 1.5% of the total market. Tantalum presents a more challenging estimate as there is little information about waste in capacitor manufacturing, but communications with the industry have indicated 92% yield on tantalum in the capacitor manufacturing process. The scrap from sputtering targets would be larger. Finally, gold waste during production is assumed to be quite low given the high cost of the material. In addition, targeted recycling of process chemicals and equipment is widespread such that even if there are inefficiencies the gold would likely be recovered.

Another limitation of the current analysis is that it is not inclusive of all ICT products. In particular, the analysis excludes devices typically used in ICT enterprise systems such as routers and switches. Printers were also excluded but can comprise upwards of 10% of the total annual shipments of IT equipment. However, based on estimations not directly reported here, the total content of each of the 3TG metals has been estimated to be lower per kg of product for printers than for the devices examined in this study. For network equipment, we reason that resource consumption is lower simply because unit volumes are lower. Future work could quantify the content across a broader range of equipment.

Society should be concerned about the potential role of natural resources in funding, intensifying, and prolonging armed conflict. One tool to diminish that potential is to shift demand away from resources (or more specifically sources) of concern. To be effective, demand-based approaches must apply to a large fraction of the market. This study has estimated that consumer electronics are typically responsible for only a portion of the total use of conflict minerals (no more than 15% of global consumption for tantalum and 5% for the other 3TG metals); therefore, to be effective, market pressure must come from multiple sectors. The use of typical consumer electronic products as examples of conflict minerals in everyday use has been very successful in highlighting the conflicts that have occurred and continue to occur in DRC.

Changes to usage patterns within the electronics sector alone, however, is unlikely to drastically alter the supply chain economics for these materials.

Simple narratives around a single sector create a risk for not fully addressing the problem. For example, the electronics industry has indicated that it is possible for all consumer electronics to source their 3TG materials from conflict free regions and steps are underway to do so, including recent announcements from chipmaker, Intel.[57] There is a risk that concerned stakeholders will lose their agenda setting influence to motivate other consuming industries once consumer electronics become "conflict free". Such an outcome would certainly not be sufficient to address the underlying problems associated with these resources. [23, 58, 70] While the electronics sector (as well as relevant metal industry associations) has shown leadership in auditing, validation and traceability, this has been achieved by a group of approximately 21 companies. Dodd-Frank affects over 1000 companies and a broader coalition of industries that benefit from the use of 3TG in their products could achieve so much more in terms of creating economic incentives to generate solutions such as bringing DRC gold into the formal economy and providing microfinance to former miners who are searching for alternative economic opportunities.[16]

Based on the analysis performed in this paper, some relevant policy outcomes are discussed. Applying economic leverage and pressure within the supply chain is most effective when it is organized and concentrated. The 3TG topic suffers from low market concentration, as the potentially most recognizable players (from a consumer perspective) in the sector account for less than 10% of total industry share. Due to the diluted nature of brand owner influence on sizeable, consolidated upstream manufacturers when it comes to materials extraction and mining, the ability to impact and direct the actions of suppliers remains challenging.[71-73] Additionally, there is an increasing trend of suppliers receiving requests for the same information from different customers, leading to supplier fatigue. Partnering enables method harmonization and standardization of the multiple, overlapping survey inquiries on the supply chain. This partnering should include as broad a representation from the industry as possible so should be extended to the other uses for each material described above. In general, legislation seems to drive towards increasing transparency in supply chains that touch materials and chemical industry through legislation such as Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) and Restriction or Use of Hazardous Substances Directive in Electrical and Electronic Equipment (RoHS). These and other efforts will continue to push understanding of materials content. Finally, another potential lever that the ICT and other relevant industry sectors can leverage to influence the impact of metal content in their products would be through increased recycling, reducing the need for primary extraction at the outset.

A NOTE ON THE DEFINITION OF CONFLICT MINERALS

At the time of the writing of this article, much of the discussion of conflict minerals has been motivated by impending implementation of relevant sections of the Dodd-Frank Act. As such, at present, the language of that act has strong influence on the effective definition of the term. As was noted earlier, the relevant sections of the act define conflict minerals to include cassiterite, columbite-tantalite, wolframite (the ores from which tin, tantalum, and tungsten are won), and gold and their derivatives originating from the Democratic Republic of Congo or an adjoining country. The scope of this list, however, is not necessarily fixed. The act allows for the list to be expanded to include any mineral or its derivatives determined by the Secretary of State to be financing conflict in the DRC or an adjoining country. Furthermore, while not legally binding, there are a number of other standards and programs that define conflict minerals even more broadly. The OECD, for example, has formal guidance for due diligence on the sourcing of these minerals from “conflict-affected and high-risk” areas throughout the globe.[74] In light of this, readers are cautioned that the definition of “conflict minerals” may well evolve in the future to a scope well beyond that covered here.

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SUPPORTING INFORMATION AVAILABLE

This information is available free of charge via the internet at http://pubs.acs.org/

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