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How can we adapt to geological scarcity of antimony? Investigation of antimony's substitutability and of other measures to achieve a sustainable use

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ABSTRACT

Antimony is an element that is applied in many useful applications for mankind. However, antimony resources are very scarce, when comparing the current extraction rates with the availability of antimony containing ores. From an inter-temporal sustainability perspective, current generations should not deprive future generations from extractable ores. The extraction rate of a mineral resource is defined sustainable, if such a rate can be sustained for 1000 years assuming the same consumption per capita in all countries of the world. To achieve a sustainable extraction of antimony, it is necessary to reduce the current extraction with 96% compared to the primary antimony extraction in 2010. We have investigated whether such an ambitious extraction reduction goal would be technically feasible, without losing any of the current services that are provided by antimony. Reduction of the use of primary antimony can be achieved through (a combination of) substitution, improved material efficiency and recycling. Because the potential of material efficiency and recycling are limited in the case of antimony, the focus is on substitution of antimony in its applications.

The major application of antimony (more than 50%) is in flame retardants. It appears that about 95% of antimony in flame retardants can be replaced by other components or systems. Overall, the substitutability of antimony in all its applications is estimated at around 90%.

The required additional extraction reduction needs to be realized by improved material efficiency and further recycling, especially from the remaining antimony containing flame retardants and from lead-alloys.

1. Introduction

Antimony is an element that is used in many applications that are useful for humanity, e.g. as component in flame retardants, as catalyst to produce polyester, in lead-acid batteries and in lead alloys. However, antimony reserves are very scarce. Comparing the extractable global resources of antimony according to the UNEP approach (2011) with the current pace of extraction of antimony as provided by USGS (2015a), antimony is one of the scarcest mineral resources. According to Henckens et al. (2014) the extractable global resources of antimony are exhausted before 2050 if the antimony extraction rate continues to increase with the current pace. This does not mean that antimony will have disappeared from the earth's crust by that year, but the relatively easily extractable ores will. Further extraction of antimony will then become much more expensive due to e.g. low ore grades, deep mining, remote locations and high energy costs. Seen the utility of antimony for humankind it is therefore important to look at ways to reduce its extraction to a sustainable level, but without losing any of the services currently provided by antimony.

What is the sustainable level of extraction and use of primary antimony?

Henckens et al. (2014) propose the following operational definition for the sustainable extraction of raw materials: *The extraction rate of a material is sustainable, if (1) a world population of 9 billion can be provided of that material for a period of at least 1000 years assuming that, (2) the average per capita consumption level of the material is equally divided over the world's countries.*

This approach is based upon four points of departure:

(1) The available amount of extractable ores. According to UNEP (2011), the approximate upper limit of the extractable amount

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of a mineral resource is 0.01% of the total amount of that mineral in the top 1 km of the continental part of the earth's crust. This is supported by Erickson (1973), Skinner (1976) and Rankin (2011).

(2) The current extraction rate and the expected future increase of the extraction rate. This can be based on USGS data.

(3) Long-time-availability of sufficient extractable ores for future generations (according to the normative principle of inter-generational equity). What is "long time" in this framework? Theoretically, it should be for eternality, but this is not possible, since ores are not renewable. For practical reasons, Henckens et al. (2014) propose a period of 1000 years as an approximation of quasi-perpetuity. Their argument is that an ore depletion period of 100 years (just a few generations ahead) would be too short a period for sustainable extraction, whereas an order of magnitude longer period of 10,000 years seems unnecessarily long in their view.

(4) The principle right of the citizens of the world on an equitable share of the available mineral resources (according to the normative principle of intra-generational responsibility). In an operational definition for sustainable extraction it would not be justified to depart from the status quo of present inequality. Henckens et al. (2014) therefore propose to depart from the assumption that in 2050, all countries in the world have the same pro capita level of consumption of mineral resources as the industrialized countries at this moment.

According to the 3R approach (Reduce, Reuse, Recycle), there are three main technical ways to reduce the use of primary materials: substitution of the resource in its applications, improved material efficiency and increased recycling. In case a substantial use reduction of a scarce mineral resource is necessary, Henckens et al. (2015) propose to investigate these types of measures in the following sequence: (1) substitution of the resource, (2) material efficiency of the resource's applications remaining after substitution, (3) recycling of the resource from the applications remaining after substitution and material efficiency measures. This approach will result in a specific mixture of the three measures for achieving the required reduction rate. However, in practice, various other scenarios are thinkable as well or economically more optimal.

In this paper we will investigate whether and how it would be possible to reduce the extraction of antimony to less than 4% of the current extraction at a global scale.

The intention of this investigation is not to make a blue print of measures to be taken, but to demonstrate whether or not a 96% reduction of the use of primary antimony is feasible at all with current technologies without losing the services provided by antimony.

We will base ourselves on literature data. With regard to the substitutability of antimony in flame retardants and glass we have consulted specialized experts.

2. The occurrence, extractable amounts and sustainable extraction of antimony

Since 110 years, China is the main antimony supplier of the world (Tri-star resources, 2015). The main mine is in the province of Hunan in the center of the east part of China. The geological conditions in this area (high porosity karst type area in or nearby active tectonic fault lines) have been favorable for the formation of deposits with a high concentration of antimony, especially stibnite (Sb_2S_3). Both in 2012 and 2013, China had 75% of the world production of antimony.

See Table 1 and Fig. 1.

Table 1
Antimony producing countries (metric tons; USGS, 2015c).

	2009	2010	2011	2012	2013
China	140,000	150,000	150,000	136,000	120,000
Canada	64	9000	10,000	6000	76
South Africa	2673	3239	3175	3066	2400
Bolivia	2990	4980	3947	5088	5081
Burma	3700	5900	7000	7400	9000
Russia	3500	6040	6348	7300	8700
Turkey	1400	1400	2400	7300	4600
Tajikistan	2000	2000	4500	4248	4675
Australia	1000	1106	1577	2481	3275
Kyrgyzstan	700	700	1500	1200	1200
Peru	145				
Mexico	74	71	100	169	294
Total	158,246	184,436	190,547	180,252	159,301

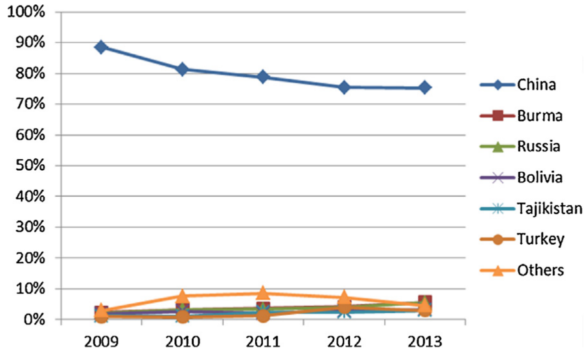

Fig. 1. Share of antimony production of the main antimony mining countries between 2009 and 2013 (USGS, 2015a).

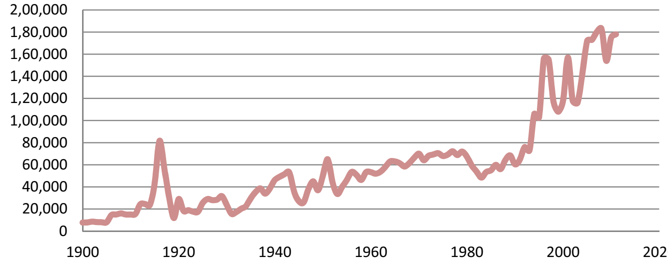

Fig. 2. Development over time of antimony world production (tons).
Source: Derived from USGS (2015b)

Fig. 2 shows that, since 1900 there is a quite steady increase of global antimony production. In recent years, the annual amount of extracted antimony shows relatively large variations, but the production trend is still upward.

Over a period of 113 years, between 1900 and 2013, the average annual production increase was 5.6%. See Table 2 for more details for selected periods.

Based on UNEP (2011) we suppose that the extractable global amount of antimony is 0.01% of the total amount of antimony in the top 1 km of the continental earth's crust. The extractable global antimony resources, according to the vision of UNEP (2011), are 8 million tons. This is about twice as much as USGS's latest reserve base estimation of antimony in 2009, which is 4.3 million tons.

Table 2
Global production trends of antimony (USGS, 2015b).

Average annual increase between 1900 and 2013	5.6%
Average annual increase between 1950 and 2013	2.8%
Average annual increase between 1990 and 2013	5.8%
Average annual increase between 2000 and 2013	3.3%

Table 3
Estimated global consumption of antimony by end-use in 2010 (tons Sb) (Roskill Consulting Group, 2011).

Non-metallurgical applications	tons Sb	%	Main use
Flame retardants	103,500	51.9%	Plastics
PET catalyst	11,400	5.7%	PET
Heat stabilizer	2,600	1.3%	PVC
Glass	1,700	0.9%	Cathode ray tubes and solar glass
Ceramics	2,500	1.3%	Construction
Other	1,840	0.9%	Various
Sub total	123,540	61.9%	
Metallurgical applications			
Lead-acid batteries	53,000	26.6%	Automotive
Lead alloys	23,000	11.5%	Construction
Sub total	76,000	38.1%	
Total	199,540	100%	

When we prudently suppose a further average annual increase of the extraction antimony of 3% from 184,000 ton in 2010 to (a virtual) 545,000 ton in 2050, it can be calculated that the extractable antimony ores will be depleted around 2040. If humanity wants to retain sufficient extractable antimony ores for future generations during a period of 1000 years, global use of primary antimony has to be reduced by 96% from 184,000 tons of antimony in 2010 to a maximum of about 7000 tons per year in the future (Henckens et al., 2014).

3. Applications and flows of antimony

The global end uses of antimony in 2010 are presented in Table 3. There are two main types of applications of antimony: non-metallurgical applications and metallurgical applications. In the supporting information we have discussed the various applications in more detail.

A growth area is the use of antimony in glass panels for photovoltaic solar cells (Roskill Consulting Group, 2011). However, on the longer term, the global use of antimony is expected to decline due to its frequent use together with halogenated hydrocarbons or lead. Worldwide, the use of both halogenated hydrocarbons and lead is scrutinized due to environmental and health reasons. Mainly due this reason, in Europe and the USA, application of antimony in flame retardants is lower than in other parts of the world. The problem is that toxic gases may be released by these flame retardants in case of fire and because of the eco-toxic properties of these substances as such. That means that environmental regulations are important determinants for the use of specific flame retardants. Polybrominated biphenyls and polybrominated diphenyl ethers have been banned from the use in electric and electronical equipment by a European Union Directive (June 2011). The application of halogenated hydrocarbons as flame retardants in building cables may be further affected by the European Construction Product Directive (March 2011) requesting testing of acidity, toxicity and smoke properties. The EU Directive on waste electrical and electronic equipment (WEEE, 2012) obliges the member states to adopt appropriate measures to minimize the disposal of WEEE in the form of unsorted municipal waste. The minimum recycling targets for various types of WEEE vary between 70 and 85%. In this framework, plastics that contain brominated flame retardants, have to be removed from the separately collected WEEE and to be disposed or recovered in compliance with the EU Waste Directive (2008). Annex VII of the WEEE-Directive prescribes selective treatment for plastic containing brominated flame retardants. This means that these substances are to be removed from collected WEEE and are to be treated separately.

Apart from the environmental concerns on the use of halogenated hydrocarbons in flame retardants, the price plays a role as well. According to USGS (2015a, p19), the flame retardant industry "*began substituting for antimony trioxide in 2011 following a significant increase in price*".

Also the use of antimony compounds as catalyst for the polycondensation of PET is under discussion because of the migration of small quantities of antimony to food and beverages in PET bottles and PET containers.

The use of antimony in lead-acid batteries is declining as well because of the development of maintenance free batteries without or with much less antimony.

To be able to investigate how the use of primary antimony can be eventually reduced by 96% we need to analyze the current antimony material flows. Part of the antimony in products is already recycled, reducing the need for primary antimony. Analysing current antimony recycling we will distinguish the recycling of metallic antimony applications from the recycling of non-metallic antimony applications.

3.1. *Recycling of antimony from metallic applications*

The recycling rate of lead-acid batteries is high. This is an important source of secondary antimony. According to Carlin (2006) by 2000, about 95% of secondary antimony in the USA originated from lead-acid batteries. Thus far, metallic antimony applications are the only source of secondary antimony. This implies that 5% of secondary antimony results from other antimony containing scrap of metallic applications (such as lead sheets, pipes, tubes and gutters). On the basis of these figures, it can be calculated that the recycling rate of antimony from antimony containing alloys was about 10% in 2000 in the USA. This low recycling rate of antimony from antimony containing alloys may be partly explained by the fact that most lead alloys are used in construction and have a long life time. So the recycled amount is relatively small compared to the amount that is newly used. So antimony is accumulating in construction. The life time of batteries is much shorter. A big part of the lead-acid grids from batteries and collected end of life antimony containing alloys are scrapped and recycled in lead smelters. Thus far, the resulting secondary antimony is mostly used again in lead-acid batteries, although this may change in future with the growing use of low maintenance and maintenance free batteries.

3.2. *Current recycling of antimony from non-metallic applications*

A substantial part of PET bottles is recycled and scrapped. According to Thiele (2009), in 2007 about 24% of PET in bottles was recycled. In 2007, 72% of the recycled PET flakes was used in polyester fiber (Noone, 2008), and 10% was used in bottles again (Thiele, 2009). The recycled PET fibers are for instance used in various textiles. According to the same author, in 2007, recycled PET fiber accounted for about 8% of the world PET fiber production.

For the rest, until now, antimony recycling from most non-metallic uses, such as from flame retardants, heat stabilizers, glass, ceramics and chemicals, is non-existent. Due to the type of use in these non-metallic applications, it is currently not economic, although technically feasible, to recycle the antimony from the end-of-life product. This means that antimony contained in these products will eventually be disposed of in landfills or incinerators.

The data provided in Section 3 are summarized in Table 4.

The data in Table 4 result in the antimony flow chart represented in Fig. 3.

4. Substitutability of antimony containing products

We will investigate potential measures that would enable the required 96% reduction of the extraction of primary antimony from

Table 4
Current recycling rates of antimony. Antimony end-use is normalized at 100 units (Roskill, 2011).

	Current distribution of antimony end-use (2010) (Roskill, 2011) Units	Antimony recycling rate %	Reference	Amount recycled Units	Current use of primary antimony Units
Non-metallurgical applications					
Flame retardants	51.9	0%		0.0	51.9
PET catalyst	5.7	8%	Thiele (2009)	0.5	5.3
Heat stabilizer	1.3	0%		0.0	1.3
Glass	0.9	0%		0.0	0.9
Ceramics	1.3	0%		0.0	1.3
Other	0.9	0%		0.0	0.9
Sub total	62	0.7%		0.5	61
Metallurgical applications					
Lead-acid batteries	26.6	90%	Carlin (2006)	23.9	2.7
Lead alloys	11.5	10%	Calculated	1.2	10.4
Sub total	38	34%		25.1	13
Total	100.0	26%		26.2	74

the current 74 units in Fig. 3 to a maximum of 3 units. In this section we will analyze the possibilities for substitution of antimony containing materials and in the next section material efficiency and recycling measures.

Regarding the substitutability of antimony in flame retardants and in glass we have consulted experts, because these application fields of antimony are both quite specific, compared to the other types of application of antimony. For the expert consultation we have prepared a list of potential substitutes from the literature. We have asked the experts to indicate for each application:

- Whether 100% substitution or replacement of antimony would be feasible within 10 years without compromising the required flame retardancy quality.
- What the applicability of the combined potential substitutes is (very poor, poor, moderate, good, very good, unknown).
- How the environment, health and safety properties of each potential substituent are compared to the original (very negative, negative, equal, positive, very positive, unknown).
- What the estimated costs of each substituent are (>200% of original, 120–200% of original, 80–120% of original, 50–80% of original, <50% of original, unknown).
- Comments, other applications, other substituents.

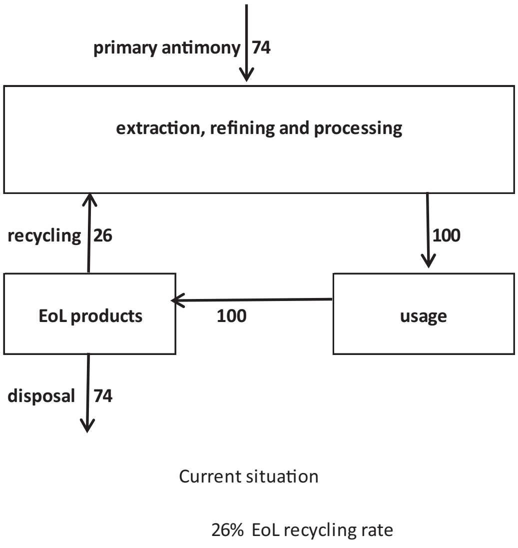

Fig. 3. Current antimony flows. Current antimony end-usage is normalized at 100 units.

A summary of the results is presented in this section. The approach and the full results are presented in the supplementary data.

4.1. *Substitutability of antimony in non-metallurgical applications*

4.1.1. *Substitutability of antimony in flame retardants*

There is a large variety of flame retardants on the market. The worldwide market share of antimony containing flame retardants (brominated hydrocarbons or chlorinated hydrocarbons with antimony trioxide) is almost 40%. See Table 5.

The supplementary data provide an overview of the main materials and the applications of these materials in which halogenated flame retardants with antimony trioxide are used, their possible substitutes and replacements. Lassen et al. (1999) provide a detailed overview. The overview makes clear that there are alternatives for halogenated flame retardants.

The consulted experts[1] in the field of flame retardancy have indicated for each application to what extent they estimate that the antimony containing product can be adequately replaced by a substituent. We have defined "*adequately*" as follows:

- The performance of the substitute compared to the performance of the original, should be adequate, meaning sufficient for the respective application. In this respect we use the following terminology: (1) very poor: antimony can be adequately substituted by alternatives in 0–20% of the uses, (2) poor: antimony can be adequately substituted by alternatives in 20–40% of the uses, (3) moderate: antimony can be adequately substituted by alternatives in 40–60% of the uses, (4) good: antimony can be adequately substituted by alternatives in 60–80% of the uses, (5) very good: antimony can be adequately substituted by alternatives in 80–100% of the uses.
- The environment, health and safety impact should not be negative compared to the original antimony containing product.
- The financial picture connected to the use of a substituent should not be very negative compared to the original antimony containing product.

Furthermore we have asked the experts whether in their opinion a 100% substitution of specific antimony containing flame

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[1] (1) Alexander Morgan of the University of Dayton, USA, National Institute of Standards and Technology, (2) Richard Horrocks of the University of Bolton, USA, Center for Materials Research and Innovation and (3) Sebastian Hoerold, Head Technical Marketing Clariant MmbH, Germany.

Table 5
Market share of various types of flame retardants (volume percent).

Flame retardant	Market share					
	Worldwide 2011[a]	EU 2006[b]	Europe, 2007[c]	United States, 2007[c]	Asia, 2007[c]	Worldwide, 2007[d]
Aluminum trihydroxide	40.4%	40%	53%	55%	16%	40%
Halogenated hydrocarbons with antimonytrioxide	39%	30%	21%	20%	67%	38%
Brominated hydrocarbons	19.7%	10%	9%	10%	45%	23%
Antimony trioxide	8.4%	7%	4%	5%	13%	8%
Chlorinated hydrocarbons	11.3%	13%	8%	5%	9%	7%
Organophosphorus	14.6%	18%	16%	12%	8%	12%
Other	5.6%	12%[e]	12%	12%	9%	11%

[a] Townsend Solutions (2013).
[b] Cusack (2007).
[c] Keyser (2009).
[d] Based on the assumption that the relative market shares of the various flame retardants worldwide are determined by the use in the USA, Europe and Asia as derived from the data provided by Keyser (2009).
[e] Magnesium hydroxide 2%, Melamine flame retardants 4%, other inorganic flame retardants 6%.

retardancy systems would be feasible within 10 years without compromising the required flame retardant quality.

Based on the experts' opinions, our conclusion is that at this moment about 55% of antimony in flame retardants would be adequately substitutable and 95% within a period of 10 years. About 90% of the substituting flame retardants are considered to have EHS (Environment, Health and Safety) properties that are equal or positive compared to the antimony containing original. The costs of more than 50% of the substitutes are estimated by the experts to be equal or lower than the costs of the original flame retardant with antimony.

The detailed, but anonymized data of the inventory of experts' opinions are included in the supplementary data.

4.1.2. Substitutability of antimony compounds as catalyst in PET production

Apart from the geological scarcity of antimony, a number of other reasons exist to substitute antimony compounds as catalysts in PET production: toxicity for human health and the environment (Shotyk et al., 2006), negative impact on polymer quality (Thiele, 2004), improvable catalytic characteristics (Thiele, 2004; Shigemoto et al., 2013).

A number of alternative catalysts are commercially available (Thiele, 2001, 2004; Yang et al., 2012, 2013; Butterman and Carlin, 2004; Gross et al., 2010; Furlong, 2014). Most of the alternative catalysts are based on (non-scarce) titanium. Others are based on germanium, zirconium, cobalt, molybdenum, organic materials or enzymes. Molybdenum is also a scarce mineral and should be avoided to replace antimony. The other alternative materials mentioned in this section are not considered scarce (Henckens et al., 2014).

Companies like *DAK Amerikas* have included antimony free PET in their sales program. Other companies make publicity for antimony free polyester clothing (for instance McLaren, 2008).

A serious hurdle to overcome is the necessity of adaptation of PET production facilities, when changing to another catalyst. Because of the large volume production of PET, its production facilities have a substantial size and therefore are quite inflexible. In practise change to another catalyst will only be realistic in case of a newly constructed PET plant (Thiele, 2006).

The conclusion regarding the substitutability of antimony in catalysts for the PET production is that antimony is 100% substitutable in this application.

4.1.3. Substitutability of antimony as heat stabilizer in plastics

Antimony-mercaptide is just one of many heat stabilizers. For an overview it is referred to Markarian (2007) and Babinsky (2006). Antimony-mercaptide is quite insignificant in this market (Butterman and Carlin, 2004).

The conclusion is that antimony's application in heat stabilizers, as far as it is still applied is 100% substitutable.

4.1.4. Substitutability of antimony in glass

The use of antimony trioxide as fining agent, decolourant and antisolorant can be avoided in melt ovens that are resistant against strongly oxidizing conditions and by using sand with a very low iron and chromium content (Rögels, 2014). In float glass, antimony compounds can be substituted by sodium sulphate. For special glasses, mixtures of various fining agents are used. Antimony sulphide as glass colorant can be replaced by other glass colorants. See Biron and Chopinet (2013). Antimony sulphide in its application of glass colorant is therefore considered to be 100% substitutable.

We have questioned glass experts[2] on the possibilities of substitution of antimony compounds in the various glass applications. On the basis of their reaction, we estimate that an average of 56% of the applications of antimony in glass is substitutable in the above mentioned ways at this moment. Within a period of 10 years a substitutability of 80% of antimony in glass is deemed possible by the experts. The detailed, but anonymized results of the expert's opinion on the substitutability of antimony in glass are included in the supplementary data.

4.1.5. Substitutability of antimony in ceramics

There are many colorants and opacifiers for ceramics on the market available, although it is not clear whether or not exactly the same color or the same effect can be obtained. Nevertheless we assume that the specific application of antimony compounds in ceramics is not unique, indispensable or non-replaceable and is therefore considered to be 100% substitutable.

4.1.6. Substitutability of antimony in other non-metallurgical uses

Due to the specific character of these applications and the relatively small volume it is assumed that antimony in these applications is not substitutable.

4.2. Substitutability of antimony in metallurgical applications

4.2.1. Substitutability of antimony in lead acid batteries

Antimony containing lead acid batteries can be replaced by antimony-free calcium–calcium lead acid batteries. Antimony free

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[2] Ruud Beerkens of TNO, The Netherlands, Hayo Müller-Simon of the Research Institute of the German Glass Industry (HVG), Germany and Masataka Kawaguchi of Nippon Electric Glass, Japan.

Table 6
Antimony substitutability in various applications. Current antimony end-use is normalized at 100 units.

	Current distribution of antimony end-use (2010) Units	Substitutability %	Remaining antimony use after substitution Units
Non-metallurgical applications			
Flame retardants	51.9	95%	2.6
Plastic catalyst	5.7	100%	0.0
Heat stabilizer	1.3	100%	0.0
Glass	0.9	80%	0.2
Ceramics	1.3	100%	0.0
Other	0.9	0%	0.9
Sub total	61.9	94%	3.7
Metallurgical applications			
Lead-acid batteries	26.6	100%	0.0
Lead alloys	11.5	50%	5.8
Sub total	38.1	85%	5.8
Total	100.0	91%	9.4

batteries have become the norm in all applications (May, 1992; Toniazzo, 2006; Misra, 2007).

4.2.2. *Substitutability of antimony in lead alloys*

Rabin (2001) and Roskill Information Services (1997) mention substitute *solders*, without antimony. They contain however bismuth, copper, indium, silver, tin and zinc in various proportions and combinations. Although these metals are less scarce than antimony, most of them are geologically scarce or moderately scarce as well. A mineral resource is defined (1) very scarce, if its extractable ores are depleted before 2050 (like antimony), (2) scarce, if its extractable ores are depleted within a period of less than 100 years after 2050 and (3) moderately scarce, if its extractable ores are depleted within a period of between 100 and 1000 years after 2050 (Henckens et al., 2014). Therefore we assume that substitution of antimony in solder is not possible from a perspective of geological scarcity of the potential substitutes.

According to Booser (1992) and Roskill Information Services (1997) many antimony containing *bearings* have substitutes including alloys of aluminum, copper, tin, zinc, silver, nylon, polyimide, silicon nitride, carbon-graphite, aluminum oxide. Also ball and roller bearings are candidates for selected uses. A part of the substitutes is scarce as well, but another part is not (Henckens et al., 2014). Substitutes for lead-antimony rolled and extruded *alloys* are stainless steels and polymers (Prengaman, 1995).

Substitutes for antimonial lead in *ammunition* for small arms are bismuth-tin alloys (97%/3%), steel and tungsten (Brown, 2001). Bismuth, tin, iron and tungsten are scarce minerals as well, although less than antimony.

In *cable covering*, laminated aluminum and organic polymers are used to substitute lead sheathing of power and communication cables (Prengaman, 1995; Roskill Information Services Ltd, 1997).

On the basis of the available data it is difficult to provide a quantitative estimation of the substitutability of antimony in its various alloys. More research will be needed. Our prudent first approximation for calculation purposes is that the overall substitutability of antimony in alloys may be in the order of 50%.

4.3. *Substitutability of antimony summarized*

The conclusion of the Sections 4.1 and 4.2 is that antimony is partly or fully substitutable in many of its applications. The overall substitutability can be estimated at about 90% of the current antimony end-use. See Table 6.

Recycling will be reduced from the current 26% to only 6%, because antimony applications as PET catalyst and in batteries will have been substituted. The remaining extraction of primary antimony is about 12% of the current extraction rate (a reduction from the current 74 units in Fig. 3 to 9 units). But we need to achieve a 96% reduction of the current extraction. In the next paragraphs we will investigate how material efficiency and extra recycling can contribute to the additionally required extraction reduction of antimony.

Whether or not, to what extent and how fast the potential antimony substitutability will be realized will depend on a number of factors, whereof the most important are government regulation and the costs of substitutes versus their performance. Another practical factor will be the time that industry will need for switching from antimony to a substitute without too many capital costs in connection with the needed adaptation of production facilities.

5. Improving material efficiency and increasing recycling of antimony containing products

5.1. *Material efficiency*

Generally, material efficiency can be improved by:

- Lower losses in production processes and supply chains
- More economical application in products (lower concentration)
- More economical use of products (longer product life times, shared use of products, e.g. electric and electronic equipment)

In principle, all these material efficiency options are applicable for many of the current antimony applications. However, in Section 4 we have seen that in a substantial part of its applications antimony is substitutable by other products. Therefore we will focus on the material efficiency potential of the antimony applications that remain after substitution. It concerns the remaining antimony use in:

- Flame retardants.
- Glass.
- Other non-metallic uses, such as additive to some lubricants, as passivating agent, as phosphoring agent, as vulcanization agent, for fireworks, as cross-linking agent and as reactant in organic chemical reactions.
- Metallic uses, such as antimony application in bearings, solders, ammunition, cable covering and various alloys for specific applications.

In a situation of a great variety of small uses it is difficult to provide a reliable estimation on the possible material efficiency.

Table 7
The reduction effect of material efficiency measures on the remaining antimony use after substitution.

	Remaining antimony end-use after substitution Units	Reduction through material efficiency %	Remaining antimony end-use after substitution and material efficiency measures Units
Non-metallurgical applications			
Flame retardants	2.6	10%	2.3
Plastic catalyst			
Heat stabilizer			
Glass	0.2	10%	0.2
Ceramics			
Other	0.9	10%	0.8
Sub total	3.7		3.3
Metallurgical applications			
Lead-acid batteries			
Lead alloys	5.8	10%	5.2
Sub total	5.8		5.2
Total	9.4	10%	8.5

Table 8
The reduction effect of improved recycling of remaining antimony use after substitution and material efficiency measures.

	Remaining antimony end-use after substitution and material efficiency measures. See Table 7 Units	Reduction through improved recycling %	Remaining primary antimony use after substitution, material efficiency and improved recycling Units
Non-metallurgical applications			
Flame retardants	2.3	70%	0.7
PET catalyst			
Heat stabilizer			
Glass	0.2	0%	0.2
Ceramics			
Other	0.8	0%	0.8
Sub total	*3.3*	*49%*	*1.7*
Metallurgical applications			
Lead-acid batteries			
Lead alloys	5.2	75%	1.3
Sub total	*5.2*	*75%*	*1.3*
Total	8.5	65%	3.0

Henckens et al. (2015) have made plausible that a prudent (default) material efficiency of 10% for the remaining antimony applications can be assumed. The result is presented in Table 7. The conclusion is that material efficiency might supposedly further reduce the antimony end-use from 9.4% of the current use to 8.5% of the current end-use and the extraction of primary antimony from about 12% of the current extraction to 11%.

The conclusion is that, after material efficiency measures, still an extra effort is needed to achieve the final goal of 96% reduction of primary antimony use.

5.2. Improved recycling

Currently, antimony recycling mainly includes antimony in PET (8% recycling), in lead batteries (90% recycling) and other metallic uses (10% recycling). Further improvement of PET recycling and antimony recycling from batteries is theoretically possible, although not simple as far as it is PET applications in textiles concerned. But considering increased antimony recycling in PET and in lead-acid batteries is not necessary anymore, because we have assumed that antimony in both applications will be 100% substituted by other products. As far as antimony in lead-acid batteries is not substituted it is easily recyclable. Recycling of antimony from ceramics and from products wherein it is used as heat stabilizer is difficult, because of the low concentration and the complex mix of materials in the end-of-life products. But also for these two applications we have supposed that antimony is 100% substitutable.

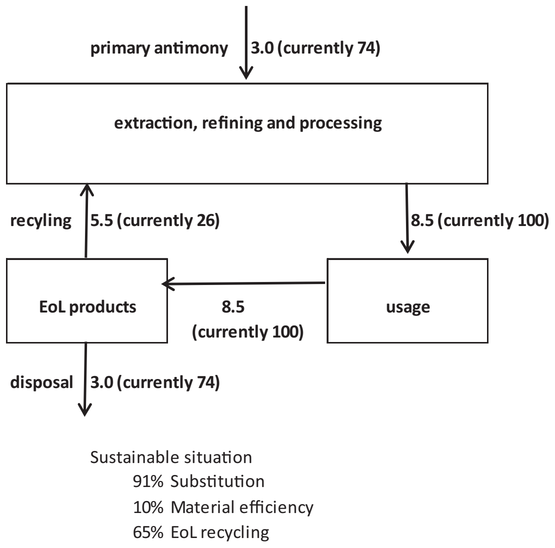

Fig. 4. Antimony flow chart with 96% reduction of primary antimony compared to the current situation. The current end-usage is normalized at 100 units.

For further increasing antimony recycling, we therefore concentrate on:

- Flame retardants
- Glass

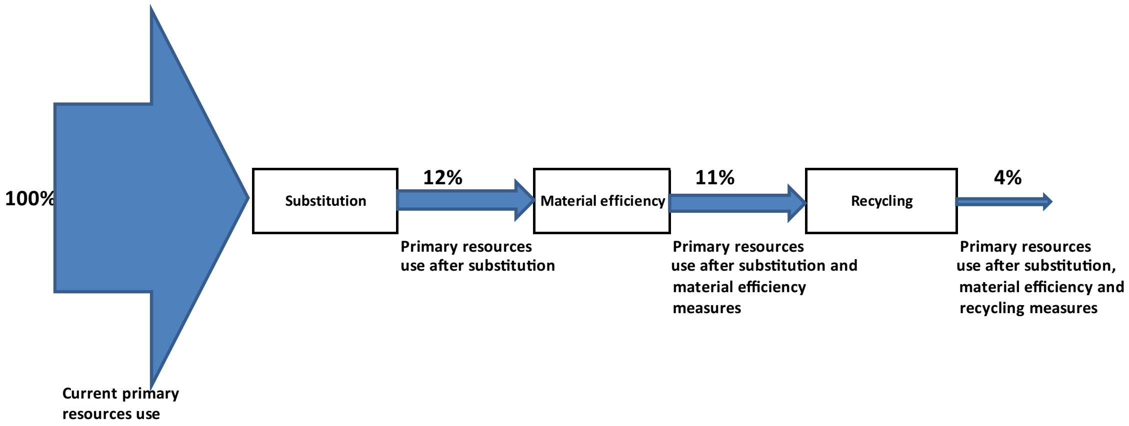

Fig. 5. Steps for a sustainable use of primary antimony.

- Other non-metallic uses (as chemical)
- Non-battery metallic uses (mainly in alloys)

The EU WEEE Directive (2012) facilitates the opportunity to concentrate antimony from WEEE. In principle various recycling routes are possible. Plastics that contain brominated flame retardants may be separated per type of material and (partially) be reused in the original products. Another possible route is incineration, whereby antimony will mainly be concentrated in the incineration fly ashes. A substantial recycling of antimony is possible in this way, if one would succeed in collecting and incinerating all products with antimony containing flame retardants.

For achieving an overall 96% reduction of primary antimony use it will be necessary to take for instance the following measures: (1) recycle 70% of the antimony from the remaining non-substituted antimony containing flame retardants instead of 0% at this moment, (2) increase recycling of antimony from other metallic uses from 10% currently to 75% in the future. These necessary extra recycling ambitions for achieving an overall 96% reduction of antimony extraction lead to the overview of Table 8 and the flow chart of Fig. 4.

The conclusion is that the required goal of 96% reduction of primary antimony use is achievable with a mix of 91% substitution of antimony in the current applications, 10% material efficiency with regard to antimony in the remaining applications and 65% reduction of the remaining antimony use by recycling of WEEE waste and improved recycling of antimony in lead alloys. The resulting end-use of antimony in products will be 8.5% of the current end-use.

6. Conclusion and discussion

The technical possibilities of a 96% reduction of the extraction of primary antimony have been investigated.

Attaining this high ambition with respect to reduction of primary antimony extraction seems hard, but could be feasible by a combination of:

- An overall substitution of antimony in its end-uses of about 90%. This requires 100% substitution of antimony in lead-acid batteries, in its use as catalyst in the PET production, as heat stabilizer (mainly in PVC) and in its use in ceramics, 95% substitution of antimony in antimony containing flame retardants, 80% substitution of antimony in its glass applications and 50% in its application in lead alloys.
- Material efficiency measures to reduce 10% of the antimony use that remains after 90% substitution of antimony in its applications.
- A 65% antimony recycling rate from the end-of-life antimony containing products that remain after 90% substitution and 10% material efficiency. This requires 70% recycling of antimony from its remaining applications in flame retardants and 75% recycling of antimony from antimony containing lead alloys.

The results of the various reduction steps are presented in the flow diagram of Fig. 5.

Because the necessary measures to reduce the use of primary antimony to a sustainable level are major, we recommend further research into the following subjects:

- The assumed substitutability of antimony, especially in flame retardants, glass and lead alloys.
- The assumed material efficiency improvement of 10%.
- The feasibility of 70% recycling of antimony from flame retardants.
- The feasibility of 75% recycling of antimony from antimony containing lead alloys.
- The economically optimal mix of measures to reduce the use of primary antimony with 96%. Maybe recycling of antimony from flame retardants and car batteries is economically more attractive than substitution of antimony in these applications.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2016.01.012.

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