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An investigation of trends in precious metal and copper content of RAM modules in WEEE: Implications for long term recycling potential

Rhys Gareth Charles [a,*], Peter Douglas [b,c], Ingrid Liv Hallin [d], Ian Matthews [e], Gareth Liversage [f]

[a] COATED Engineering Doctorate, Room 333, Grove Building, Swansea University, Singleton Campus, Swansea SA2 8PP, UK
[b] Chemistry Group, College of Engineering, Swansea University, Singleton Park, Swansea SA2 8PP, UK
[c] School of Chemistry and Physics, University of KwaZulu-Natal, Westville Campus, Durban 4000, South Africa
[d] School of Geography, Earth and Environmental Sciences, Plymouth University, Plymouth, Devon PL4 8AA, UK
[e] College of Engineering, Swansea University, Bay Campus, Swansea SA1 8EN, UK
[f] Metech Recycling (UK) Ltd, Unit 49 Hirwaun Industrial Estate, Hirwaun, Aberdare, Mid Glamorgan CF44 9UP, UK

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ABSTRACT

Precious metal (PM) and copper content of dynamic-RAM modules placed on the market during 1991–2008 has been analysed by AAS following comminution and acid digestion. Linear regression analysis of compositional data ordered according to sample chronology was used to identify historic temporal trends in module composition resulting from changes in manufacturing practices, and to project future trends for use in more accurate assessment of future recycling potential. DRAM was found to be ‘high grade’ waste with: stable levels of gold and silver over time; 80% reduction in palladium content during 1991–2008; and 0.23 g/module/year increase in copper content with a 75% projected increase from 2008 by 2020.

The accuracy of future recycling potential projections for WEEE using current methods based on static compositional data from current devices is questionable due to likely changes in future device composition. The impact on recycling potential projections of waste laptops, smart phones, cell phones and tablets arising in Europe in 2020 resulting from a 75% increase in copper content is considered against existing projections using static compositional data. The results highlight that failing to consider temporal variations in PM content may result in significant discrepancies between projections and future recycling potential.

1. Introduction

Waste electrical and electronic equipment (WEEE) is the fastest growing waste stream on the planet (Dalrymple et al., 2007; Ongondo et al., 2011) with global generation reaching 41.8 million tonnes/year in 2014 (UNU-ISP, 2015), increasing by 3–5% annually (Menikpura et al., 2014). It accounts for 5% of all municipal solid waste (Widmer et al., 2005). Within the EU, 9.1 million tonnes was generated in 2014 with a projected increase to 12 million tonnes/year by 2020 (Goosey, 2009).

WEEE is a heterogeneous combination of materials (Tuncuk et al., 2012), the major mass fractions being bulk metals (aluminium, copper and ferrous), plastics (Arnold et al., 2010) and glass. Individual items may contain up to 60 elements (Schluep et al., 2009) including trace amounts of strategically/economically important critical materials such as rare earth metals, indium, and platinum group metals (PGMs) (Buchert et al., 2012). Many elements are found in WEEE at higher concentrations than in their respective ores (Li et al., 2007) making WEEE a potentially significant secondary material resource. WEEE is also hazardous as it contains toxic heavy metals and halogenated flame retardants which pose risks to human health and the environment (Tsydenova and Bengtsson, 2011; Song and Li, 2014).

Abbreviations: AAS, atomic absorption spectroscopy; BATRRT, best available treatment, recovery and recycling techniques; CMs, critical materials; COG, cut-off grade; DDR, double data rate (SDRAM); DRAM, dynamic RAM; DIMMs, dual in-line memory modules; EDO, extended data output (RAM); EEE, electrical and electronic equipment; EoL, end-of-life; EPR, extended producer responsibility; FPM, fast page mode (RAM); HWRC, household waste recycling centre; IC, integrated circuit; MFA, material flow analysis; MLCCs, multi-layer ceramic capacitor; PCB, printed circuit board; PM, precious metal; PMR, material for precious metal recovery; POM, placed on the market; SDR, single data rate (SDRAM); SDRAM, synchronous DRAM; SIMMs, single in-line memory module; SMD, surface mounted device; WEEE, waste electrical and electronic equipment.

[*] Corresponding author.

E-mail addresses: 290952@swansea.ac.uk, rhys.charles@hotmail.com (R.G. Charles), p.douglas@swansea.ac.uk (P. Douglas), Ingrid.hallin@plymouth.ac.uk (I.L. Hallin), i.matthews@swansea.ac.uk (I. Matthews), gareth.liversage@metechrecycling.uk.com (G. Liversage).

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The rate at which electrical and electronic equipment (EEE) is discarded/replaced contributes to global resource depletion; a high replacement rate accelerates resources consumption and pollution (Ongondo et al., 2011; J. Li et al., 2015). Production of a single 32 MB RAM module requires 32 L of water, 1.6 kg of fossil fuels, 700 g of gasses and 72 g of other chemicals (Goosey, 2009). A 2006 UNEP report showed that at least 240 kg of fossil fuels were consumed in manufacturing a whole PC and monitor (UNEP, 2006). Recovery of materials from WEEE yields significant environmental, economic and social benefits (Bunting et al., 2006; WCED, 1987).

The EU introduced, and recently recast, the WEEE directive (EU, 2003b, 2012) and the RoHS directive (EU, 2003a, 2011), which aim to enhance the industrial ecology of the EEE industry and establish infrastructure for appropriate management of WEEE by diversion from landfill to facilities employing Best Available Treatment, Recovery and Recycling Techniques (BATRRT) (DEFRA, 2006). The WEEE directive places emphasis on the waste hierarchy, prioritising reuse and remanufacturing, and supports the 'circular economy' (MacArthur, 2012). Globally, many countries have introduced their own WEEE legislation, all of which aim to minimise the environmental impacts of WEEE and maximise its diversion from landfill (California Department of Toxic Substances Control, 2010; Ministry of Environment and Urban Development, 2012; Washington State Department of Ecology, 2010; Kuschnik, 2008; J. Li et al., 2015; METI, 2001, 2006; RoHSGuide.com, 2012; Spiegel, 2011; UNU-ISP, 2015).

In recent years, demand has risen for 'critical materials' (CMs). This has resulted in global concerns over resource security (Peck et al., 2015). In the EU, where manufacturing is heavily reliant upon imported raw materials (EC, 2010, 2014), the 'Resource Efficient Europe Flagship Initiative' is a key pillar of the Europe 2020 strategy for sustainable growth (EC, 2011a). More efficient recycling is an important component of this initiative (EC, 2011b). In the UK the Resource Security Action Plan (DEFRA and BIS, 2012) outlines national strategy to enhance resource efficiency and mitigate resource criticality by securing domestic supplies of secondary materials. Much attention has been focussed on WEEE as a secondary resource of CMs (Binnemans et al., 2013; Buchert et al., 2008, 2012; EC, 2010, 2014; Cucchiella et al., 2015; EPOW, 2011; Gasser and Aly, 2013; Hasegawa et al., 2013; Jha et al., 2013; WRAP, 2012).

Concerns have been raised over the future viability of WEEE recycling due to component miniaturisation and substitution of expensive/rare materials in EEE (Bleiwas and Kelly, 2001; Zhang and Forssberg, 1999). Data on temporal trends in precious metal (PM) and copper content is important in order to verify these concerns and help predict future recycling potential. For example, the PM content of mobile phones, which have high PM content (Oguchi et al., 2011), has been shown to increase as more functions are added (Takahashi et al., 2009). It is the purpose of the work presented in this paper to contribute to such data through the analysis of PM and copper content of PC DRAM modules placed on the market (POM) over the period 1991–2008.

2. Background

2.1. Criticality of precious metals and copper

The strategic importance of recovering PMs and copper has been well explored; PGMs have been highlighted in the EU14 and EU20 critical materials reports (EC, 2010, 2014) and recovery of silver and gold has been shown by the Resource Efficiency Knowledge Transfer Network (KTN) to be of key importance to the UK economy with gold being the most unsecure of 69 metals assessed (Morley and Eatherley, 2008). Schneider et al. have shown that PGMs have high economic resource scarcity potential (ESP) and that gold and silver have high abiotic depletion potentials (ADP) (Schneider et al., 2014). Nasser et al. have shown copper, silver and gold to score highly in criticality assessment (Nassar et al., 2012). The UK Resource Security Action Plan also identifies gold, silver and copper as unsecure or at risk (DEFRA and BIS, 2012).

2.2. Global demand

Global demand for gold in 2015 was 4,124 tonnes, approximately 20% lower than the record demand of 5,087 tonnes reached in 2013. Supply from secondary sources currently accounts for 28% of global production. EEE accounts for 6% of global gold demand (O'Connell et al., 2016a). Gold is predominantly used in EEE for contacts and in ICs (Hagelüken and Meskers, 2008).

Silver demand reached a record high of 36,406 tonnes in 2015, with supply from secondary sources accounting for 12% of global supply. EEE is the major consuming industry accounting for 21% of global demand, exceeding supply from secondary sources (O'Connell et al., 2016b). Major applications of silver in EEE include: contacts; multilayer ceramic capacitors (MLCCs); thick film chip resistors; and more recently lead-free solders on circuit boards (Hagelüken and Meskers, 2008). The photovoltaics industry also consumes a significant proportion of Ag for use in bus bars of solar cells (Dias et al., 2016).

Global palladium demand in 2015 was 294 tonnes, only 0.5 tonnes below record demand set in 2014. Supply from secondary sources is sufficient to meet 20% of global demand. EEE accounts for 13% of global demand (O'Connell et al., 2016c) with the major use being manufacture of MLCCs (Hagelüken and Meskers, 2008).

In 2015, 21.8 million tonnes of copper were produced globally with 16% supplied from secondary sources (O'Connell et al., 2016d). The electronics sector is the largest consumer of copper, accounting for ~39% of global demand (O'Connell et al., 2015). Major applications for copper in EEE include cables, wires, connectors, contacts and conductive tracks such as those on PCBs (Hagelüken and Meskers, 2008).

The large proportions of these metals consumed by the EEE industry and the significance that secondary production has in meeting global demand, emphasises the importance of efficient recovery from WEEE to offsets demand for primary resources. Significant environmental savings are achieved by recovering metals with high primary production environmental impacts (Bigum et al., 2012; Slade, 1980). For example, recovery of 70,000 tonnes of metals at Umicore Precious Metals Refining (UPMR, Hoboken, Belgium) has resulted in a saving of 1 Mt of CO_2, which is 79% of the CO_2 that would have been generated by primary production (Hagelüken and Meskers, 2008).

2.3. Financing recycling

The economic driving force for WEEE recycling has been recovery of material value >95% of which has been attributed to PMs and copper, with >80% attributed to gold alone (Fig. 1) (Sodhi and Reimer, 2001). WEEE flows through the recycling process chain in which it is collected and delivered to pre-processing facilities where items are sorted/disassembled and their components separated into distinct material streams (e.g. bulk metals, plastics, batteries, LCDs, cables, etc.) rich in specific target materials of the subsequent recovery processes to which they are sent (Chancerel et al., 2009; Cui and Forssberg, 2003). Pre-processing is carried out with manual, automated, or semi-automated processes, and PM rich output fractions (including PCBs) are directed towards pyrometallurgical and/or hydrometallurgical recovery processes.

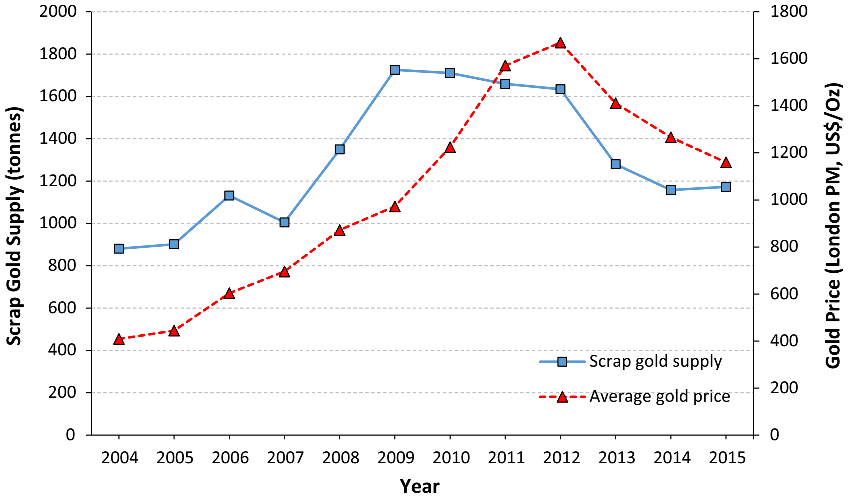

Fig. 1. Annual gold production from scrap and average gold price. Data from O'Connell et al. (2016a).

2.4. WEEE as a resource

WEEE is a secondary resource and a reserve of speciality metals (Reck and Graedel, 2012) i.e. "a concentration or occurrence of material of intrinsic economic interest in or on the Earth's crust in such form, quality and quantity that there are reasonable prospects for eventual economic extraction" (JORC, 2012). Useful analogies between primary and secondary resources have been made by others when assessing the potential of scrap materials as metal sources (Cuddington, 2008; Oguchi et al., 2011; Ongondo et al., 2013, 2015). When assessing primary resources a cut-off grade (COG) is established, below which it is not economically feasible to mine. It is possible to establish similar recycling COGs based upon levels of PMs and copper in WEEE items. These will vary between particular recycling processes and depend upon: total quantities of items available for recycling (governed by number of items POM and their lifespan); collection efficiency; recovery efficiencies of target materials; costs of recycling (including costs of labour, plant, energy, transport, and compliance with regulation); and value of recovered materials (Manhart, 2011). Some WEEE items contain gold in concentrations ~200 times greater than in typical gold ores e.g. gold can be 0.04 wt% (400 g/t) of a mobile phone, 200 times greater than typical gold ore – 1–3 g/t, and 14 times higher than the highest known grade deposit – 28 g/t (Tau Tona, RSA) (Takahashi et al., 2009). The cost of recycling an item and the ability to effectively recover precious metals is also significantly influenced by product design.

2.4.1. Collection

Under the WEEE directive, imposed extended producer responsibility (EPR) and collection, recycling and recovery targets, have generated a collection infrastructure in Europe. EPR based reverse logistics systems are also operated around the world, with examples in Australia, Japan, Taiwan, South Korea and many of the US states, with numerous other countries such as India exploring how EPR may be incorporated into current regulation (Dempsey and McIntyre, 2009; Garlapati, 2016). Despite this, global collection rates remain low. Much of the world is yet to develop sufficient reverse logistics systems and recycling infrastructure, and even those countries which have done so see low collection rates due to illegal exports, stockpiling and loss of items in residual waste streams (Bigum et al., 2013). It is estimated that 80% of global WEEE is exported to Asia with significant further quantities being exported to African locations where BATRRT is not employed (Ongondo et al., 2011). Much of the UK's household WEEE, particularly small domestic appliances which are easily concealed within household residual waste streams, is still landfilled despite infrastructure for collection. It was estimated that 154,372 tonnes of WEEE was disposed of as residual waste in England during the 2010/11 financial year (Bridgewater, 2012), a quantity equivalent to 32% of WEEE collected throughout the UK during that period (Environment Agency, 2015). Currently the UK WEEE collection rate is 34.6% and the collection rate for category 3 WEEE: IT & telecoms equipment (which has highest potential of all WEEE as a PM source) is only 21.2% (Environment Agency, 2015). The majority of WEEE generated is still unaccounted for.

2.4.2. Pre-processing

Automated processes involving shredding of items with PCBs inside cause PMs to be dispersed. Separation of fractions then results in significant PM losses by unintended co-separation (Chancerel et al., 2009; Chancerel and Rotter, 2009; Hagelüken, 2006; Morley and Eatherley, 2008). Material Flow Analysis (MFA) studies have shown bottom-line recovery efficiencies of gold and palladium from ICT equipment to be as low as 25% when such processes are employed. Manual isolation of PCBs achieves the highest bottom-line recovery rates (~95% for gold) (Hagelüken and Meskers, 2013). Manual pre-processing is costly, with high COGs in comparison to automated pre-processing, but efficient bottom-line recovery of PMs from high grade items justifies the costs, which are greatly affected by product design and the resulting ease of disassembly (Hagelüken and Corti, 2010).

When items are difficult to disassemble due to poor design for End-of-Life (EoL), or when low recoverable value prohibits manual isolation (i.e. item grade <COG), semi-automated approaches using coarse crushing to break open housings and hand picking of PCBs has given intermediate pre-processing recovery rates for PMs (~70% for gold) at lower cost than manual processes (Hagelüken and Meskers, 2013). As a consequence of the concentration-yield function (Hagelüken, 2006), COGs for WEEE and PM recovery rates are inversely related to the degree of automation used in pre-processing. Therefore, bottom-line recovery efficiencies, COGs, and the viability of WEEE as a PM source, are all largely determined by the pre-processing method.

2.4.3. Recovery

Modern pyrometallurgical and hydrometallurgical refineries achieve >95% recovery of gold, and are capable of recovering numerous metals in addition to PMs and copper. Because of high refining efficiencies the recovery process is generally less significant than the method of pre-processing in determining the recycling viability of WEEE (Cui and Zhang, 2008; Tuncuk et al., 2012; Hagelüken and Meskers, 2013).

2.5. Market values of metals

Metal recycling is highly dependent upon the vagaries of metal values as shown by the dramatic reduction in quantities of gold supplied from secondary sources in 2013 and 2014 (Fig. 1), which mirrors annual reductions in the price of gold since 2012 (O'Connell et al., 2016a). As metal prices fall, COGs for recycling rise and the viability of PM recovery from WEEE is reduced.

2.6. Waste management strategies

The recycling of circuit boards involves long and complex logistics systems. Take the UK as an example. WEEE is collected via numerous mechanisms: from consumers at household waste recycling centres (HWRCs) and through distributor takeback schemes (DTSs), and from businesses by waste management and reverse logistics organizations. WEEE then finds its way to authorized approved treatment facilities (AATFs). Here PCBs are isolated from items and segregated according to grade. These are sold abroad to refiners operating pyrometallurgical and/or hydrometallurgical recovery processes such as Umicore and Boliden in Europe and Mitsubishi Metals in Asia (Bigum et al., 2012; Cui and Zhang, 2008). Often PCBs are sold to brokers who amass sufficient quantities to ship to refiners. In order to maintained economic viability of recycling, sufficient value generated from the sale of recovered metals must filter back through the value chain to finance costs incurred at each stage of recycling and during transport between them.

2.7. Future outlook for waste management and viability of WEEE recycling

As global WEEE volumes increase, appropriate waste management will be crucial for mitigating environmental impacts, materials criticality and enhancing resource efficiency. The continued viability of WEEE recycling is crucial to global sustainability and management of the growing 'WEEE problem'. This is determined to a large extend by the recycling potential of future WEEE i.e. "that potential e-waste recycling revenues exceed costs of collection, transportation and processing" (Zeng et al., 2016), and that grade of items continue to remain above COGs for recycling. Doubts over the future viability of WEEE recycling have been raised. Reductions in the value of precious metals present in WEEE coupled with rising overheads for recycling raises COGs for recycling processes. This issue was highlighted as early as 2001 (Bleiwas and Kelly, 2001). Since 2013 costs of recycling have risen by 1.9% annually, a trend which is expected to continue until 2019 (Recycling Today, 2016). The rising costs of electronics recycling via BATTRT has led to much WEEE being stockpiled, or exported to regions where recycling and recovery of PMs is conducted in a manner resulting in low recovery yields and harm to the environment & human health (Risen, 2016; Sepúlveda et al., 2010; Terazono et al., 2016). This has effectively reduced the size of the 'reserve' of metals present in WEEE, as a smaller proportion of WEEE generated (i.e. the total secondary resource) can be diverted to BATRRT processes. Additionally, the trend in the electronics industry towards miniaturisation and 'thrifting' has reduced the amount of PMs in items, affecting the grade of items and recycling revenues (Risen, 2016).

Despite rising recycling costs and diminishing metal content in individual items, volumes of WEEE are increasing rapidly due to greater market penetration of electronics, technological innovation and decreasing product lifetimes. The size of the potential secondary resource is therefore increasing and higher collection rates enabled by statutory recycling targets imposed by the growing global e-waste legislation will effectively increase the quantity of WEEE made available for recycling. When larger quantities of WEEE are available, processing of lower grade materials becomes viable (Oguchi et al., 2011). Resulting economies of scale will compensate for reductions in grade of individual items to some extent, although uncertainty exists over how collection costs may scale with collection rate (Magalini et al., 2016). Recyclability, i.e. the probability of an item being recycled, taking into account the recycling difficulty of its material components in physical treatment and chemical recovery processes, (Zeng and Li, 2016) will also improve in the future as a result of superior product design for EoL (J. Li et al., 2015; Stevels et al., 2013) driven by the proliferation of EPR (particularly IPR), restrictions on hazardous substances, and proliferation of product eco-labels (Williams, 2012). The effect will be lower recycling costs for items and greater recovery efficiencies of target metals.

Obtaining information related to future recycling potential of WEEE is essential for the development of legislation and new recycling capacity necessary to deal with ever growing volumes of WEEE (Yang et al., 2008). This information is acquired through three types of analyses: projections of mass flow of products over time; product lifespans; and material composition of items (Cucchiella et al., 2016; Yu et al., 2010; Zeng et al., 2016). This enables quantities of WEEE items arising over time to be estimated and the material content and potential recycling revenues to be established. Over ten methods and models have been used to estimate WEEE generation in previous studies (B. Li et al., 2015), the method of choice depending primarily upon the availability and quality of data (B. Li et al., 2015). In addition to these considerations, components within items should also be investigated as these vary with change in technology (Kalmykova et al., 2015).

Zeng et al. projected the recycling potential of 'new' WEEE arising in China for the period 2010–2030 using MFA analysis and Weibull function of lifespan model (Zeng et al., 2016). Based on previous projections of WEEE arising in Europe, Cucchiella et al. predicted the potential revenues from WEEE recycling in Europe in 2020 (Cucchiella et al., 2016). The issue with such projections is that the compositional data of items applied to the mass flow projections are based on current and historical compositional data. Insufficient data on temporal changes in metal content of devices is available to allow changes in PM and Cu content over time to be applied to projections. Both studies indicate a majority of the recoverable value from WEEE into the future will to be present as Cu and PMs, however without data highlighting temporal trends in Cu and PM content, it is difficult to take account of the potential effect of miniaturisation and 'thrifting' in manufacturing. It is the purpose of this paper to present data on historical temporal changes in PM and Cu content of DRAM modules, and projections for future recycling potential of PCBs based on observed trends in RAM.

Precious metals are predominantly found in the PCBs of items which are constructed from common surface mount device (SMD) components. Dynamic RAM (DRAM) modules are essential PCB based components of PCs (Fig. 2). To investigate historical changes in PM and Cu content of PC DRAM modules, samples have been gathered from Metech Recycling (UK) Ltd., dated, and analysed. DRAM was chosen for study as these devices are relatively simple PCBs, containing only those few components which represent the main applications of PMs and Cu in PCBs in general i.e. ICs, chip resistors, MLCCs, copper tracks and edge contacts. In each

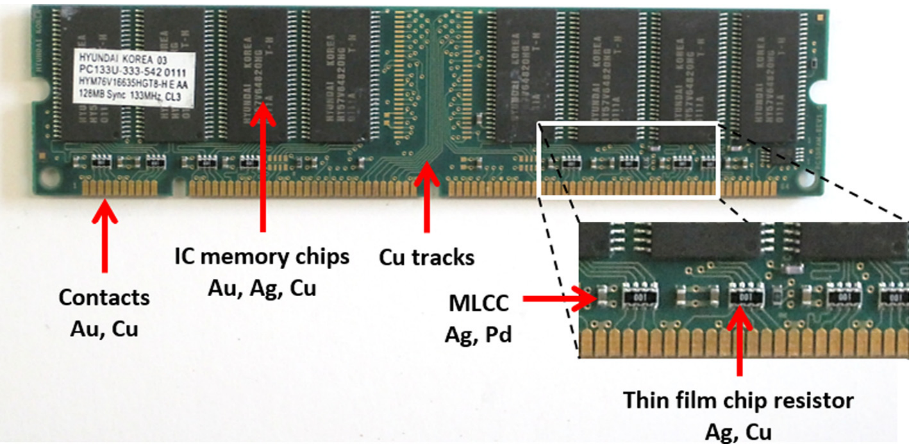

Fig. 2. Anatomy of PC DRAM module and locations of precious metals and copper.

of these categories of SMD component, only a single type is present. This simplifies the task of rationalizing observable temporal trends in metal content in terms of changes to common PCB components over time. This task would be difficult for more complex PCBs such as motherboards and mobile phone PCBs with dozens of different kinds of SMD components. Historical temporal trends observed in DRAM, once rationalised against changes in PCB design, can then be used to make predictions on temporal changes in PM and Cu content of items into the future.

This paper: presents to the best of the authors' knowledge the first published compositional data for DRAM modules; provides temporal data on PM and Cu content in PCBs; provides projections on future changes to PM and Cu content of PCBs; and applies temporal changes to compositional data and product mass flow data to create a picture of future recycling potential which takes account of the potential future impact of miniaturisation and 'thrifting' trends in manufacturing; and highlights the value of inclusion of temporal trend data in projections of recycling potential.

3. Materials and methods

A range of PC DRAM samples, covering memory sizes and RAM types from 4 MB FPM single in-line memory modules (SIMMs) through to 2 GB DDR3 dual in-line memory modules (DIMMs), were identified and gathered for analysis (Table 1). An investigation of historical data on the size of memory available in PCs POM (Polsson, 2013), and the date of introduction of different RAM technologies (Karbo, 2012; Mueller, 2011; Ögren et al., 2016) was made in order to create a timeline of the samples (Fig. 3).

PCB dimensions of SIMM samples (**1**–**3**) are 108.5 × 26.0 mm while DIMM sample (**4**–**15**) PCBs are 133.5 × 31.5 mm. Sample masses range from 13.1 to 21.9 g with an average mass of 17.5 g.

To compare surface areas of edge contacts in samples, pairs of modules for comparison were photographed side by side. Using Adobe Photoshop, the areas of the edge contacts in the images can be highlighted and the number of pixels in these areas counted using the pixel counting feature in the software. Comparison of the number of pixels within the areas of contacts in the images of each sample enables a comparison of their surface areas to be made.

To analyse PM and copper content of the modules, a process of comminution followed by acid leaching of metals from powder samples and subsequent analysis of leachate using atomic absorption spectroscopy (AAS) was conducted.

Powder samples of all modules for digestion and analysis were prepared by removing all ICs and cutting the PCBs into pieces approximately 25 mm^2 in size. ICs and PCB fragments were then recombined and cooled in liquid nitrogen before grinding to give a reasonably homogenised powder (Ernst et al., 2003) of particle size <0.2 mm, sufficient for complete leaching of PMs and copper from samples (Oguchi et al., 2011; Ogunniyi et al., 2009; Veit et al., 2006; Yamane et al., 2011). Grinding was carried out using an IKA A10 cutting mill with tungsten carbide blade suitable for grinding of PCBs for effective leaching (Zhang and Forssberg, 1999). 0.1 g samples of the homogenous powder were taken and subjected to oxidative acid digestion. A minimum of 3 powder samples were analysed for each module and results were taken as the average of the 3 samples. For gold and copper analysis aqua regia (HCl/HNO_3 3:1 v/v) digestion was used, nitric acid digestion was used for palladium and silver analysis. Digestions were carried out by boiling samples in acids for 3 h while maintaining an acid volume/sample mass ratio of 40 ml/g. Such conditions have been shown to be effective for the quantitative determination of precious metals and copper content of PCBs (Charles, 2012; Park and Fray, 2009). HCl (31.5–33.0%) and HNO_3 (69–72%) were CertiFied AR (analytical reagent) obtained from Fisher Chemicals and were used as received. Atomic absorption spectroscopic analysis was carried out using a Perkin Elmer AAnalyst 200 instrument. Standard TraceCERT Au, Ag, Pd and Cu solutions for calibration were obtained from Sigma Aldrich and used as received.

Market values used for metals are as follows: Au: USD 1,221.50/Oz (LBMA 19/2/16 AM); Ag: USD 15.37/Oz (LBMA 19/2/16); Pd: USD 513.00/Oz (LBMA 18/2/16 AM); Cu: USD 4,575.00/tonne (LME 18/2/16 cash buyer) except in recycling potential projections where stated values are used for consistency with previous studies (Table 5).

Projections and confidence intervals for future quantities of metals in waste DRAM were obtained by linear regression analysis carried out in python (Hunter, 2007; Pérez and Granger, 2007; van der Walt et al., 2011).

4. Results and discussion

Analyses are given in Table 2. For comparison, Table 3 shows literature values for precious metal and copper content of general PC PCBs.

4.1. Gold

The gold content of the EDO SIMMs (**2** and **3**) is low (Fig. 4) due to the use of tin rather than gold in edge contacts. The gold content of the other modules varies from 480 to 1320 ppm, a factor of 2.6.

Table 1
DRAM modules selected for analysis.

Sample	Brand	Model	Memory type	Module type	Capacity (MB)	Size (mm)	Mass (g)	mass per IC[a] (g)
1	Samsung	KMM5361000G-7	FPM[b] DRAM	72-pin SIMM[g]	4	108.5 × 26.0	18.19	*0.8483*
2	Micron Technology	MEMSIM016AAWW	EDO[c] DRAM	72-pin SIMM	8	108.5 × 26.0	21.93	*0.9045*
3	Micron Technology	MT8D432M-6X	EDO DRAM	72-pin SIMM	16	108.5 × 26.0	15.09	*0.8626*
4	Discovery	DISCOVERY S/N 1212772	SDR[d] SDRAM[e]	168-pin DIMM[h] PC100	32	133.5 × 31.5	13.13	*0.5590*
5	Samsung	KMM366S823CTS-GH	SDR SDRAM	168-pin DIMM PC100	64	133.5 × 31.5	18.04	*0.5555*
6	Hyundai	HYM76V16635HGT8-H E AA	SDR SDRAM	168-pin DIMM PC133	128	133.5 × 31.5	20.30	*0.5292*
7	Infineon	HYS64V16300GU-7.5-C2	SDR SDRAM	168-pin DIMM PC133	128	133.5 × 31.5	15.55	*0.5409*
8	Samsung	M368L1716ETM-CB0	DDR[f] SDRAM	184-pin DIMM PC2100	128	133.5 × 31.5	17.61	*0.5649*
9	Micron Technology	MT9VDDT3272LAG-265C4	DDR SDRAM	184-pin DIMM PC2100	256	133.5 × 31.5	17.14	*0.6387*
10	Kingston Technology	KTH-D530/512	DDR SDRAM	184-pin DIMM PC3200	512	133.5 × 31.5	21.34	*0.5665*
11	Hynix	HYMD512646PC8J-D3 AA-C	DDR SDRAM	184-pin DIMM PC3200	1024	133.5 × 31.5	21.69	*0.5510*
12	Promos Technologies	V916764K24QAFW-E4	DDR2 SDRAM	240-pin DIMM PC2-4200	512	133.5 × 31.5	15.91	*0.2456*
13	Micron Technology	MT8HTF12864AY-667G1	DDR2 SDRAM	240-pin DIMM PC2-5300	1024	133.5 × 31.5	13.68	*0.1517*
14	Kingston Technology	kvr800d2n5k2/2g	DDR2 SDRAM	240-pin DIMM PC2-6400	2048	133.5 × 31.5	16.39	*0.1974*
15	Samsung	M378B5673FHO-CF8	DDR3 SDRAM	240-pin DIMM PC3-8500	2048	133.5 × 31.5	16.14	*0.1321*

[a] IC: integrated circuit.
[b] FPM: fast page mode.
[c] EDO: extended data output.
[d] SDR: single data rate.
[e] SDRAM: synchronous DRAM.
[f] DDR: double data rate.
[g] SIMM: single in-line memory module.
[h] DIMM: double inline memory module.

The average gold content of these modules is 18.2 mg/module (1030 ppm). This is a higher gold content than PC PCBs generally reported in the literature, except by Yamane et al. (Table 3), suggesting that RAM modules contain gold in higher concentrations than other PC PCBs such as mother boards and PCI cards.

Comparison of results for modules **2** and **3** with the rest of the samples shows that the bulk of gold in DRAM is found in the edge contacts. The results do not correlate with the number of ICs or edge contacts on modules. To the naked eye it appears that the surface areas of edge contacts on SDR, DDR, DDR2 and DDR3 modules are very similar; and measurement of contact surface areas of the DDR and DDR2 samples made from photographs using Adobe Photoshop pixel counting function shows them to be within 2% of one another.

While gold content varies significantly from module to module, for those with gold edge contacts, no general trend over time is obvious. Manufacturers have opted to increase memory using the same module size, and with it roughly the same gold contact areas, rather than maintain memory capacity and reduce the module size. Variation in gold content in DIMMs may be explained by differences in thickness or composition of the Au alloy layer of the contacts plated onto the module during manufacturing. This alloy is electroplated onto the module, and differences in the thickness of this layer may result from variation in manufacturing processes around the globe.

4.2. Palladium

Palladium content per PCB varies significantly, ranging from ~3.5 to 0.5 mg/module, and shows a marked decrease over time (Fig. 5). The average palladium content (1.5 mg/module; 86 ppm) is somewhat lower than that generally reported in the literature for other PC PCB samples (90–309 ppm, Table 3). On these PCBs, Pd is principally found in the multi-layer ceramic capacitors (MLCCs), and while there is no correlation with the number of MLCCs per board (which has generally increased over time), the size of individual MLCCs has been reduced significantly over time. Capacitance improves with smaller units which results in a techni-

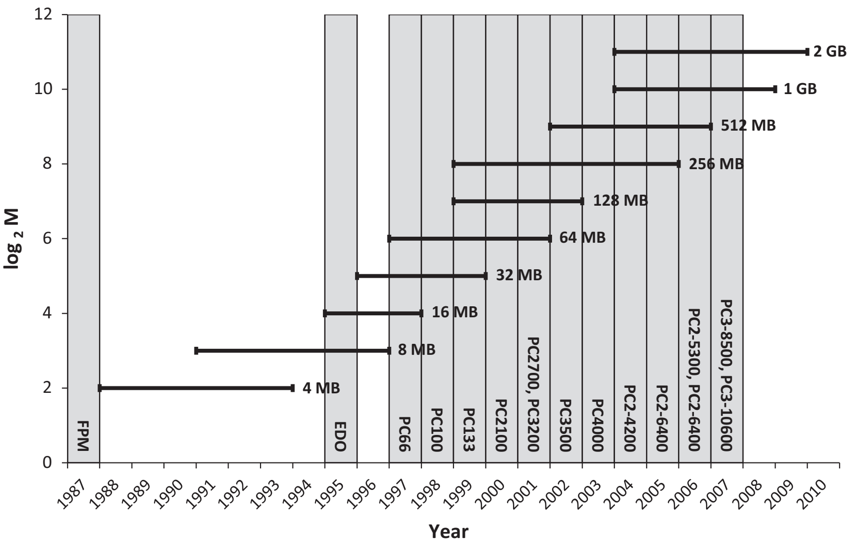

Fig. 3. Timeline of DRAM technologies in PCs POM. **M** is the module memory capacity (MB); the vertical blocks (▭) show the year of introduction of RAM type (data from Karbo, 2012; Mueller, 2011; Ögren et al., 2016). The horizontal lines show the period when PCs POM were available with memory capacity **M** (data from Polsson, 2013).

Table 2
Precious metal and copper content of PC DRAM samples **1**–**15**[a] (errors given as ranges for triplicate analyses).

Sample	Contacts	No. of		Gold		Palladium[c]		Silver		Copper	
		ICs	MLCCs	mg	ppm	mg	ppm	mg	ppm	g	ppm × 10^3
1	Gold	12	12	20.8 (±0.5)	*1144* *(±26)*	3.43 (±0.03)	*189* *(±2)*	133 (±5)	*7321* *(±281)*	3.8 (±0.2)	*207* *(±10)*
2	Tin	16	16	7.2 (±0.3)	*327* *(±12)*	3.2 (±0.6)	*150* *(±30)*	62 (±3)	*2841* *(±136)*	4.8 (±0.2)	*218* *(±10)*
3	Tin	8	8	3.8[b] (±0.3)	*251*[b] *(±17)*	1.9[d] (±0.1)	*124*[d] *(±8)*	54 (±1)	*3567* *(±91)*	1.77 (±0.09)	*117* *(±6)*
4	Gold	4	15	10.5 (±0.2)	*484* *(±10)*	1.49 (±0.03)	*114* *(±3)*	7.4 (±0.3)	*562* *(±20)*	2.67 (±0.03)	*203* *(±2)*
5	Gold	8	39	17.8 (±0.1)	*1099* *(±7)*	2.1[e] (±0.2)	*118*[e] *(±11)*	24.0 (±0.7)	*1329* *(37)*	2.9 (±0.2)	*162* *(±10)*
6	Gold	16	34	26.8 (±0.6)	*1319* *(±27)*	2.1 (±0.1)	*103* *(±5)*	25 (±1)	*1251* *(±56)*	2.36 (±0.06)	*116* *(±3)*
7	Gold	8	16	17.5 (±0.4)	*1127* *(±28)*	1.6 (±0.1)	*102* *(±8)*	13.5 (±0.5)	*767* *(±26)*	2.13 (±0.02)	*137* *(±2)*
8	Gold	8	49	20.8 (±0.3)	*1179* *(±19)*	1.69 (±0.08)	*96* *(±5)*	14.5 (±0.7)	*822* *(±42)*	3.8 (±0.07)	*216* *(±4)*
9	Gold	8	49	18.2 (±0.5)	*1064* *(±32)*	1.0[f] (±0.1)	*57*[f] *(±7)*	124 (±5)	*7232* *(±300)*	2.2 (±0.1)	*126* *(±7)*
10	Gold	16	42	16.8 (±0.5)	*786* *(±22)*	1.3 (±0.07)	*59* *(±3)*	27.5 (±0.6)	*1290* *(±28)*	2.95 (±0.04)	*138* *(±2)*
11	Gold	16	39	23.4 (±0.7)	*1078* *(±31)*	1.0[g] (±0.2)	*44*[g] *(±9)*	33 (±1)	*1507* *(±68)*	3.3 (±0.2)	*152* *(±9)*
12	Gold	8	39	15.6 (±0.3)	*980* *(±19)*	0.59 (±0.04)	*37* *(±2)*	15.6 (±0.7)	*979* *(±41)*	5.0 (±0.2)	*313* *(±15)*
13	Gold	8	27	13.2 (±0.2)	*968* *(±17)*	0.60 (±0.03)	*44* *(±2)*	16.3 (±0.4)	*1195* *(±30)*	3.2 (±0.1)	*233* *(±9)*
14	Gold	16	47	18.0 (±0.6)	*1098* *(±36)*	0.399 (±0.004)	*24.32* *(±0.05)*	20.5 (±0.2)	*1248* *(±13)*	5.08 (±0.04)	*310* *(±2)*
15	Gold	16	114	17.8 (±0.1)	*1083* *(±7)*	0.58 (±0.01)	*35.7* *(±0.4)*	19.5 (±0.6)	*1208* *(±35)*	4.76 (±0.04)	*295* *(±2)*
Average composition		All samples (**1**–**15**)		16.5	*932*	1.5	*86*	39	*2208*	3.4	*196*
		DIMMs (**4**–**15**)		18.0	*1022*	1.2	*70*	28	*1616*	3.4	*200*

[a] Sample to sample variation is generally 0.2–5.0% except where indicated.
[b] Sample to sample variation is 6.6%.
[c] Sample to sample variation where specified is >5.0% due to Pd levels in leachates close to the detection limit of AAS instrument.
[d] Sample to sample variation of 19%.
[e] Sample to sample variation 9%.
[f] Sample to sample variation of 12%.
[g] Sample to sample variation of 20%.

cal advantage from miniaturisation as well as cost savings for producers. The same is true for thinner layers of Pd in devices which has enabled manufacturers to achieve additional cost savings by reducing the thickness of the internal electrode plates reducing Pd content further. In the early 1990s 100%Pd was favoured as the inner electrode material of MLCCs. But since then, AgPd alloys

Table 3
Literature values for precious metal and copper content of PC PCBs.

Source	Metal content (ppm)				Model year
	Au	Ag	Pd	Cu	
Oguchi et al. (2011)	220	570	110	210×10^3	Na
	120	680	160	160×10^3	Na average of 8 kinds of PCB
	270	760		260×10^3	1985
	270	510		340×10^3	1989
	450	590	150	300×10^3	1994
	300	400		170×10^3	1985
	130	230		200×10^3	1989
	140			140×10^3	1994
Chancerel et al. (2009)	81	905			Unavailable
	250	1000	110		Unavailable
	230	1000	90		Unavailable
	156	775	99		Unavailable
	300	600			Unavailable
	600	700	100		Unavailable
Tuncuk et al. (2012)	250	1000	110	200×10^3	Unavailable
	86	694	309	185×10^3	Unavailable
Yamane et al. (2011)	1300	1600		202×10^3	Analysis of 10 g sample from large batch of various models
Cui and Zhang (2008)	566	639	124	143×10^3	Unavailable
	250	1000	110	200×10^3	Unavailable

Table 4
Estimated quantities of precious metals and copper in globally generated waste DIMMs in PCs POM 2013, their values and proportions of global demand, demand from the EEE sector, and global secondary production each represents (calculated from average metal contents of samples **4**–**15**, data provided in O'Connell et al., 2015, 2016a–d; Statista, 2015, and metal prices February 2016).

	Au	Ag	Pd	Cu	Total value
DIMM average composition	18.0 mg	28.4 mg	1.2 mg	3.4 g	
Total metal available in DRAM of PCs sold in 2013 (tonnes)	2.46	3.88	0.16	465	
Market value of metals (million USD)	96.6	1.9	2.7	2.1	103.4
Value fraction	93.5%	1.9%	2.7%	2.1%	
As % of global demand	0.06%	0.01%	0.06%	0.002%	
As % of demand from EEE sector	0.21%	0.05%	0.44%	0.006%	
As % of global secondary production	0.97%	0.09%	0.28%	0.013%	

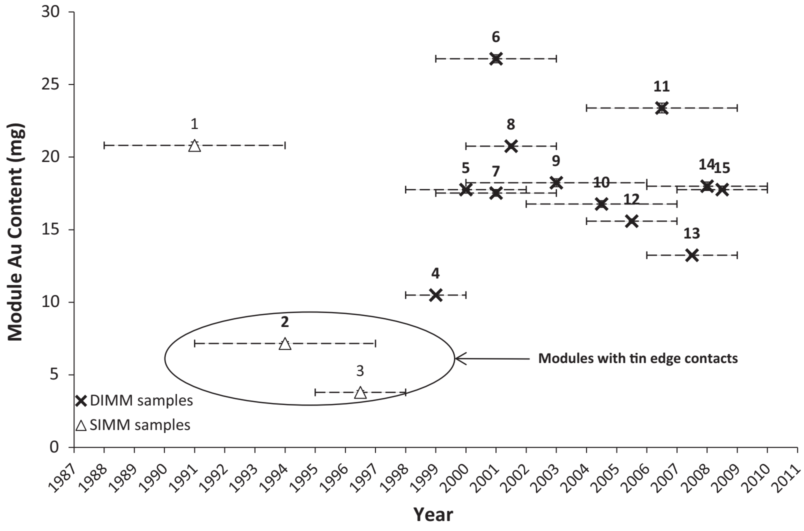

Fig. 4. Gold content of PC DRAM modules over time. The dashed lines represent best estimates of time period in which modules were on the market (Mueller, 2011; Polsson, 2013). Modules **2** and **3**, have tin rather than gold edge contacts.

of decreasing Pd content have been developed. By 2004 MLCCs using 2%Pd alloy were in development. A minimum Pd content of the electrode alloy has now been reached as 100% silver alloys do not perform well due to technical and structural limitations (Cross, 2004). Because of this, a similar decrease in palladium content over time will almost certainly be seen in other PC components and PCB based devices in which MLCCs have been used.

4.3. Platinum

No platinum was detected in any of the samples, which, using our detection limit of 60 µg/L for platinum in solution, puts the quantity of platinum in samples at <6 µg per module (<0.5 ppm). This is unsurprising since platinum is used in PC HDD platters rather than PCBs.

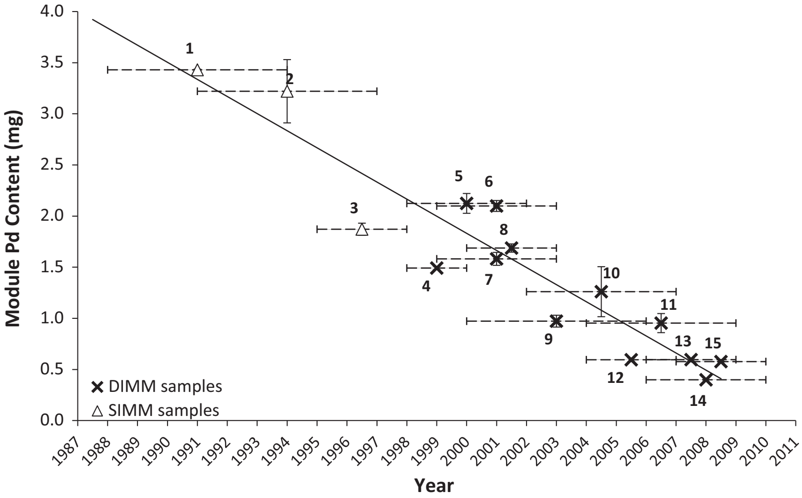

Fig. 5. Palladium content of PC DRAM modules over time. The dashed lines represent best estimates of time period in which modules were on the market (Mueller, 2011; Polsson, 2013); the solid line shows the temporal trend in Pd content.

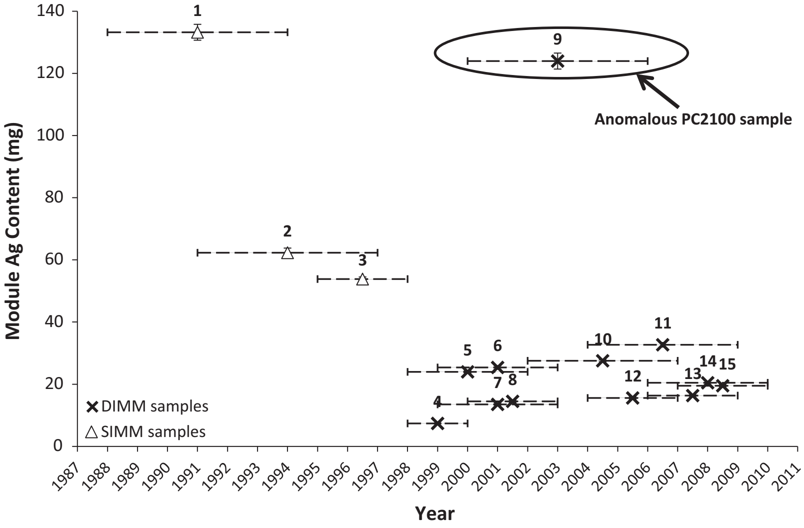

Fig. 6. Silver content of PC DRAM samples over time. The dashed lines represent best estimate of time period in which modules were on the market (Mueller, 2011; Polsson, 2013).

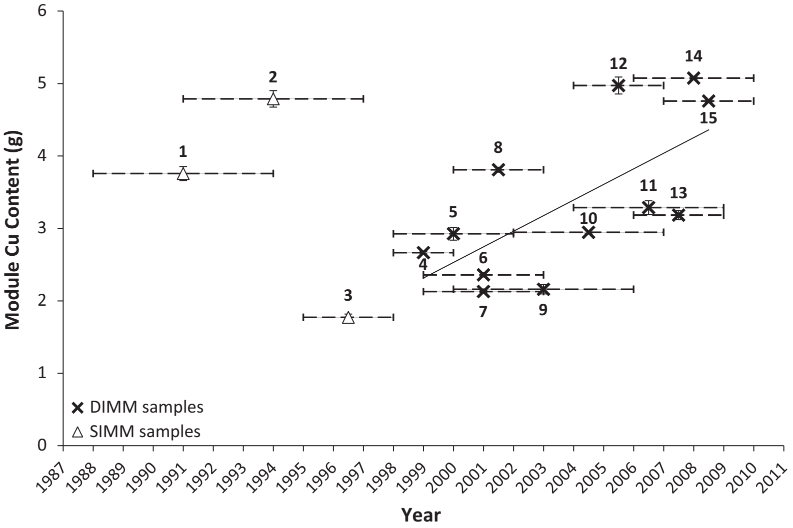

Fig. 7. Copper content of PC DRAM samples over time. The dashed lines represent best estimate of time period in which modules were on the market (Mueller, 2011; Polsson, 2013); solid line shows the temporal trend in Cu content in DIMMs.

4.4. Silver

Silver content of modules varies quite widely from ~10 to 130 mg/module. In general SIMMs (samples **1**–**3**) contained significantly higher levels of silver (~50–130 mg) than DIMMs (typically <40 mg) (Fig. 6) with the exception of the 256 MB PC2100 DIMM (sample **9**), which has a very high silver content, a result confirmed by repeat analyses. SIMMs contain significantly higher concentrations of silver than any of the PC PCB samples reported in the literature (Table 3). Such modules however, have not been utilised in PCs since the introduction of DIMMs (c. 1997) and are now infrequently found in the waste stream. With the exception of sample **9**, DIMMs contain comparable levels of silver to PC PCBs reported by others (Table 3). Excluding sample **9**, the silver content of DIMMs is low, ~10–40 mg/module, with no trend over time.

4.5. Copper

Copper content ranges from 1.8 to 5.1 g/module (Fig. 7). With an average copper content of ~200 × 10^3 ppm, samples exhibit comparable copper content to PC PCBs reported in the literature (Table 5). Taken as a whole, no general trend in copper content of RAM samples is seen. However, if we consider DIMMs alone (Fig. 7) copper content has generally increased over the years.

4.6. Trends in inherent value of RAM modules

Before discussing the trends in value of RAM modules it is necessary to identify the following two caveats: (1) our analyses do not cover every module used over the time period studied, and (2) we do not have data on the numbers of each individual module produced, or found in the waste stream, which would be necessary to provide a weighted average analysis.

Table 5
Projections of recycling potential of various WEEE items generated in Europe in 2020 (based on data from Cucchiella et al., 2015).

	Avg. value Mar-Aug 2014 (€/kg)	Item					Total metal content			
		LCD notebooks	LED notebooks	Smart phones	Cell phones	Tablets	Mass (t)	% of global demand	% of demand from EEE	% of secondary production
Au	34,070	0.22	0.22	0.038	0.024	0.044				
Ag	23,214	0.25	0.25	0.244	1	0.005				
Pd	514	0.04	0.04	0.015	0.009	0.008				
Cu	5.2	135	135	14	26	27				
Item weight (kg)		3.5	3.5	0.12	0.08	0.5				
2014 mass (kt)		80	22	19	11.5	5.2				
2020 mass (kt)		97	45	39	52	10				
<u>*2020 Scenario 1*</u>										
Au										
Content (t)		6.1	2.8	12.4	15.6	0.9	37.8	0.9%	3.2%	14.9%
Value (€ million)		208	96	421	531	30				
Value fraction		56%	56%	19%	3%	93%				
Ag										
Content (t)		6.9	3.2	79	650	0.1	740	2%	10%	16%
Value (€ million)		161	75	1841	15,089	2				
Value fraction		44%	44%	81%	97%	7%				
Pd										
Content (t)		1.1	0.5	4.9	5.85	0.16	12.5	4%	33%	21%
Value (€ million)		0.6	0.3	3	3	0.08				
Value fraction		0.2%	0.2%	0.1%	0.02%	0.3%				
Cu										
Content (t)		3741	1736	4550	16,900	540	27.4	0.1%	0.3%	0.8%
Value (€ million)		19	9	24	88	2.81	67			
Value fraction		5%	5%	1%	0.6%	8%				
Total value (€ million)		389	180	2288	15,711	35				
<u>*2020 Scenario 2*</u>										
Au										
Content (t)		6.1	2.8	12.4	15.6	0.9	37.8	0.9%	3.2%	14.9%
Value (€ million)		208	96	421	531	30				
Value fraction		52%	52%	18%	3%	80%				
Ag										
Content (t)		6.9	3.2	79	650	0.1	740	2%	10%	16%
Value (€ million)		161	75	1841	15,089	2				
Value fraction		40%	40%	80%	96%	6%				
Pd										
Content (t)		1.1	0.5	4.9	5.85	0.16	12.5	0.1%	0.3%	0.8%
Value (€ million)		0.6	0.3	3	3	0.08				
Value fraction		0.1%	0.1%	0.1%	0.02%	0.2%				
Cu										
Content (t)		6548	3037	7963	29,575	945	48.0	0.2%	0.6%	1.4%
Value (€ million)		34	16	41	154	5	68			
Value fraction		8%	8%	2%	1%	13%				
Total value (€ million)		403	187	2306	15,777	37				
% increase		4%	4%	1%	0.4%	6%				

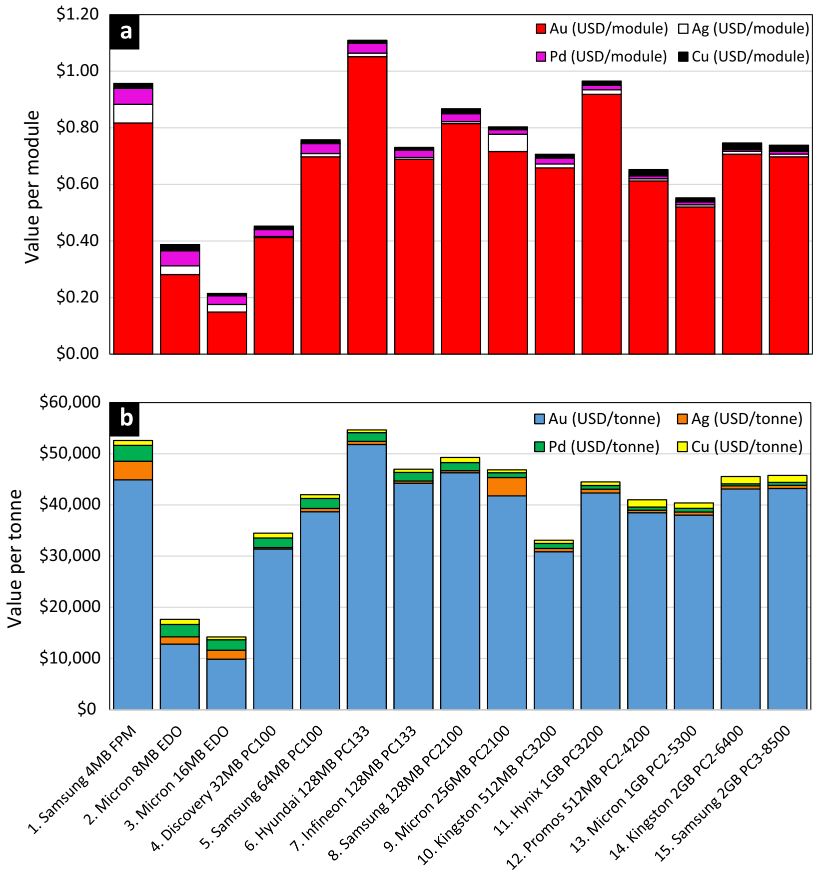

Fig. 8. Inherent value of DRAM samples, (a) per module and (b) per tonne, showing value contributions of PMs and copper.

While recognising these two factors we can make the following general comments on the trends in value of RAM modules in the waste stream. The value of individual samples per module and per tonne, showing value contributions of PMs and copper, are given in Fig. 8. Values range from USD 0.23/g to USD 1.11/g. The two lowest value modules are EDO samples with tin contacts. The more modern DIMM samples (**4**–**15**) vary in value by a factor of 2.4 from USD 0.46/g to USD 1.11/g, with average value exhibited across all DIMM samples of USD 0.76/g. Gold represents the majority of inherent value in DRAM modules; 85–95% for the more modern DIMMs (**4**–**15**). Over the time period represented by the samples there is a small increase in the value fraction of copper and a decrease in the value fraction of palladium. Over time, values and grades of modules have remained relatively stable since the introduction of DIMMs and the elimination of tin edge contacts from module designs. As SIMMs have not been included in PCs since 1997, they no longer represent a significant portion of DRAM in the waste stream. Therefore, the composition of waste DRAM modules generated today is more accurately represented by the average composition of DIMM samples (**4**–**15**).

The per tonne values of DRAM samples (Fig. 8) follow those for individual modules, and in general are significantly higher than those calculated from average compositional data for PC PCBs available in the literature (Table 3). Perhaps what is most important, in terms of the long term recycling viability of DRAM modules, is that the per tonne values of the most recent module types analysed, DDR2 and DD3 DIMMs (**12**–**15**), appear stable.

As an indication of the potential contribution of DIMMS to global metal supply and demand, Table 4 gives minimum estimates of total potentially recoverable metals in DRAM in PCs POM in 2013 assuming metal contents are given by the averages of those for samples 4–15 and that each of the 136.7 million PCs POM globally in 2013 contain a single DIMM (Statista, 2015).

The actual number of DRAM modules POM is likely to be higher than the number in PCs POM, as modules malfunction and are replaced and PCs are upgraded. Some PCs POM contain two modules, so data in Table 4 are probably minimum values. It should also be noted, that the quantities presented represent the size of the theoretical 'reserve' of metals in waste arising and not the quantities that will be available for recovery, due to inefficiencies in collection and pre-processing stages of recycling.

The estimated total value of metals in waste DRAM modules POM in PCs in 2013 was USD 103 million. 2.46 tonnes of gold were present, worth USD 97 million, 93.5% of total inherent value of the DRAMs. This is equivalent to 0.06% of global demand for gold, 0.21% of demand from the EEE sector and 1% of gold supplied from secondary sources that year. 3.9 tonnes of silver were present with a market value of USD 1.9 million and 1.8% of inherent value. This is equivalent to 0.01% of global demand, 0.05% of demand from the EEE sector and 0.09% of silver supplied from secondary sources. 0.16 tonnes of palladium were present with a market value of USD 2.7 million equal to 2.7% of inherent value. Palladium in DRAM is equivalent to 0.06% of global demand, 0.44% of demand from the EEE sector and 0.28% of palladium supplied from secondary sources that year. 465 tonnes, USD 2.1 million worth of copper were present in waste DRAM in PCs POM in 2013. This equates to 2.1% of inherent value, 0.002% of global demand, 0.006% of demand from the EEE sector and just 0.013% of copper supplied from secondary sources.

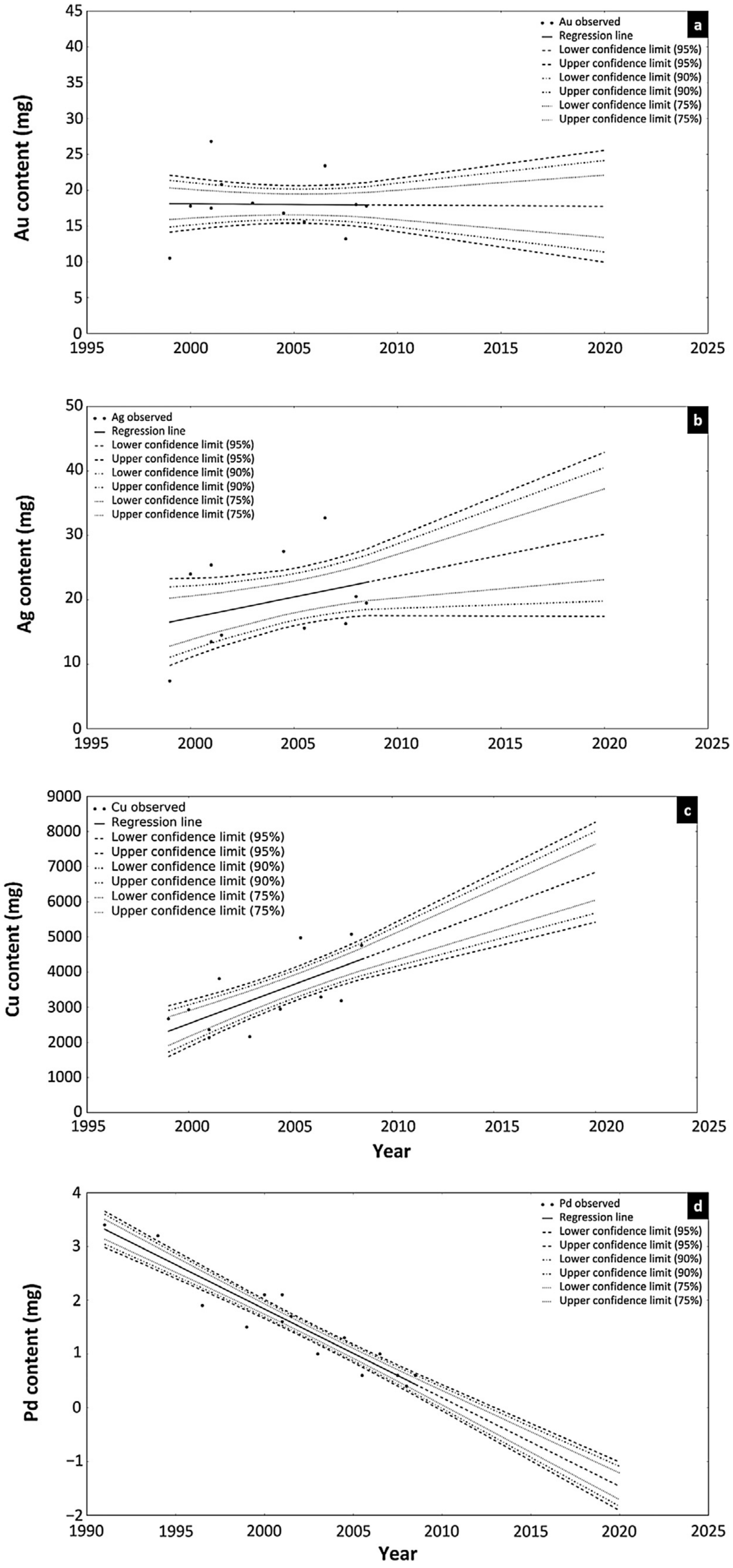

Fig. 9. Confidence intervals for projected quantities of (a) gold; (b) silver; (c) copper and (d) Pd in future waste DIMMs.

4.7. Future outlook

Fig. 9 shows projected Au, Ag, Cu and Pd content of RAM modules to 2020 from a statistical analysis of DIMM data presented here, with 95%, 90% and 75% confidence limits shown as dashed lines. Gold content is projected to remain reasonably stable, while silver content will most likely remain roughly constant or even increase somewhat. Copper content is projected to increase by ~75%. Projection of Pd content in modules shows it decreases to a very small value. Pd content in the alloy of the MLCC electrodes has already reached a minimum viable content of 2%. It is reasonable to assume that Pd content in individual MLCCs may continue to decrease until a minimum viable size of electrodes is reached, at which point Pd content of MLCCs will stabilise. If the number of MLCCs per module continues to rise as has been the case to date, then Pd content may begin to increase again, at least until technological innovation results in replacement of Pd in MLCCs, or there is outright replacement of MLCCs in modules (and other PCBs).

Global desktop PC sales are declining due to uptake of laptops, notebooks and tablets. Projections suggest a 28% reduction in global desktop PC sales over the next 5 years, from 133.9 million units in 2014 to 109.3 million units in 2019 (Statista, 2015). That said, PC sales in general are rising in the form of laptops and tablets (Yu et al., 2010). This highlights the changing nature of the waste stream driven by technological innovation and changes in consumer demands. Projections of recycling potential and recovery potential (i.e. the total amount of potentially recoverable metals in items) of future items as their volumes grow in the waste stream, such as the study by Cucchiella et al., are important (Cucchiella et al., 2015). The purpose of this 2015 study was to create a system through which the richest items in terms of material value for recovery could be targeted. The study applied available compositional data for numerous WEEE items to quantities of waste items generated in 2014, gave a projection of generated waste in 2020, and calculated the potentially recoverable value from waste in Europe in 2020. To account for potential changes to composition a sensitivity analysis was performed in which the content of particular materials in items were varied by 5%. To highlight the impact that applying observable temporal trends in metal content has on projections we have repeated this analysis for 2 different scenarios. *Scenario 1* is a base scenario and uses all data available in the Cucchiella study to quantify PMs and Cu available in selected equipment types including a static composition of items; *scenario 2* repeats the process but takes into account the temporal change in copper content observed in this study of RAM modules, and applies a 75% increase in Cu content in 2020 (Table 5). For consistency with the original study, average weekly market values for metals from the period March-August 2014 are used. Items selected for analysis are those in which Cu and PMs will be concentrated in PCBs, as the temporal data observed for RAM modules is indicative of temporal variations in PCB composition, not whole items which may contain additional quantities of copper as cables. In contrast to the original study, we have only included the values of PMs and copper in items and neglected valuable bulk materials such as plastic and aluminium to highlight the impact on the value of items where Cu and PMs in PCBs represent a considerable fraction of recoverable value.

It can be seen by comparison of the scenarios that applying the trend of increasing copper content results in, at most, a 6% increase in projected potentially recoverable value. This is primarily due to the low proportion of recoverable value represented by Cu in these items. The high dependence of recycling viability on Au in notebook computers and tablets, and silver in smart phones and cell phones, emphasises the importance of monitoring changes in manufacturing practice which may result in reductions in the content of these metals and accounting for these in future projections of recycling potential. Failing to account for such variations over time may result in a considerable mismatch between projections and future recycling potential.

5. Conclusion

Elemental analysis of PC DRAM modules placed on the market over a period of approximately 17 years has shed light on temporal trends in PM and copper content of ICT PCBs with which to assess current and future recycling potential of PC DRAM modules, and PC PCBs in general.

DRAM is of a particularly high grade compared to other PC PCBs (Table 4) with an average composition for DIMMs of ~1,000 pm gold, ~70 ppm palladium, ~1,600 ppm silver and ~200 ppt copper. The number of RAM modules in PCs POM in 2013 has been shown to be 137 million units which, based on the average composition determined for DIMMs, contained 2.5 tonnes of gold, 3.9 tonnes of silver, 160 kg of palladium and 465 tonnes of copper with a total market value of USD 103 million. Quantities of gold and silver in DRAM modules have been stable over the time period 2000–2010. DIMMs show an increase in copper content over time, with a doubling of copper content of samples between 1999 and 2010. A decrease in the palladium content of modules at a rate of 5% per year is observed, which is attributable to miniaturisation of MLCCs over time. The palladium content of modules on the market in 2007 was only ~20% of that for modules on the market in 1993. It is unlikely that this trend will continue, but rather a minimum Pd content in MLCCs will be reached as Pd content of electrode alloys in these SMDs has reached a minimum, and there is likely to be a limit to how small these electrodes can be made in order to achieve sufficient capacitance for their function. But it may be that, in the future, the Pd content of modules (and other PCBs utilising MLCCs) will slowly rise again when additional MLCCs are incorporated to support advanced functionality.

In modern DIMMs, a general increase in copper content of 0.23 g/module/year is observed over the period 1999–2008, which would result in an increase in copper content of ~75% if this trend were to continue until 2020. There is some question as to whether such a linear trend can continue, although as PCBs become more complex then additional layers are incorporated into multilayer boards and this may support the trend in increasing copper content enabling it to continue for the foreseeable future.

The value of the target metals in DRAM modules analysed ranges from USD 14,000–55,000/tonne. Modern DIMMs, which represent the majority of RAM modules available in the waste stream today, vary in value by a factor of 1.65 over the range of USD 33,000–55,000/tonne with an average value across samples of USD 44,000/tonne. The grade of DIMMs is higher than other PC PCBs reported, with the exception of results from Yamane et al. (Table 4). The major value fraction is consistently gold (>90% average for DIMMS).

Global sales of desktop PCs and therefore DRAM modules are diminishing as laptops and tablets gain further market share, and thus the total size of the 'reserve' of metals in PC DRAM modules is decreasing and therefore so is their recycling potential. Based on projections of global PC sales, it is likely that the annual number of waste DRAM modules produced will decrease in proportion with PC sales. Total quantities of gold and silver available in globally produced waste DRAM will decrease proportionally, it is likely that palladium content will be reduced significantly, but the amount of copper per DRAM module may well increase enough to compensate for the reduction in PCs sold so that the overall recoverable quantity of copper remains stable.

By replication of projections of PMs and Cu in notebooks, smart phones, cell phones and tablets made by Cucchiella et al., it has been shown that incorporating temporal trends observed in DRAM modules into projections of recycling potential results in a discrepancy of the total recoverable PM and Cu value of 0.4–6% for items considered. Although no major discrepancy in this case is observed between projections made on current, static compositional data, the high proportion of recoverable value in laptops and tablets as Au and Ag; and silver in smart phones and cell phones suggest that were temporal variations in these metals to occur in the future, major discrepancies between projections and future recycling potential could be considerable, to the detriment of waste management operations and legislation based upon such projections.

We have found no temporal trends in PM content of DRAM which suggest that diminishing PM content in any one particular item will affect its recycling potential in the near future. However, shifts in consumption patterns of consumers away from current technologies to emerging technologies with lower PM content would have a detrimental effect on recycling potential of WEEE overall.

Finally, we note that the shift to cloud based software and data storage means that many of the current components of computers may no longer be necessary. Miniaturisation of computing devices, as has been seen in the shift from the use of conventional desktop PCs to the use of tablets for example, may result in modular components such as DIMMs, being eliminated. Such a shift in the design of devices would result in elimination of large gold contacts and significantly less recoverable value in devices, which would have a significant impact on recycling potential. It should be considered though that this shift to cloud based storage is accompanied by increased volumes of servers in data centres, and these servers are still composed of modular components designed to be swapped out and replaced as necessary, which today still use gold edge contacts. Previous studies have shown that between 2008 and 2015 the amount of gold in German data centres would have increased by 61%, reflecting the increase in number of installed servers (Hintemann and Fichter, 2012). So, while the total mass of equipment that makes up the recycling feedstock may be reduced because of ‘cloud computing’, the amount of precious metals in ICT overall may remain stable. More PMs installed in servers may simply result in a change of where PMs are located and recovery may even be higher because centralisation of equipment may result in more efficient collection.

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References

Arnold, J.C., Watson, T., Alston, S., Carnie, M., Glover, C., 2010. The use of FTIR mapping to assess phase distribution in mixed and recycled WEEE plastics. Polym. Test. 29, 459–470.

Bigum, M., Brogaard, L., Christensen, T.H., 2012. Metal recovery from high-grade WEEE: a life cycle assessment. J. Hazard. Mater. 207–208, 8–14.

Bigum, M., Petersen, C., Christensen, T.H., Scheitz, C., 2013. WEEE and portable batteries in residual household waste: quantification and characterisation of misplaced waste. Waste Manage. 33, 2372–2380.

Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., Buchert, M., 2013. Recycling of rare earths: a critical review. J. Clean. Prod. 51, 1–22.

Bleiwas, D., Kelly, T., 2001. Obsolete computers, “gold mine,” or high-tech trash? Resource recovery from recycling. In: Eastern Publications Group Web Team (Ed.), USGS Fact Sheet United States Geological Survey (USGS), p. 4 <http://pubs.usgs.gov/fs/fs060-01/> (accessed 20/6/2016).

Bridgewater, E., 2012. Defra EV0801 National Compositional Estimates for Local Authority Collected Waste and Recycling in England, 2010/11. DEFRA <http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=18237> (accessed 20/6/2016).

Buchert, M., Manhart, A., Bleher, D., Pingel, D., 2012. Recycling Raw Materials from Waste Electronic Equipment. Oeko Institute e.V..

Buchert, M., Schuler, D., Bleher, D., 2008. Critical Metals for Future Sustainable Technologies and Their Recycling Potential. Oko-Institut & UNEP & UNU, Darmstadt, Germany.

Bunting, G., Huxtable, L., Clement, M., 2006. Strategic solutions for resource efficiency. In: The 13th International Conference of the Greening of Industry Network – Integration and Communication: A Clear Route to Sustainability? Cardiff, Wales, UK.

California Department of Toxic Substances Control, 2010. Restrictions on the Use of Certain Hazardous Substances (RoHS) in Electronic Devices. State of California. CA.gov – Official Website of the State Government of California. <http://www.dtsc.ca.gov/HazardousWaste/rohs.cfm> (accessed 20/6/2016).

Chancerel, P., Meskers, C.E.M., Hagelüken, C., Rotter, V.S., 2009. Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. J. Ind. Ecol. 13, 791–810.

Chancerel, P., Rotter, V.S., 2009. Assessing the Management of Small Waste Electrical and Electronic Equipment through Substance Flow Analysis – The Example of Gold in Germany and the USA. IEEE International Symposium on Sustainable Systems and Technology-ISST, New York, pp. 380–385.

Charles, R.G., 2012. The Assessment of Ferrous and Non-Ferrous Metals in WEEE MRes Thesis. Swansea University, College of Engineering, Swansea, UK, p. 136.

Cross, J., 2004. Precious metals in electronics: the winners and losers. In: The LBMA Precious Metals Conference, Shanghai, pp. 75–76.

Cucchiella, F., D’Adamo, I., Lenny Koh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sustain. Energy Rev. 51, 263–272.

Cucchiella, F., D’Adamo, I., Lenny Koh, S.C., Rosa, P., 2016. A profitability assessment of European recycling processes treating printed circuit boards from waste electrical and electronic equipments. Renew. Sustain. Energy Rev. 64, 749–760.

Cuddington, J.T., 2008. An analogy between secondary and primary metals production. Resour. Policy 33, 48–49.

Cui, J., Forssberg, E., 2003. Mechanical recycling of waste electric and electronic equipment: a review. J. Hazard. Mater. 99, 243–263.

Cui, J., Zhang, L., 2008. Metallurgical recovery of metals from electronic waste: a review. J. Hazard. Mater. 158, 228–256.

Dalrymple, I., Wright, N., Kellner, R., Bains, N., Geraghty, K., Goosey, M., Lightfoot, L., 2007. An integrated approach to electronic waste (WEEE) recycling. Circ. World 33, 52–58.

Dias, P., Javimczik, S., Benevit, M., Veit, H., Bernardes, A.M., 2016. Recycling WEEE: extraction and concentration of silver from waste crystalline silicon photovoltaic modules. Waste Manage. 57, 220–225.

DEFRA, 2006. Guidance on Best Available Treatment Recovery and Recycling Techniques (BATRRT) and Treatment of Waste Electrical and Electronic Equipment (WEEE).

DEFRA and BIS, 2012. Resource Security Action Plan: Making the Most of Valuable Materials, DEFRA, Nobel House, 17 Smith Square, London, SW1P 3JR <https://www.gov.uk/government/publications/resource-security-action-plan-making-the-most-of-valuable-materials> (accessed 20/6/2016).

Dempsey, M., McIntyre, K., 2009. 2009. The role of collective versus individual producer responsibility in e-waste management: key learnings from around the world. In: Hester, R.E., Harrison, R.M. (Eds.), Electronic Waste Management – Design, Analysis and Application. The Royal Society of Chemistry, Cambridge, pp. 212–235.

EC, 2010. Critical Raw Materials for the EU – Report of the Working Group on Defining Critical Raw Materials. D.G. Enterprise and Industry, European Commission (Ed.) <http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm> (accessed 20/6/2016).

EC, 2011a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Resource-Efficient Europe – Flagship Initiative under the Europe 2020 Strategy. European Commission, COM (2011) 21. <http://ec.europa.eu/resource-efficient-europe/pdf/resource_efficient_europe_en.pdf> (accessed 20/6/2016).

EC, 2011b. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Tackling the Challenges in Commodity Markets and on Raw Materials. European Commission, COM (2011) 25 Final, p. 22. <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2011:0025:FIN> (accessed 20/6/2016).

EC, 2014. Report on Critical Raw Materials for the EU – Report of the Ad hoc Working Group on Defining Critical Raw Materials; D.G. Enterprise and Industry, European Commission (Ed.). <http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm> (accessed 20/6/2016).

Environment Agency, 2015. Statistics – Waste Electrical and Electronic Equipment in the UK <https://www.gov.uk/government/statistics/waste-electrical-and-electronic-equipment-in-the-uk-2013> (accessed 20/6/2016).

EPOW, 2011. Study into the Feasibility of Protecting and Recovering Critical Raw Materials through Infrastructure Development in the South East of England. European Pathway to Zero Waste (EPOW) <http://www.criticalrawmaterials.eu/wp-content/uploads/EPOW-recovering-critical-raw-materials-combined.pdf> (accessed 20/6/2016).

Ernst, T., Popp, R., Wolf, M., van Eldik, R., 2003. Analysis of eco-relevant elements and noble metals in printed wiring boards using AAS, ICP-AES and EDXRF. Anal. Bioanal. Chem. 375, 805–814.

EU, 2003a. Directive 2002/95/EC of the European Parliament and of the council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, RoHS. Off. J. Eur. Union L37, 19–23.

EU, 2003b. Directive 2002/96/EC of the European Parliament and of the council of 27 January 2003 on waste electrical and electronic equipment (WEEE). Off. J. Eur. Union L37, 24–38.

EU, 2011. Directive 2011/65/EU of the European Parliament and the council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast), RoHS 2. Off. J. Eur. Union L174, 88–110.

EU, 2012. Directive 2012/19/EU of the European Parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast). Off. J. Eur. Union, 38.

Garlapati, V.K., 2016. E-waste in India and developed countries: management, recycling, business and biotechnological initiatives. Renew. Sustain. Energy Rev. 54, 874–881.

Gasser, M.S., Aly, M.I., 2013. Separation and recovery of rare earth elements from spent nickel–metal-hydride batteries using synthetic adsorbent. Int. J. Miner. Process. 121, 31–38.

Goosey, M., 2009. Introduction and overview. In: Hester, R.E., Harrison, R.M. (Eds.), Electronic Waste Management – Design, Analysis and Application. The Royal Society of Chemistry, Cambridge, pp. 4–39.

Hagelüken, C., 2006. Improving metal returns and eco-efficiency in electronics recycling – a holistic approach for interface optimisation between pre-processing and integrated metals smelting and refining. In: IEEE International Symposium on Electronics & the Environment, San Francisco, pp. 218–223.

Hagelüken, C., Corti, C.W., 2010. Recycling of gold from electronics: cost-effective use through 'design for recycling'. Gold Bull. 43, 209–220.

Hagelüken, C., Meskers, C., 2008. Mining our computers—opportunities and challenges to recover scarce and valuable metals from end-of-life electronic devices. Electronics Goes Green 2008+, Berlin, Germany.

Hagelüken, C., Meskers, C., 2013. Recycling of technology metals. In: Hieronymi, K., Kahhat, R., Williams, E. (Eds.), E-Waste Management, From Waste to Resource. Routledge, Oxon, pp. 63–64.

Hasegawa, H., Rahman, I.M.M., Egawa, Y., Sawai, H., Begum, Z.A., Maki, T., Mizutani, S., 2013. Recovery of Indium from end-of-life liquid-crystal display panels using aminopolycarboxylate chelants with the aid of mechanochemical treatment. Microchem. J. 106, 289–294.

Hintemann, R., Fichter, K., 2012. Energy consumption and quantities of materials in German data centers. Electronics Goes Green 2012+ (EGG), Berlin, 1–6.

Hunter, J.D., 2007. Matplotlib: a 2D graphics environment. Comput. Sci. Eng. 9, 90–95.

Jha, A.K., Jha, M.K., Kumari, A., Sahu, S.K., Kumar, V., Pandey, B.D., 2013. Selective separation and recovery of cobalt from leach liquor of discarded Li-ion batteries using thiophosphinic extractant. Sep. Purif. Technol. 104, 160–166.

JORC, 2012. Australasian Code for Reporting of Exploration Results. Mineral Resources and Ore Reserves – The JORC CODE – 2012 ed. AusIMM (Ed.). <http://www.jorc.org/docs/JORC_code_2012.pdf> (accessed 20/6/2016).

Kalmykova, Y., Patrício, J., Rosado, L., Berg, P.E., 2015. Out with the old, out with the new – the effect of transitions in TVs and monitors technology on consumption and WEEE generation in Sweden 1996–2014. Waste Manage. 46, 511–522.

Karbo, M., 2012. Karbo's Book on PC Hardware. RAM Technologies. <http://karbosguide.com/books/pcarchitecture/chapter20.htm> (accessed 20/6/2016) (Chapter 20).

Kuschnik, B., 2008. The European Union's energy using product – EuP – directive 2005/32 EC: taking transnational eco-product design regulation one step further. Templ J. Sci. Technol. Environ. Law 27, 1–33.

Li, B., Yang, J., Lu, B., Song, X., 2015. Estimation of retired mobile phones generation in China: a comparative study on methodology. Waste Manage. 35, 247–254.

Li, B., Yang, J.X., Lü, B., Song, X.L., 2015. Generation estimation of waste electrical and electronic equipment: methods review and selection strategy. Shengtai Xuebao/Acta Ecol. Sin. 35, 7965–7973.

Li, J., Lu, H., Guo, J., Xu, Z., Zhou, Y., 2007. Recycle technology for recovering resources and products from waste printed circuit boards. Environ. Sci. Technol. 41, 1995–2000.

Li, J., Zeng, X., Stevels, A., 2015. Ecodesign in consumer electronics: past, present, and future. Crit. Rev. Environ. Sci. Technol. 45, 840–860.

Li, J., Zeng, X., Chen, M., Ogunseitan, O.A., Stevels, A., 2015. "Control-Alt-Delete": rebooting solutions for the E-waste problem. Environ. Sci. Technol. 49, 7095–7108.

MacArthur, E., 2012. Towards a Circular Economy – Economics and Business Rationale for an Accelerated Transition. <http://www.ellenmacarthurfoundation.org/business/reports> (accessed 20/6/2016).

Magalini, F., Wang, F., Huisman, J., Kuehr, R., Balde, K., Straalen, V.V., Hestin, M., Lecerf, L., Sayman, U., Akpulat, O., 2016. Study on Collection Rates of Waste Electrical and Electronic Equipment (WEEE), Possible Measures to be Initiated by the Commission as Required by Article 7(4), 7(5), 7(6) and 7(7) of Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE). In: EC (Ed.). European Commission (EC). <http://ec.europa.eu/environment/waste/weee/pdf/Final_Report_Art7_publication.pdf> (accessed 19/10/16).

Manhart, A., 2011. International cooperation for metal recycling from waste electrical and electronic equipment. J. Ind. Ecol. 15, 13–30.

Menikpura, S.N.M., Santo, A., Hotta, Y., 2014. Assessing the climate co-benefits from waste electrical and electronic equipment (WEEE) recycling in Japan. J. Clean. Prod. 74, 183–190.

METI, 2001. Law for the Promotion of Effective Utilisation of Resources (LPEUR). Japanese Ministry of Economy, Trade and Industry (Ed.). <http://www.meti.go.jp/english/information/data/cReEffectLe.pdf> (accessed 20/6/2016).

METI, 2006. Home Appliance Recycling Law (HARL). Japanese Ministry of Economy, Trade and Industry (Ed.). <http://www.meti.go.jp/policy/recycle/main/english/law/home.html> (accessed 20/6/2016).

Ministry of Environment and Urban Development, 2012. Regulation on the Control of Waste Electrical and Electronic Equipments. Official Gazette. Ministry of Environment and Urban Development. 22nd May 2012.

Morley, N., Eatherley, D., 2008. Materials Security: Ensuring Resource Availability for the UK Economy. Resource Efficiency Knowledge Transfer Network, Chester <http://www.oakdenehollins.co.uk/pdf/material_security.pdf> (accessed 20/6/2016).

Mueller, S.M., 2011. Memory. In: Wiegand, G. (Ed.), Upgrading and Repairing PCs. 20th ed. Pearson Education Inc., USA.

Nassar, N.T., Barr, R., Browning, M., Diao, Z., Friedlander, E., Harper, E.M., Henly, C., Kavlak, G., Kwatra, S., Jun, C., Warren, S., Yang, M.Y., Graedel, T.E., 2012. Criticality of the geological copper family. Environ. Sci. Technol. 46, 1071–1078.

O'Connell, R., Alway, B., Leyland, A., Strachan, R., Norton, K., Chan, D., Wong, L., Yao, W., Sun, R., Aranda, D., Aragon, J., Salmon, B., Troman-Taylor, M., 2015. GFMS Copper Survey 2015. Thompson Reuters, London, UK. <http://trmcs-documents.s3.amazonaws.com/377d4e994bb540b286d7ccf30b81bece_20150506123937_gfms-copper-survey-2015-v3.pdf> (accessed 1/11/2017).

O'Connell, R., O'Connell, R., Tankard, W., Alexander, C., Strachan, R., Nambiath, S., Litosh, S., Tourney, J., Wiebe, J., Wong, L., Rannestad, E., Li, S., Scott-Gray, N., Aranda, D., Rodwell, G., Ji, A., Cheng, H., Imangaliyeva, T., Salmon, B., 2016a. GFMS Gold Survey 2016. Thompson Reuters, London, UK. <http://trmcs-documents.s3.amazonaws.com/377d4e994bb540b286d7ccf30b81bece_20160331023311_gfms_gold_survey_2016_2.pdf> (accessed 20/6/2016).

O'Connell, R., Tankard, W., Alexander, C., Strachan, R., Namblath, S., Norton, K., Litosh, S., Wiebe, J., Yao, W., Rannestad, E., Li, S., Imangaliyeva, T., Scott-Gray, N., Rodwell, G., Ji, A., Cheng, H., 2016b. The Silver Institute – World Silver Survey 2016. Thompson Reuters, London, UK. <http://trmcs-documents.s3.amazonaws.com/377d4e994bb540b286d7ccf30b81bece_20160505120341_World%20Silver%20Survey%202016.pdf> (accessed 20/6/2016).

O'Connell, R., Tankard, W., Alexander, C., Strachan, R., Nambiath, S., Litosh, S., Tourney, J., Wiebe, J., Wong, L., Rannestad, E., Li, S., Aranda, D., Scott-Gray, N., Imangaliyeva, T., Rodwell, G., Ji, A., Cheng, H., Salmon, B., 2016c. GFMS Platinum and Palladium Survey. Thompson Reuters, London, UK. <http://trmcs-documents.s3.amazonaws.com/377d4e994bb540b286d7ccf30b81bece_20160512074418_GFMS%20Platinum%20Group%20Metals%20Survey%202016.pdf> (accessed 20/6/2016).

O'Connell, R., Alway, B., Sischka, B., Norton, K., Yao, W., Wong, L., Bakourou, V., Salmon, B., 2016d. GFMS Copper Survey 2016d. Thompson Reuters, London, UK. <http://trmcs-documents.s3.amazonaws.com/377d4e994bb540b286d7ccf30b81bece_20160405034444_GFMS%20Copper%20Survey%202016.pdf> (accessed 20/6/2016).

Ögren, J., Ögren, T., Edmundsson, N., Jonsson, M., 2016. Hardware Book (HwB). <http://www.hardwarebook.info/Memory> (accessed 20/6/2016).

Oguchi, M., Murakami, S., Sakanakura, H., Kida, A., Kameya, T., 2011. A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. Waste Manage. 31, 2150–2160.

Ogunniyi, I.O., Vermaak, M.K.G., Groot, D.R., 2009. Chemical composition and liberation characterization of printed circuit board comminution fines for beneficiation investigations. Waste Manage. 29, 2140–2146.

Ongondo, F.O., Williams, I.D., Cherrett, T.J., 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Manage. 31, 714–730.

Ongondo, F.O., Williams, I.D., Dietrich, J., Carroll, C., 2013. ICT reuse in socio-economic enterprises. Waste Manage. 33, 2600–2606.

Ongondo, F.O., Williams, I.D., Whitlock, G., 2015. Distinct urban mines: exploiting secondary resources in unique anthropogenic spaces. Waste Manage. 45, 4–9.

Park, Y.J., Fray, D.J., 2009. Recovery of high purity precious metals from printed circuit boards. J. Hazard. Mater. 164, 1152–1158.

Peck, D., Kandachar, P., Tempelman, E., 2015. Critical materials from a product design perspective. Mater. Des. 65, 147–159.

Pérez, F., Granger, B.E., 2007. IPython: a system for interactive scientific computing. Comput. Sci. Eng. 9, 21–29.

Polsson, K.R., 2013. Chronology of Personal Computers. <http://pctimeline.info> (accessed 20/6/2016).

Reck, B.K., Graedel, T.E., 2012. Challenges in metal recycling. Science 337, 690–695.

Risen, T., 2016. Americas Toxic Electronic Waste Trade. U.S. News & World Report L.P. <http://www.usnews.com/news/articles/2016-04-22/the-rising-cost-of-recycling-not-exporting-electronic-waste> (accessed 14/10/2016).

RoHSGuide.com, 2012. RoHS Guide Compliance, Other RoHS Green Initiatives Worldwide. <http://www.rohsguide.com/rohs-future.htm> (accessed 20/6/2016).

Recycling Today, 2016. Analysis Points to Slowly Rising Disposal Costs in the US. GIE Media Inc <http://www.recyclingtoday.com/article/landfill-waste-recycling-costs-ibisworld/> (accessed 14/10/16).

Schluep, M., Hagelueken, C., Kuehr, R., Magalini, F., Maurer, C., Meskers, C., Mueller, E., Wang, F., 2009. Sustainable Innovation and Technology Transfer Industrial Sector Studies: Recycling – From E-waste to Resources. United Nations Environment Programme & United Nations University, Bonn, Germany.

Schneider, L., Berger, M., Schüler-Hainsch, E., Knöfel, S., Ruhland, K., Mosig, J., Bach, V., Finkbeiner, M., 2014. The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. Int. J. Life Cycle Assess. 19, 601–610.

Sepúlveda, A., Schluep, M., Renaud, F.G., Streicher, M., Kuehr, R., Hagelüken, C., Gerecke, A.C., 2010. A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. Environ. Impact Assess. Rev. 30, 28–41.

Slade, M.E., 1980. The effects of higher energy prices and declining ore quality: copper—aluminium substitution and recycling in the USA. Resour. Policy 6, 223–239.

Sodhi, M.S., Reimer, B., 2001. Models for recycling electronics end-of-life products. OR Spektrum 23, 97–115.

Song, Q., Li, J., 2014. A systematic review of the human body burden of e-waste exposure in China. Environ. Int. 68, 82–93.

Spiegel, R., 2011. India Passes WEEE and RoHS Regulations, Green Scene, UBM Canon (Ed.). <http://www.designnews.com/author.asp?section_id=1387&doc_id=230705> (accessed 20/6/2016).

Statista, 2015. Global Desktop PC Shipments from 2010 to 2019 (in millions). Statista. <www.statista.com>. <http://www.statista.com/statistics/269044/worldwide-desktop-pc-shipments-forecast/> (accessed 5/10/2015).

Stevels, A., Huisman, J., Wang, F., Li, J., Li, B., Duan, H., 2013. Take back and treatment of discarded electronics: a scientific update. Front. Environ. Sci. Eng. 7, 1–8.

Takahashi, K.I., Tsuda, M., Nakamura, J., Otabe, K., Tsuruoka, M., Matsuno, Y., Adachi, Y., 2009. Elementary analysis of mobile phones for optimizing end-of-life scenarios. In: 2009 IEEE International Symposium on Sustainable Systems and Technology, pp. 145–146.

Terazono, A., Oguchi, M., Kuzuhara, S., Medina, R.P., Ballesteros, F.C.J., 2016. Survey of material recovered by informal e-waste processing in the Philippines [abstract]. Electronic Goes Green 2016+ (EGG2016+), Berlin, Germany.

Tsydenova, O., Bengtsson, M., 2011. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manage. 31, 45–58.

Tuncuk, A., Stazi, V., Akcil, A., Yazici, E.Y., Deveci, H., 2012. Aqueous metal recovery techniques from e-scrap: hydrometallurgy in recycling. Miner. Eng. 25, 28–37.

UNEP, 2006. Press Release – Basel Conference Addresses Electronic Wastes Challenge. United Nations Environment Programme <http://www.unep.org/Documents.Multilingual/Default.asp?DocumentID=485&ArticleID=5431&l=en> (accessed 20/6/2016).

UNU-ISP, 2015. Solving the E-Waste Problem (StEP) Initiative – StEP E-Waste World Map. <http://www.step-initiative.org/step-e-waste-world-map.html> (accessed 20/6/2016).

van der Walt, S., Colbert, C., Varoquaux, G., 2011. The NumPy array: a structure for efficient numerical computation. Comput. Sci. Eng. 13, 22–30.

Veit, H.M., Bernardes, A.M., Ferreira, J.Z., Tenório, J.A.S., Malfatti, C.d.F., 2006. Recovery of copper from printed circuit boards scraps by mechanical processing and electrometallurgy. J. Hazard. Mater. 137, 1704–1709.

Washington State Department of Ecology, 2010. First year of Washington's Electronics Recycling Program Collects over 38 Million Pounds. Department of Ecology News Release, Access Washington – Official State Government Website <http://www.ecy.wa.gov/news/2010news/2010-012.html> (accessed 20/6/2016).

WCED, 1987. Report of the World Commission on Environment and Development: Our Common Future. Oxford University Press, Oxford <http://un-documents.net/ocf-02.htm> (accessed 20/6/2016).

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., 2005. Global perspectives on E-waste. Environ. Impact Assess. Rev. 25, 436–458.

Williams, E., 2012. Future perspectives on electronic scrap. In: Hieronymi, K., Kahhat, R., Williams, E. (Eds.), E-Waste Management: From Waste to Resource. Routledge, London and New York, p. 251.

WRAP, 2012. Strategic Raw Materials, Recovery Capacity and Technologies. WRAP (Ed.). <http://www.wrap.org.uk/sites/files/wrap/IMT002%20Strategic%20Raw%20Materials%20Capacity%20Report%20-%2027th%20March%202012.pdf> (accessed 20/6/2016).

Yamane, L.H., de Moraes, V.T., Espinosa, D.C.R., Tenório, J.A.S., 2011. Recycling of WEEE: characterization of spent printed circuit boards from mobile phones and computers. Waste Manage. 31, 2553–2558.

Yang, J., Lu, B., Xu, C., 2008. WEEE flow and mitigating measures in China. Waste Manage. 28, 1589–1597.

Yu, J., Williams, E., Ju, M., Yang, Y., 2010. Forecasting global generation of obsolete personal computers. Environ. Sci. Technol. 44, 3232–3237.

Zeng, X., Gong, R., Chen, W.Q., Li, J., 2016. Uncovering the recycling potential of "new" WEEE in China. Environ. Sci. Technol. 50, 1347–1358.

Zeng, X., Li, J., 2016. Measuring the recyclability of e-waste: an innovative method and its implications. J. Clean. Prod. 131, 156–162.

Zhang, S., Forssberg, E., 1999. Intelligent Liberation and classification of electronic scrap. Powder Technol. 105, 295–301.