Does the Restriction of Hazardous Substances (RoHS) Directive Help Reduce Environmental Impacts?

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Abstract: Toxin-free materials may be a prerequisite for the circular economy. However, the integrated overall environmental impact induced by banning the use of certain harmful materials should be assessed beforehand. No comprehensive analysis of the environmental impact basis of RoHS exemptions has been published. The scope of the present investigation is the production of a unit of mass of material systems using upstream life cycle assessment (LCA) and Spearman rank correlation for four proxies of environmental impact (Cumulative Energy Demand, LIME2 eco-cost, EPS2015 resource depletion eco-cost and abundance in earth's crust and in the Oceans). The present investigation points to issues in the upstream caused by revoking certain exemptions for cadmium, lead and mercury. Strikingly, more than a few “non-toxic” alternatives have several orders of magnitude higher potential environmental impact than its toxic counterparts. Nevertheless, as material changes might have large effects on the use and end-of-life stages in the EEE life cycle, full LCA of several applications are required for more comprehensive understanding.

Keywords: Alternatives, cumulative energy demand, environmental impact, eco-cost, exemptions, life cycle assessment, Spearman, resource scarcity, RoHS.

1. INTRODUCTION

The circular economy is thought to be the definitive solution to achieve sustainability if it can be accomplished with non-toxic and natural materials.

On the issue of reducing the toxicity of e-waste, the restriction of hazardous substances (RoHS) directive [1] - administrated by the European Union (EU) - prohibits the use of certain hazardous substances, including lead, cadmium and mercury, in electrical and electronic equipment (EEE) [2]. RoHS was first published in 2003 and then revised in 2011. RoHS applies to electronic goods imported into the EU market and the intention is to detoxify the e-waste stream. Several regions globally have adopted their own adaptation of RoHS. The trend is that more elements, substances and product categories are added to RoHS as time goes by. The target of RoHS is to minimize certain concentration ranges of e.g. lead in homogeneous materials found in so called articles. For an integrated circuit the underfill, the die, the solder balls, the solder and lead frame are examples of articles. A well-known target for RoHS in the last decade was lead-free low-melting point solder (typically 63 wt% tin and 37wt% lead). Industry successfully used a transition period to shift to lead-free low-melting point solder. Anyway, several so called exemption applications exist for which the use of lead, cadmium and mercury is still allowed. One of the current exemptions is for lead used in high-melting point solders. However, these exemptions are reviewed frequently. Generally exemptions could be revoked if viable technical alternatives have been developed which do not lead to higher environmental impacts. That is, the industry may claim that the environmental impact will increase as a result of revoking the exemptions. A striking example is exemption application 7(c) for which it was shown - by using life cycle assessment (LCA) - that the lead-free alternative potassium sodium niobate has significantly higher overall environmental impact than lead zirconate titanate [3]. Undoubtedly, the substitution of hazardous substances in EEE – which is the target of RoHS - may lead to increased energy consumption in production and increased losses of scarce metals [4]. The present research deals with that kind of dilemma. However, deliberate improvements of impact assessment methods, e.g. for resource assessment [5], is however outside the scope. Data availability is a key factor for several impact assessment methods [6]. Therefore practical methods – such as easily found abundance data - are emphasized to get the message across.

Anyway, no comprehensive analysis of the environmental impact basis has been published for several other RoHS exemptions under review found in Annex III in [1]: 4f, 6a, 6b, 6c, 7a, 8b, 15(a), 15 and 34. For the first time several exemptions are analysed at the same time as far as environmental implications.

The scope of the present investigation is the production of material systems combining LCA and hazardous substance process management. However, material changes might have large effect on the use

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and end-of-life stages. Although no full LCAs will be performed, instrumental parts of the LCA methodology will be explored, such as environmental burden weighting compared to mid-point indicators. As such the present research can support the RoHS substance methodology, information about substance environmental risks, and exemption methodology updates.

For the sake of clarity the mathematical framework for the linear attributional LCA model is repeated from [7] in (1) to (6) and the sections which this article deals with are highlighted:

$$g = BA^{-1}f \quad (1)$$

$$g = \begin{pmatrix} g_1 \\ \vdots \\ g_i \\ \vdots \\ g_n \end{pmatrix} \quad \text{for } i = 1,2,,,n \quad (2)$$

$$I_{i(j)} = g_i k_{i(j)} \text{ for } i = 1,2,,,n \quad (3)$$

$$I_j = \sum_{i=1}^{n} I_{i(j)} \text{ for j} = 1,2,,,\text{q} \quad (4)$$

$$I_{j(w)} = \frac{I_j}{w_j} \quad (5)$$

$$EB = \sum_{j=1}^{q} I_{j(w)} \quad (6)$$

where

g = vector of environmental loadings (not shown, aggregated to I_j. and EB)

B = flow of environmental loadings (not shown, aggregated to I_j. and EB)

A = flow of products and materials (alloy composition products and input metal materials)

f = demand vector (e.g. one kg of CuZn39Pb3 alloy in Supplementary information Sheet 6(c))

f_u = functional unit of f (e.g. one kg of 11S30Mn - Bi alloy in Supplementary information Sheet 6(a))

i = environmental loading (not shown).

j = environmental impact category (shown for Cumulative Energy Demand (CED) [8] and Abundance in earth's crust and in the Oceans (ABU) [9] but not for Environmental Priority Strategies (EPS2015) [10, 12] and Life Cycle Impact Assessment Method based on Endpoint modeling (LIME2) [11, 12].

q = number of environmental impact categories (not shown).

n = number of environmental loadings (not shown).

$I_{i(j)}$ = impact indicator values for one compound, e.g. 0.43 kg/mg for ABU for Sn in Supplementary information Sheet 7(a))

$k_{i(j)}$ = characterization factor for one compound (not shown).

I_j = overall indicator of the environmental category j (shown for CED for included metals, e.g. 78 MJ/kg for Zn in in Supplementary information Sheet 6(c)).

$I_{j(w)}$ = normalized overall indicator of the environmental category j (not shown).

w_j = normalization factors for overall environmental impact indicators, e.g. 'distance to target' weighting factors (not shown).

EB = total environmental burden, e.g. summary of some chosen normalized overall indicators of some of the environmental categories, e.g. for EPS2015, 482 euro per kg for Sn in Supplementary information Sheet 6(c)) (shown for EPS2015 and LIME2 for included metals).

The news value of the present research concerns the comparative I_j (4) for mid-point categories CED and ABU for several metal alloys in a specific RoHS context. It also mentions EB (6) as eco-costs [13] using EPS2015 and LIME2 for the first time for some applications and metal alloys.

A conversion factor of 1 kg CO_2 - equivalents = 16.66 MJ CED is applied all through the article.

2. PROBLEM FORMULATION

The present research focuses on finding trends for the relative production environmental impact resulting from banning lead, cadmium and mercury in certain RoHS exemptions. Understanding the effectiveness of RoHS and other substance legislations is crucial in order to build valid policies.

In the present research the hypotheses are:

- The combined environmental impact of material manufacturing will overall rise as a result of derogating RoHS exemptions 4f, 6a, 6b, 6c, 7a, 8b, 15 and 34.
- There is a perfect positive correlation between CED score of metal alloys and scores for LIME2, EPS2015 and ABU.

3. RESEARCH APPROACH

The proposed research approach is to list lead, cadmium or mercury based alternatives and chosen corresponding proposed lead, cadmium and mercury-free alternatives. Then add all data for (*A, f_u*), i.e. alloy compositions and alloy metal inputs) into the LCA software tool SimaPro version 9.0.0.31 which facilitates logic connections between all parameters. The LCA software contain proxy data (*A*, *B*) for all relevant metals and has capability to translate (1) to (6) for execution. EMLCA, which is a matrix-based LCA software, is also used as shown in the Supplementary Information [14]. Spearman correlation coefficients [15] are calculated to establish the strength and direction of the relationships between the ranks of data.

4. UPSTREAM LCA OF MATERIALS USED IN CURRENT AND FUTURE TECHNOLOGIES

In this research different classes of materials systems will be compared; lead, cadmium mercury baselines and corresponding alternatives free of those elements. Most of them feature metal alloy comparisons. LCI databases are used for production of single metals (see Supplementary Information Sheet LCI). However other literature is analysed further to determine the relative impacts of bismuth [16,17] and germanium [16].

4.1. Bismuth CED Intensity for 2018 in the Antamina Mine

It is possible to estimate bismuths MJ/kg intensity from various data from mining operations such as the Antamina mine in Peru [18]. By extensive internet searches the approximate output from Antamina in 2018 of copper, zinc, molybdenum and silver is estimated as shown in Table **1** (more details in Supplementary information Sheet Antamina)

From Antamina mine CSR report [18] it can be derived that ≈12000 TJ were used in total in 2018 and by guessing the output of metals, especially for small by-products lead and bismuth, prices in 2018 can be used to do an economic allocation to each metal of the primary energy. Antamina bismuth has a quite small MJ/kg compared to [16,17] but the uncertainties of the allocation factors are high.

The allocation for bismuth will in any circumstance be very low for the Antamina mine and therefore the MJ/kg numbers allocated to the metal outputs from the Antamina mine have low uncertainty. Hence, the MJ/kg for bismuth should be fairly correct. The other metals have recognizable - however relatively low – MJ/kg intensities. However, these intensities vary a lot as shown by [19] which e.g. use 40000 MJ/kg for gold (lower than expected) and 333 MJ/kg for lead (higher than expected). It is fair to assume that CED (MJ/kg) for metals can vary one order of magnitude. Reference [16] is used here for bismuth. Table **2** shows some chosen element indicators.

Table **3** shows the Spearman rank correlations for CED, EPS, LIME and abundance of metals.

Table 1: Economic Allocation of the Cumulative Energy Demand for Antamina Mine to Metal Outputs

	≈ton	≈USD/ton in 2018	≈USD value	≈Allocation, economic value	≈MJ/kg (Cumulative Energy Demand)
Output					
Cu	444000	6896	3.06×10^9	70.20%	19
Zn	311000	3000	9.33×10^8	21.39%	8.2
Mo	4030	16005	6.45×10^7	1.48%	44
Pb	1000	2240	2.24×10^6	0.0514%	6.2
Bi	1	5000	5.00×10^3	0.000114%	14
Ag	622	482315	3.00×10^8	6.88%	1331
Input					
Primary energy, TJ	12036.4				

Table 2: Chosen Indicators for 22 Elements Occurring in the Present Research. ABU = Abundance in Earth's Crust and in the Oceans

	CED (MJ/kg)	EPS2015 (euro/kg)	LIME2 (JPY/kg)	Abundance in earth's upper continental crust (ABU), (1/[mg/kg])	CED	EPS2015	LIME2	ABU
Zn	77.82	32.4	1060	0.014	13	13	14	13
Pb	22.49	392	776	0.071	17	9	15	10
Sn	338.52	482	44900	0.435	7	8	5	8
Au	257007.96	2020000	57600000	250.000	1	1	1	1
Bi	49.83	28000	485	117.647	15	5	16	2
Sb	180.21	18200	29600	5.000	11	6	6	5
Ag	6549.72	72800	273000	13.333	3	3	2	3
Al	296.50	0.363	1500	0.000	8	17	12	20
Cu	106.50	90.9	9170	0.017	12	12	7	12
Ga	0.85	214	3.18	0.053	21	10	22	11
Ge	26333.33	2270	48000	0.667	2	7	3	7
Mg	758.33	0.01	8090	0.000	5	21	8	19
Si	0.76	0.01	4	0.000	22	21	21	21
P	206.67	5.2	1280	0.001	9	15	13	18
Mn	56.17	4.92	1590	0.001	14	16	11	17
Cr	488.33	5.95	3210	0.010	6	14	10	15
Cd	17.33	70500	110	6.667	18	4	18	4
O	6.87	0.01	16.8	0.000	20	21	19	22
In	3616.67	72800	47800	4.000	4	3	4	6
B	35.67	0.05	327	0.100	16	19	17	9
S	9.37	0.1	6.16	0.003	19	18	20	16
Ni	185.00	107	8020	0.012	10	11	9	14

Table 3: Spearman Rank Correlations for CED, EPS, LIME and Abundance of Metals

	CED (MJ/kg)	EPS2015 [10], (Euros/kg)	LIME2 (JPY/kg) [11]	Abundance in earth's crust and in the Oceans (ABU) (kg/mg) [9]
CED (MJ/kg)	1	0.44	0.92	0.34
EPS2015, (euros/kg)	0.44	1	0.54	0.91
LIME2 (JPY/kg)	0.92	0.54	1	0.45
ABU (kg/mg)	0.34	0.91	0.45	1

Table **3** shows a very strong positive correlation between CED and LIME2 eco-costs. It is expected that EPS2015 scores for metals are strongly correlated to ABU (kg/mg).

4.2. Mercury in other Discharge Lamps for Special Purposes – 4 (f)

The exemption 4(f) refers to High Pressure Sodium (vapour) lamps (HPS) for horticulture lighting, high pressure lamps for projection, studio and stage lighting and medium and high-pressure UV lamps.

4.2.1. Environmental Impact of Mercury in other Discharge Lamps for Special Purposes

LED-based replacement lamps are currently not available for lamps covered by this exemption. The existing technologies are suspected to have a negative impact coming from mercury use. In those cases where

Table 4: Indicative Change Per GigaLumenhour for CED, EPS, LIME and ABU for Exemption 4(f)

	HPS	LED	Change
CED (MJ)	4484.5	13623.5	+204%
EPS2015 (euro)	2317.5	55272	+2285%
LIME2 (JPY)	14511	601500	+4045%

alternative technologies are available usually these are less material efficient [20,21].

Detailed information on environmental impacts can only be evaluated by the producers and users of the equipment in which the lamps are used. Still two LCA studies comparing HPS to LED is here used to estimate the effect of scrapping HPS luminaires. Here follows a simplified reasoning demonstrating the environmental impact of premature scrapping of HPS lamps.

Tähkömö and Halonen [20] estimated - for the function *"1 Giga Lumenhour over 30 years for illumination of roads"* - that a LED lighting system has a smaller environmental impact than the HPS lighting system (17% reduction). The use phase dominates the "total environmental impacts" using the *EB* method Eco-indicator 99 (approximately 97% for HPS lighting system, and 78%–100% for LEDs). More importantly for the present research, the manufacturing of HPS is just around 25% of the LED manufacturing impacts.

Similarly, Zhang *et al*. [21] compared greenhouse lighting systems using a 1000 W HPS lighting system vs. a 650 W LED lighting system with the functional unit defined as *"producing 653 kg tomatoes from 8 sq. ft. floor area over 15 years"*. Overall the LED lighting system has a smaller "environmental impact" than the HPS lighting system (38%–47% reduction). The use phase dominates the total "environmental impacts" (approximately 74%–97% for HPS lighting systems, and 78%–100% for LEDs).

Table **4** shows the potential change in the manufacturing stage when HPS lamps are replaced with LED in 4(f).

The increase is significant for energy demand, eco-cost and potential for future sustainable production (EPS2015).

See Supplementary information Sheet 4(f) for full details.

4.3. Lead as an Alloying Element in Steel for Machining Purposes and in Galvanised Steel Containing Up to 0,35 % Lead by Weight - 6(a)

4.3.1. Environmental Impact of Lead Compared to Bismuth as an Alloying Element in Steel for Machining Purposes

Low levels of lead (0.2-0.35wt%) are added to free cutting steels (e.g. 11S30Mn and 16Mn5Cr) to improve machinability. For environmental reasons, there is interest in alternatives to lead that are technically and commercially viable [22].

This exemption is heavily reliant on the overall impact of bismuth compared to lead. Bismuth has a lower toxicity but a higher overall impact than lead mainly due to resource scarcity issues [16]. Table **5** shows the potential change when Pb is replaced with Bi in 6(a).

The increase is insignificant for energy demand and eco-cost but very high for relative resource scarcity (ABU) and potential for future sustainable production (EPS2015).

Table 5: Indicative Change for CED, EPS, LIME and ABU for Exemption 6(a)

	11S30Mn with 0.35wt% Pb	11S30Mn with 0.35 wt% Bi	Change
CED	17.96	18.05	+0.53%
EPS2015	2.86	99.5	+3380%
LIME2	480	479	-0.21%
ABU	0.00088	0.41	+46763%

See Supplementary information Sheet 6(a) for full details.

4.4. Lead as an Alloying Element in Aluminium Containing up to 0,4 % Lead by Weight - 6(b)

4.4.1. Environmental Impact of Lead as an Alloying Element in Aluminium Containing Up to 0,4 % Lead by Weight

When secondary aluminium – used in products partially made of mixed aluminum in turn made of some secondary aluminium – is recycled, lead (Pb) may be transferred to the next secondary aluminium. This suggests that the lead concentration over time will increase in secondary aluminium. One option to reduce the lead concentration in aluminium scrap – required if 6(b) is revoked - is to dilute with primary aluminium. Hence, the environmental trade-off is heavily reliant on the net overall impact of less import of EEE articles as source for recycled aluminum compared to more primary aluminum production to replace the import (see Figure **1**).

Table **6** shows the potential change when secondary Al imports are replaced with primary aluminum in 6(b).

The increases are quite significant for both energy demand and eco-cost. However, more sensitivity analyses are necessary, e.g. regarding shares of imported EEE article related scrap (containing aluminium) and domestic aluminum scrap (from all sources) for aluminium recycling processes in the EU, respectively. Currently 5% and 95% are assumed, respectively. These shares will determine the lead (Pb) content more precisely and thereby the amount of primary aluminum required for decreasing the lead concentration.

See Supplementary information Sheet 6(b) for full details.

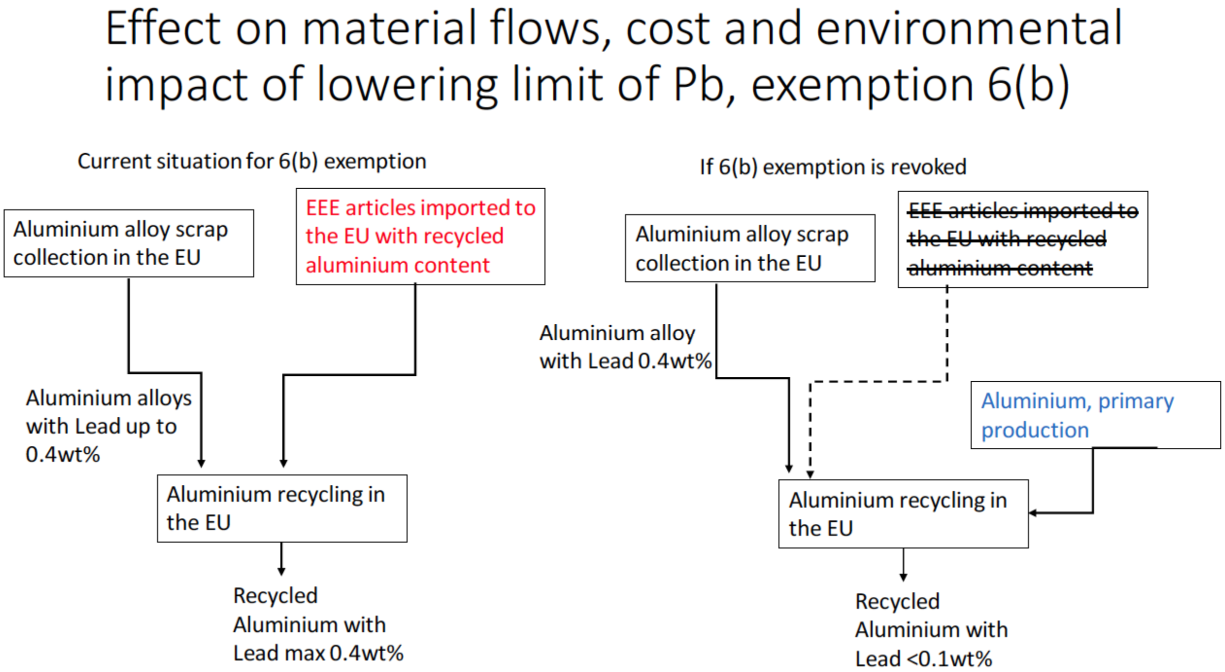

Figure 1: Principal effect of revoking exemption 6(b).

Table 6: Indicative Change for CED, EPS, LIME and ABU for Exemption 6(b)

	Secondary Aluminum with 0.4 wt% Pb (using domestic and imported EEE becoming Al scrap source)	Secondary Aluminum with 0.1 wt% Pb (using domestic scrap and primary Aluminium)	Change
CED	27	43	+45%
EPS2015	0.036	0.053	+45%
LIME2	150	218	+45%
ABU	1.22E-06	1.76E-06	+45%

Table 7: Indicative for CED, EPS, LIME and ABU for Exemption 6(c)

	CuZn39Pb3	CuZn37	CuZn42	CuZn40	CuZn21Si3P
CED	92.80	95.89	94.46	95.03	96.22
EPS2015	77.12	69.26	66.33	67.50	74.98
LIME2	5755.28	6169.30	5763.80	5926.00	7100.10
ABU	0.0174	0.0158	0.0157	0.0157	0.0155

Table 8: Indicative Change for CED, EPS, LIME and ABU for Exemption 6(c) – Lead-Free Brass Compared to Leaded Brass

	CuZn37	CuZn42	CuZn40	CuZn21Si3P
CED	3.3%	1.8%	2.4%	3.7%
EPS2015	-10.2%	-14.0%	-12.5%	-2.8%
LIME2	7.2%	0.1%	3.0%	23.4%
ABU	-9.2%	-9.9%	-9.6%	-10.8%

4.5. Copper Alloy Containing Up to 4 % Lead by Weight - 6(c)

4.5.1 Environmental Impact of Copper Alloy Containing Up to 4 % Lead by Weight Compared to Lead-Free Alternatives

Lead is added to brass (zinc-copper alloys, e.g. CuZn39Pb3). For health and safety reasons, there is interest in alternatives to lead that are technically and commercially viable [23].

This environmental trade-off is heavily reliant on the overall impact of copper and zinc compared to lead. Tables **7** and **8** show the potential change when lead is removed from brass.

The increase is insignificant for energy demand and for eco-cost, except for CuZn21Si3P. However, lead-free brass alternatives seem to have lower relative resource scarcity (ABU) and better availability of future sustainable production (EPS2015).

See Supplementary information Sheet 6(c) for full details.

4.6. Lead in High Melting Temperature Type Solders (i.e. Lead- Based Alloys Containing 85 % by Weight or More Lead) - 7(a)

4.6.1. Environmental Impact of Sn-95Pb Compared to Alternatives for Use in High Melting Temperature Type Solders

High-melting point (HMP) solders are used widely in electronics [2,6]. The traditional HMP has a very large share of lead why alternatives are sought.

Tables **9** and **10** show the potential change when lead is removed from HMP.

Table 9: Indicative for CED, EPS, LIME and ABU for Exemption 7(a)

	CED	EPS2015	LIME2	ABU
Alloys included for 7(a)				
Sn-95Pb	38	397	2982	0.09
Sn-58Bi	171	16442	19139	68.42
Au-20Sn	205674	1616096	46088980	200.09
Bi-2.5Ag	212	29120	7298	115.04
Sn-43Sb	270	8101	38321	2.40
Sn-5Sb	331	1368	44135	0.66
Bi-11Ag	765	32928	30462	106.17
Sn-25Ag10Sb	1875	20333	100395	4.12
Zn-30Sn	156	167	14212	0.14
Epoxy-80Ag	5240	58240	218400	10.67

Table 10: Indicative Change for CED, EPS, LIME and ABU for Exemption 7(a) – Lead-Free HMP Solder Compared to Sn-95Pb Solder

	Sn-58Bi	Au-20Sn	Bi-2.5Ag	Sn-43Sb	Sn-5Sb	Bi-11Ag	Sn-25Ag10Sb	Zn-30Sn	Epoxy-80Ag
CED	347%	537088%	455%	606%	763%	1898%	4798%	308%	13585%
EPS2015	4047%	407491%	7244%	1943%	245%	8205%	5028%	-58%	14589%
LIME2	542%	1545369%	145%	1185%	1380%	921%	3266%	377%	7223%
ABU	76262%	223221%	128297%	2576%	640%	118401%	4494%	57%	11805%

Several other HMP solder alloys have been proposed, e.g. Au-30Ga, Au–20Sn/Ni and Au–12Ge/Ni [24]. However, those are assumed similar to Au-20Sn in this context.

Tables **11** and **12** show the Spearman rank analysis for 7(a).

As shown in Table **12**, there is a strong positive correlation between CED and LIME2 and also between EPS2015 and ABU.

See Supplementary information Sheet 7(a) for full details.

4.7. Cadmium and its Compounds in Electrical Contacts – 8(b)

4.7.1. Environmental Impact of Cadmium and its Compounds Compared to Alternatives for Use in Electrical Contacts

Silver cadmium oxide (AgCdO) is used in switching electrical contacts. The traditional silver oxides may use Cd why alternatives are sought to avoid the use of cadmium [25,26].

This environmental trade-offs are heavily reliant on the overall impact of cadmium compared to silver, zink,

Table 11: Ranking of 7(a) Metal Alloys for CED, EPS2015, LIME2 and ABU

Alloys included for 7(a)	CED	EPS2015	LIME2	ABU
Sn-95Pb	10	9	10	10
Sn-58Bi	8	6	7	4
Au-20Sn	1	1	1	1
Bi-2.5Ag	7	4	9	2
Sn-43Sb	6	7	5	7
Sn-5Sb	5	8	4	8
Bi-11Ag	4	3	6	3
Sn-25Ag10Sb	3	5	3	6
Zn-30Sn	9	10	8	9
Epoxy-80Ag	2	2	2	5

Table 12: Spearman Correlation of Ranking of Metal Alloys of 7(a) Metal Alloys for CED, EPS2015, LIME2 and ABU

	CED (MJ/kg)	EPS2015 [10], (Euros/kg)	LIME2 (JPY/kg) [11]	Abundance in earth's crust and in the Oceans (ABU) (kg/mg) [9]
CED (MJ/kg)	1	0.82	0.93	0.58
EPS2015, (euros/kg)	0.82	1	0.61	0.88
LIME2 (JPY/kg)	0.93	0.61	1	0.36
ABU (kg/mg)	0.58	0.88	0.36	1

Table 13: Indicative for CED, EPS, LIME and ABU for Exemption 8(b)

	AgCdO	AgZnO	$AgSnO_2$	AgNi
CED	2998	3760	2889	4509
EPS2015	66777	41499	30593	47161
LIME2	124678	155950	134511	179646
ABU	9.26	7.60	5.76	8.63

Table 14: Indicative Change for CED, EPS, LIME and ABU for Exemption 8(b) – Cadmium-Free Silver Oxide Compared to Cadmium Silver Oxide

	AgZnO	$AgSnO_2$	AgNi
CED	25.4%	-3.6%	50.4%
EPS2015	-37.9%	-54.2%	-29.4%
LIME2	25.1%	7.9%	44.1%
ABU	-17.9%	-37.8%	-6.8%

tin and nickel. Tables **13** and **14** show the potential change when cadmium is removed from silver oxides.

The increase is noticeable for energy demand and for eco-cost except for $AgSnO_2$. However, cadmium-free alternatives seem to have lower relative resource scarcity (ABU) and better availability of future sustainable production (EPS2015).

See Supplementary information Sheet 8(b) for full details.

4.8. Lead in Solders to Complete a Viable Electrical Connection between Semiconductor Die and Carrier within Integrated Circuit Flip Chip Packages for Bonding to Cadmium Zinc Telluride (CZT) and Special Criteria – 15 and 15(a)

4.8.1. Environmental Impact of Lead in Solders to Complete a Viable Electrical Connection between Semiconductor Die and Carrier within Integrated Circuit Flip Chip Packages

Lead is used is solders on bumps as first level flip chip interconnections [27,28]. Lead-free alternatives are explored such as Sn-3.5Ag-0.7Cu [29], Sn-54Bi-29.7In [30], and Sn-58Bi [31].

Table **15** shows the potential change when lead is removed from SnPb37.

Table **15** confirms earlier research [32].

Tables **16** and **17** show the potential change when lead is removed from bismuth-lead alloys.

The increase is noticeable for energy demand, eco-cost, relative resource scarcity (ABU) and EPS2015 for all lead-free alloys.

See Supplementary information Sheet 15 and 15(a) for full details.

4.9. Lead in Cermet-Based Trimmer Potentiometer Element – 34

4.9.1. Environmental Impact of Lead Compared to Alternatives for Use in Cermet-Based Trimmer Potentiometer Element

Lead is used as PbO in glass resistive inks in cermet based trimmer potentiometers. Alternatives to lead are sought. Boron, phosphorus, zinc, tin, bismuth oxides may be used [33]. Tables **18** and **19** show the potential change when lead atoms are replaced with other metalss.

Table 15: Indicative for CED, EPS, LIME and ABU for Exemption 15(a) – Node and Die Geometry

	Sn-Pb37	Sn-Ag3.5-Cu0.7	Change
CED	221	554	+151%
EPS2015	449	3010	+570%
LIME2	28574	52633	+84%
ABU	0.30	0.88	+193%

Table 16: Indicative for CED, EPS, LIME and ABU for Exemption 15 - Bonding to Cadmium Zinc Telluride

	Bi50-Sn22.9-Pb27.1	Bi54-In29.7-Sn16.3	Sn-58Bi
CED	108	1156	171
EPS2015	14216	36820	16442
LIME2	10735	21777	19139
ABU	58.9	64.8	68.4

Table 17: Indicative Change for CED, EPS, LIME and ABU for Exemption 15

	Bi54-In29.7-Sn16.3	Sn-Bi58
CED	970%	58%
EPS2015	159%	16%
LIME2	103%	78%
ABU	10%	16%

Table 18: Indicative for CED, EPS, LIME and ABU for Exemption 34

	PbO	B_2O_3	P_2O_5	ZnO	SnO_2	Bi_2O_3
CED	21.4	15.8	94	63.9	268	45.4
EPS2015	363.9	0.022	2.27	26	379.6	25116
LIME2	721	113	568	855	35371	437
ABU	0.066	0.031	0.00042	0.0115	0.342	105.5

Table 19: Indicative Change for CED, EPS, LIME and ABU for Exemption 34 – Lead-Free Oxides Compared to Lead Oxide

	B_2O_3	P_2O_5	ZnO	SnO_2	Bi_2O_3
CED	-26%	339%	199%	1152%	112%
EPS2015	-100%	-99%	-93%	4%	6802%
LIME2	-84%	-21%	19%	4806%	-39%
ABU	-53%	-99%	-83%	418%	159748%

In total SnO_2 and Bi_2O_3 are likely worse than PbO while B_2O_3 is clearly better seen from all "environmental" angles.

See Supplementary information Sheet 34 for full details.

5. DISCUSSION

The present research is illuminating the problem of focusing environmental legislation on one issue, e.g. low-toxicity of the e-waste, while neglecting the manufacturing impact. Also, even if some low-toxic alternatives show environmental promise, they may not show enough technical prowess.

As for 4(f), seen over a longer period of time, use stage electricity savings may reduce the environmental impacts for LED lamps. A model has been proposed by which the electricity saved, the mercury avoided and the amount of e-waste generated can be estimated [34]. However, instead of just looking at mercury avoided in the production stage, the present research summarize the impacts of scrapping HPS lamps. Tables **1** and **2** in [20] and Table **4** in Section 4.2.1

indicate that scrapping one HPS lamp (producing 1 gigalumenhour) would lead to 12 kg waste generated (=resource depletion), and net 9000 MJ energy "wasted" by replacing existing HPS lamps with production of new LED lamps. See Supplementary Information Sheet 4(f) for details.

However, the LCAs [20,21] show that the full life cycle may favour LED. Logically, full LCA of the most common applications of each exemption should be attempted.

For exemption 6(a) the key divider is bismuth's scarcity compared to lead, reflected by EPS2015 and ABU methods. However, it is not really clear if the unit based environmental impact (eco-cost and primary energy) of bismuth is higher than for lead.

For exemption 6(b) the share of aluminium to EU secondary aluminium production from EEE imports is not clear. A higher share than 5% of imported EEE Al scrap would enhance the negative consequential effect resulting from more primary aluminium production.

For exemption 6(c) the lead-free alternatives show promise explained by zincs higher abundance compared to lead.

For exemption 7(a) the lead-free alternatives are not by any stretch of the imagination a good idea from an overall environmental standpoint. Au-20Sn is several orders of magnitude worse than Sn-95Pb for all four indicators. All others alloys follow suit. Zn-30Sn is better than Sn-95Pb for EPS2015 but clearly detrimental for the other three indicators.

Exemption 8(b) resembles 6(c) in the sense that no clear conclusion for overall sustainability can be drawn. While having slightly higher overall environmental eco-cost impacts, the cadmium-free alternatives have a better resource abundance than AgCdO.

For exemption 15(a) the lead-free alternative is worse due to tin and silver properties.

For exemption 15 neither of the lead-free alternatives are not preferable, especially that based on indium.

For exemption 34 the pattern is different from the other exemptions as one of the lead-free alternatives show extraordinary high promise compared to the others, namely B_2O_3 for all for four indicators (See Tables **18** and **19**). Also P_2O_5 and ZnO are way better for EPS2015 and ABU. SnO_2 and Bi_2O_3 are significantly worse than PbO expect for LIME2 for Bi_2O_3.

Impact Assessment and Background Systems

The actual meaning of the weighting methods and the (secondary) LCI data is more often than not trickier than the routine based calculations imply. The practitioner more or less need to check every data point for precision and reasonableness. The difference between EPS2015 evaluation of the secondary LCI data and single EPS2015 ore damage factors may be very different. Zinc is one example, 32.4 euro/kg for zinc resource in EPS2015 however 1770 euro/kg when analysing "Zinc {GLO}| market for | Alloc Def, U" with the full EPS2015 method. 95% of the 1770 euro/kg are related to Cd and Pb resources when Zn is produced as a by-product. The full EPS2015 evaluation will be strongly dependent on how the metal has been produced. A plain and clean approach with transparent assumptions for all metals is preferable. Al and Mg are abundant but still cause relatively high environmental impacts when produced. Conversely for Bi, modelling of one mine may show very small environmental impacts (e.g. low CED) but still the metal is not particularly abundant. Au production causes great environmental impacts as it takes much primary energy to produce an ingot from cradle to gate. Au is also not abundant. Au is ranked first in all four indicators in Table **2**.

Generally, one data source and economic allocation may show more divergence than more comprehensive secondary LCI data.

In summary:

- For 4(f) mercury-free LED lamps are likely preferable to present HPS lamps seen from a full life cycle perspective, but not from manufacturing standpoint.
- For 6(a) 11S30Mn with Pb is environmentally preferable to 11S30Mn with Bi.
- For 6(b) the extra production of primary aluminium - as a way of reducing the lead concentration in secondary aluminium scrap – is not advantageous.
- For 6(c) lead-free brasses induce somewhat higher eco-costs but lower resource risks.

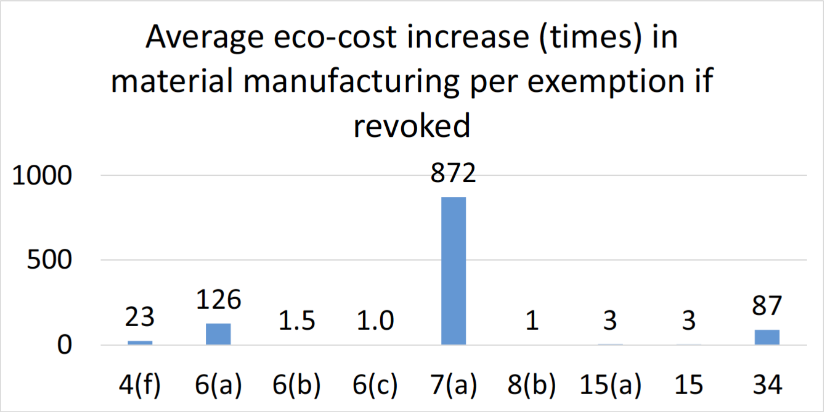

Figure 2: Average eco-cost increase in material manufacturing per exemption.

- For 7(a) Sn-95Pb is preferable to all other alloys except for Zn-30Sn for EPS2015.
- For 8(b) Compared to AgCdO, Cd-free alternatives lead to higher eco-costs but lower resource risks.
- For 15 and 15(a) all lead-free alternatives mean that the environmental impact increase in manufacturing.
- For 34, B_2O_3 is remarkably better than PbO whichever way one measure.

There are indeed examples of Pb, Cd, Hg-free alternatives in the present scope which may be adequate (Cu-40Zn, Cu-42Zn, $AgSnO_2$ and especially B_2O_3), but the opposite examples are in the majority.

Figure **2** shows how many times on average the material manufacturing costs will increase if the exemptions at hand are revoked. The average concerns all material combinations for all four indicators (See Supplementary Information Sheet Figure **2**).

6. CONCLUSIONS

- The combined environmental impact of material manufacturing will overall rise as a result of derogating RoHS exemptions 4f, 6a, 6b, 6c, 7a, 8b, 15a, 15 and 34.
- There is not a perfect positive correlation between CED score of metal alloys and scores for LIME2, EPS2015 and ABU. However, there are very strong positive correlations between CED and LIME2 on one hand and EPS2015 and ABU on the other.

7. NEXT STEPS

Obviously the use stage in an LCA may be significantly affected by material properties of lead, cadmium and mercury-free alternatives. The most noticeable technical parameters are reliability affecting the EEE lifetime, electrical losses, surface/volume resistivity, and electric conductivity affecting the power consumption.

The co-product situations in the global mining industry lead to almost irresolvable allocation problems in terms of estimating the resource risks for several metals. However, ABU factors as such are fairly well defined and strongly correlated to EPS2015 damage factors.

HPS lamps for horticulture lighting may need less material compared to batteries of horticulture LED modules for the same plant area. This could be included in future LCAs.

AUTHOR CONTRIBUTIONS

Anders S.G. Andrae wrote the entire paper.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

SUPPLEMENTAL MATERIALS

The supplemental materials can be downloaded from the journal website along with the article.

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