

## THE SHIFT TO LEAD-FREE SOLDERS - AN ANALYSIS OF THE ENVIRONMENTAL EFFECTS USING TWO DIFFERENT LIFE CYCLE INVENTORY MODELS

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### Abstract

Electronics packaging is a research field that deals with everything in electronics, from the chip to the complete system, including the solder interconnection materials. As of July 1<sup>st</sup> of 2006, lead will not be allowed in solder pastes. This has called for evaluations of alternatives to tin-lead solders, and especially the environmental consequences of the shift from tin-lead solder paste (TL) to lead-free solder paste (LF). In 2003 a life cycle assessment (LCA) was initiated, having two aims: (i) to compare an TL (62% tin, 36% lead, 2% silver) to an LF (95.5% tin, 3.8% silver, 0.7% copper); both pastes assumed to include 10% flux, and (ii) to compare attributional and consequential LCA methodologies. The attributional LCA describes the environmental burdens of the solder life cycle. It describes, for example, the obvious fact that the shift from TL to LF means that lead is essentially eliminated from the solder life cycle. Our attributional LCA is largely based on literature data. Lacking environmental data for flux production, we used the economic input-output model from Carnegie Mellon to obtain approximate values<sup>1</sup>. Preliminary results from the attributional LCA, indicate that LF contributes 10% more to the global warming potential (GWP) than TL. 60% of the difference, can be related to an increased reflow energy consumption, and 40% to an increased tin production. The production of flux contributed to about 5 % of the total GWP results for both solders. We have recently started the consequential LCA. It aims at describing how the environmental burdens of the technosphere are affected by a shift from TL to LF. It will describe, for example, to what extent the shift means that the total use of lead is reduced, and to what extent it means that the use of lead will increase in other life cycles. We do not expect the consequential LCA to include all inputs to the solder, because, for each input in the analysis, we need to investigate the supply curve as well as the demand curve, identifying price elasticities, marginal production, and marginal consumption.

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<sup>1</sup> <http://www.eiolca.net>

## 1. Introduction

Solder pastes are used by electronics manufacturers to provide electrical interconnections between electrical components and the Printed Wiring Board (PWB). Lead (Pb) has been used in solders for a long time. As the poisonous Pb has been banned from paint and tubes, it has also been proposed to ban it from solder use. Lead-free solders are not entirely new materials but, so far, have not been extensively used. Of the Pb present in European landfills, 40 % originates from consumer electronics<sup>2</sup>. The analysis of environmental impact of lead-free solders compared to lead-tin solders would be relevant as not to introduce a worse alternative, worldwide for a long time. Various environmental investigations of the introduction of lead-free solders have been performed. The conclusions by Griese et al.<sup>3</sup>, Mihaescu et al.<sup>4</sup> on one hand, and on the other Turbini et al.<sup>5</sup>, Verhoef et al.<sup>6</sup> seem to contradict one another on the issue whether lead-free solders are environmentally better or worse than tin-lead solders.

## 2. Goal and scope definition

### 2.1 Goal definition

The main goals of this study are:

- To investigate the potential environmental effects associated with a global shift from the common solder paste Sn62Pb36Ag2 (TL) to a common lead-free solder paste Sn95.5Ag3.8Cu0.7 (LF) during the whole life-cycle.
- To compare attributional and consequential methodologies for life cycle inventory analysis (LCI), and analyse how they complement each other in environmental assessments. The attributional LCI (ALCI) describes the environmental burdens of the solder life cycles. The consequential LCI (CLCI) aims at describing how the environmental burdens of the technosphere are affected by a shift from TL to LF.

### 2.2 Scope definition

The functional unit chosen in this study is the volume (approx. 300 mm<sup>3</sup>) of solder paste corresponding to 2.5 g TL needed to mount components onto one PWB. The density is higher for TL, 8.4 g/cm<sup>3</sup> compared to 7.39 for LF. The flux constituent and share of the weight is assumed to be the same for both solder pastes. The schematic product system structure of both solder paste systems in the ALCI is shown in Fig. 1.

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<sup>2</sup> Verhoef, E. V., Reuter, M.A., Scholte, A., "A Dynamic LCA Model For Assessing the Impact of Lead Free Solder" in *Proc. Yazawa International Symposium: Metallurgical and Materials Processing: Principles And Technologies*, Vol. 2: High Temperature Metal Production, San Diego, CA, U.S.A. pp. 605-623, 2003.

<sup>3</sup> Griese H. J., Müller J., Reichl H., Somi G., Stevels A., Zuber K. H., "Environmental Assessment of Lead Free Interconnection Systems" in *Proc. Lead Free Interconnect Technology*, SMTA, Boston, USA, 2000.

<sup>4</sup> Mihaescu R., Carstea, H., "Ecological Technologies for Soldering Without Lead in Electronic and Telecommunications - Today and Tomorrow" in *Proc. 26th IEEE International Spring Seminar on Electronics Technology*, Stara Lesna, Slovak Republic, pp. 232-234, 2003.

<sup>5</sup> Turbini L. J., Munie, G.C., Bernier, D., Gamalski, J., Bergman, D.W., "Examining the environmental impact of lead-free soldering alternatives" *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 24, no. 1, pp. 4-9, 2001.

<sup>6</sup> Verhoef, E. V. et al. see ref. 2

The use phase of the electronic product is excluded from the study, because the choice of solder has little effect on the energy demand of the electronic product. The electrical resistance of solders is insignificant compared to other resistance in the product (a typical resistance value for a solder joint is 0.01 Ohm and for a resistor 10,000 Ohm<sup>7</sup>). The TL solder has a lower melting point than LF (183 °C compared to 217 °C) but we assume the cooling of electronic products to depend on other factors than the solder melting point.

The end-of-life stage may differ considerably in different regions of the world but it was decided to make the world the geographical system boundary. The dismantling process outflow of PBAs has a positive economic value. For this reason, we regard it not as a waste but a raw material inflow to the life cycles where the recycled metals are used. Thus the metal recycling processes belong to subsequent life-cycles and not the present one. As far as landfill emissions are concerned, metal emission factors, of landfilled metals during a surveyable time period<sup>8</sup>, were used. Another approach would be the hypothetical, infinite time period, which is the period from the start until the landfilled material is completely released to the environment<sup>9</sup>.

To describe how the environmental burdens of the technosphere are affected by a shift from TL to LF, the CLCI needs to include an analysis of how the relevant markets are affected. The preliminary structure for the CLCI system is presented in Fig. 2. The main difference compared to Fig. 1 is that the CLCI includes the lead, lead scrap, and electricity markets and the use of these goods outside the solder life cycle. On the other hand, it excludes the production of metals other than lead, and also the production of fuels. The reason is that we do not expect to be able to analyse the markets for more than a few goods in this project. The use of lead is the environmental issue that is addressed by the switch from TL to LF. Preliminary results from the ALCI indicate that electricity production is the subsystem that contributes the most to greenhouse gas emissions (cf. Fig. 4). For these reasons, we focus on lead and electricity in the consequential study.

An overview of initial data quality goals and data used is presented in Table 1. The study concerns the global shift from one solder paste to another. Solders are produced and applied worldwide. Metals, energy carriers and electronic products are traded on international markets. For this reason, the initial data quality goal is global averages for many subsystems in the ALCI. A change in demand for a metal, energy carrier etc. in the solder life cycle will affect the international markets at the margin. For this reason, the initial data quality goal is global marginal data for many subsystems in the CLCI. To analyse how the lead, lead scrap, and electricity markets are affected by a shift from TL solder, we need information about how sensitive the production and alternative use of these goods are to changes in the price.

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<sup>7</sup> Personal communication with Jerry Börjesson, engineer at Industrial Research and Development Corporation, (IVF), Mölndal, Sweden, 2004-05-17

<sup>8</sup> A surveyable time period is a period until a pseudo-state in the landfill has been obtained. This period should usually be in the order of one century. See ref. 20, page 27.

<sup>9</sup> See ref. 20, page 27.

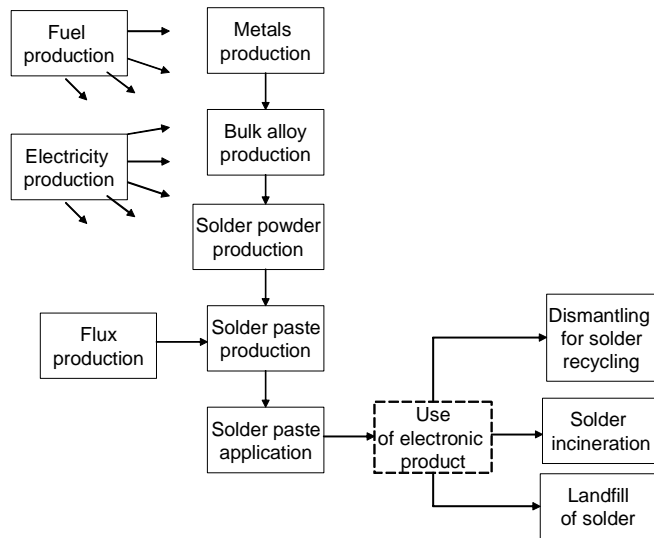


Fig. 1: Schematic structure of the attributional modelling of solder pastes TL and LF.

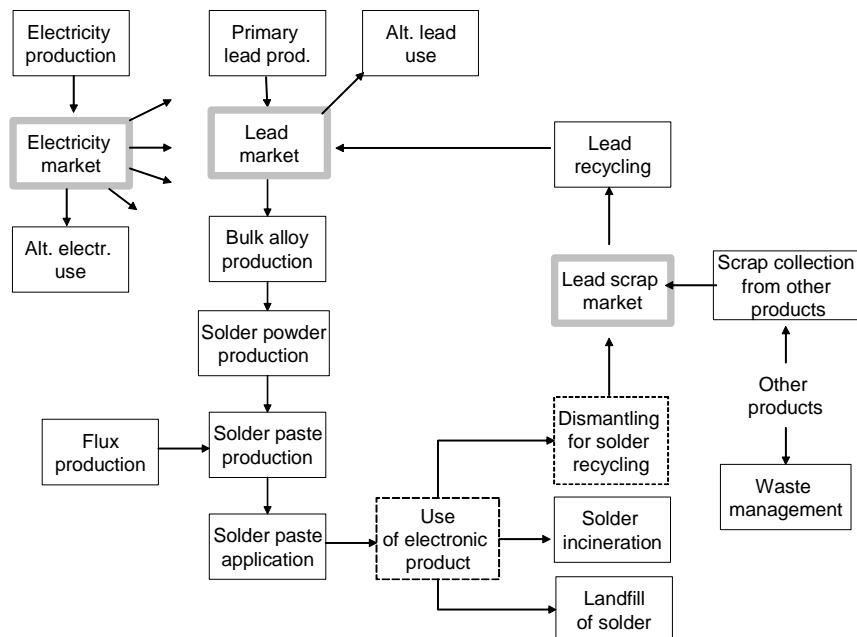


Fig. 2: Schematic structure of the consequential modelling of the switch from TL solder paste to LF solder paste.

Table 1. An overview of initial data quality goals and data used.

Subsystem	Attributional LCI		Consequential LCI
	Initial data goals	Data used	Initial data goals
Fuel production	Global average	Literature data <sup>10</sup>	n.a.
Electricity production	Global average	Global average mix of technologies <sup>11</sup> Environmental data from literature <sup>12</sup>	Global marginal
Electricity market	n.a.	n.a.	Global own price elasticity of demand and supply
Alternative electricity use	n.a.	n.a.	Global marginal
Metals production	Global average for specific metals	Literature data on primary metals production <sup>13</sup>	Global marginal for lead
Lead market	n.a.	n.a.	Global own price elasticity of demand and supply
Alternative lead use	n.a.	n.a.	Global marginal
Bulk alloy production	Global average for solder alloy	Data from one supplier of another alloy <sup>14</sup>	Global average for specific solders
Flux production	Global average for solder flux	Data from environmentally extended input/output table <sup>15</sup>	Global average for specific solders
Solder powder production	Global average for solder powder	Data from one supplier of another metal powder <sup>16</sup>	Global average for specific solders
Solder paste production and application	Global average for specific solders	Literature data <sup>17</sup>	Global average for specific solders
Dismantling for solder recycling	Global average for electronic products	Primary from one electronics dismantler <sup>18</sup>	Global average for electronic products

<sup>10</sup> The cradle-to-gate processes hard coal production, heavy fuel oil production, and diesel production included in the LCI data base from Chalmers Industriteknik (CIT), were used

<sup>11</sup> International Energy Agency (2003): Key World Energy Statistics 2003. p. 24.

<sup>12</sup> For hydropower and nuclear electricity production, the Vattenfall environmental product declarations for "Electricity from the River Lule Älv" and "Electricity from the Nuclear Power Plant at Forsmark" were used respectively, obtained from <http://www.environdec.com>. CIT provided LCI data for hard coal production/combustion, natural gas production/combustion, and heavy fuel oil production and combustion

<sup>13</sup> **Sn**: tin, at regional storage, Indexnumber 1155, obtained February 20, 2004, from the ecoinvent database at [www.ecoinvent.org](http://www.ecoinvent.org) (ECOINV), **Pb**: lead, at regional storage, Indexnumber 1103, ECOINV, **Ag**: Boustead, I and Panvalkar, S. G. "Ecoprofile of Primary Copper Production" A Report for the International Copper Association, January 1998. Boustead Consulting Ltd. Recovery of silver from copper production. pp. 71-73. Tables 92-99. **Cu**: copper, primary, couple production nickel, GLO, Indexnumber 1089, ECOINV.

<sup>14</sup> Boliden Bergsöe AB, Landskrona, Sweden. Pb and Sn alloy production, environmental report for 2002, pp. 11, 14-16

<sup>15</sup> [www.eiolca.net](http://www.eiolca.net) on "chemicals and chemical preparations, n.e.c." corresponding to the price of solder flux, obtained from <http://www.mouser.com/catalog/618/1267.pdf> for SP 44 Paste Flux, accessed 2004-06-28

<sup>16</sup> Höganäs AB, Höganäs Halmstadsverken, Halmstad, Sweden. Iron powder production, environmental report for 2002, pp. 7, 10, 12

<sup>17</sup> **Solder paste manufacturing**: Geibig, J and Socolof, M. "Summary of activities for a Life-Cycle Environmental Impact Evaluation of Tin-Lead and Lead Free Solder", SPVC Meeting, April 1, 2003. Powerpoint presentation, energy inputs were obtained from slide 13 of 31. **Solder paste application**: *Oven power consumption*: Geibig and Socolof, slide 18 of 31, *Oven length*: <http://www.novastarinc.com/>, *Maximum number of boards in oven*: e-mail from Bert-Ove Johansson at Ascom Taceco AB, Herrljunga, Sweden, March 2, 2004, *Process time*: estimated by Ph.D. student Cristina Andersson, Chalmers

Solder incineration	Global average for specific solder metals	Literature data <sup>19</sup> and emission estimates <sup>20</sup>	Global average for specific solder metals
Landfill of solder	Global average for specific solder metals	Literature data <sup>21</sup> and emission estimates <sup>22</sup>	Global average for specific solder metals
Lead scrap market	n.a.	n.a.	Global own price elasticity of demand and supply
Waste management of other products	n.a.	n.a.	Global mix of regional marginals

n.a.: not applicable; subsystem excluded from study.

### 3. Inventory

Starting the solder paste life-cycle the metals silver, lead, tin and copper are globally mined. Metal bars are transported to the bulk alloy material production plant where a wave solder of the specific composition, in the present study Sn62Pb36Ag2 and Sn95.5Ag3.8Cu0.7, is manufactured by melting metals. Both primary and secondary metals can be used for bulk alloys,<sup>23</sup> but due to lack of data on metals recycling we only used data for primary metals production. The bulk alloy is transported to powder production where the solder is atomized into small spherical balls. The next step is the solder paste production where the powder is mixed with the flux system to form a paste. The flux is manufactured in parallel with the powder in another factory. The first step in the electronics assembly solder application plant is the screen printing where the paste is put onto a Printed Wiring Board (PWB). Then follows the reflow soldering process where electrical components are placed onto the PWB and the solder is melted to form a Printed Board Assembly (PBA). Thereafter the PBAs are mounted inside the electronic products (EP), which are next shipped all over the world and used. Likely no losses of solder occur during the use phase of EP. Used EP including solder are globally transported to landfills, incineration or recycling. Table 3 presents selected results from the ALCI. The electricity consumed in the life-cycles is 1.41 MJ for TL and 1.56 MJ for LF. The metal resources consumption is roughly indicated by the respective material composition.

<sup>18</sup> Phone conversation with Per Frisell at Ragn-Sells Elektronikåtervinning AB, where electricity consumption per amount dismantled electronics was obtained, May 2004.

<sup>19</sup> Environmental report for 2002 from combined heat and power plant driven by Renova AB at Sävenäs, Sweden. Most heat and electricity is produced on-site by waste incineration but the electricity bought from other suppliers was modeled as global average. pp. 4-54, 2003.

<sup>20</sup> E-mail from Jan-Olov Sundqvist, Swedish Environmental Institute, May 2004.

<sup>21</sup> Environmental report for 2002 from waste treatment facility Sänkmossen 1982-60-001, Fagersta, Sweden. <http://www.vafab.se/foretag/Smmmilr03.htm>. Electricity, Diesel and Gasoline consumptions were allocated per mass of waste handled

<sup>22</sup> Life cycle assessments and solid waste – Guidelines for solid waste treatment and disposal in LCA, AFR-report 279, ISSN 1102-6944, IVL, Swedish Environmental Research Institute, December 1999, Table 8.6, the column Municipal Solid Waste, mixed landfill, p. 129

<sup>23</sup> E-mail from Hector Steen at Multicore, United Kingdom, December 2003.

Table 2. Selection of preliminary results from the attributional LCI expressed per functional unit of Sn62Pb36Ag2 (TL) and Sn95.5Ag3.8Cu0.7 (LF).

Substance	Category	Unit	TL	LF
Coal	Resource	g	8.12E+01	8.34E+01
Oil	Resource	g	1.19E+01	1.35E+01
Natural gas	Resource	g	1.17E+01	1.28E+01
CH <sub>4</sub>	Emission to air	g	7.53E-01	8.33E-01
CO <sub>2</sub>	Emission to air	g	2.14E+02	2.31E+02
NO <sub>x</sub>	Emission to air	g	4.87E-01	5.40E-01
SO <sub>x</sub>	Emission to air	g	1.74E+00	1.97E+00
Pb	Emission to air	g	3.21E-02	5.51E-04
Pb <sup>+</sup>	Emission to water	g	2.93E-02	8.95E-06
Pb	Waste at landfill	g	7.29E-01	

In the CLCI we aim at estimating the changes in production ( $\Delta S$ ) and alternative use ( $\Delta D$ ) of lead, lead scrap and electricity. These can be estimated based on the own price elasticity of supply ( $\eta_S$ ) and demand ( $\eta_D$ ) for each of the goods:

$$\eta = \Delta Q/Q * P/ \Delta P,$$

where  $\Delta Q$  is the change in the quantity produced or demanded of a specific good, which is caused by a change in the price ( $\Delta P$ ) of the good. Hence:

$$\Delta S/ \Delta D = \eta_S/\eta_D$$

Our initial data collection indicates that  $\eta_S$  and  $\eta_D$  are difficult to find for lead and lead scrap. Several estimates of  $\eta_D$  exist for electricity, but  $\eta_S$  for electricity is complicated to estimate on a global level.

To describe how the environmental burdens of the technosphere are affected by a shift from TL to LF, we also want to identify the marginal production technologies for lead and electricity. Such technologies can be identified using, for example, a five-step procedure presented by Weidema et al.<sup>24</sup> The marginal electricity production at a global level can be assumed to be based on coal, unless climate-change policy succeeds in setting a global “ceiling” for this technology. The marginal lead production is yet unknown.

<sup>24</sup> Weidema Bo P., Frees N., Nielsen A-M., 1999, 'Marginal Production Technologies for Life Cycle Inventories', Int. J. LCA 4 (1), pp. 48-56, © ecomed publishers

In addition, we want to identify the marginal application of lead and electricity outside the solder life cycles. It is unclear if a procedure exists for identifying the marginal use of a specific good.

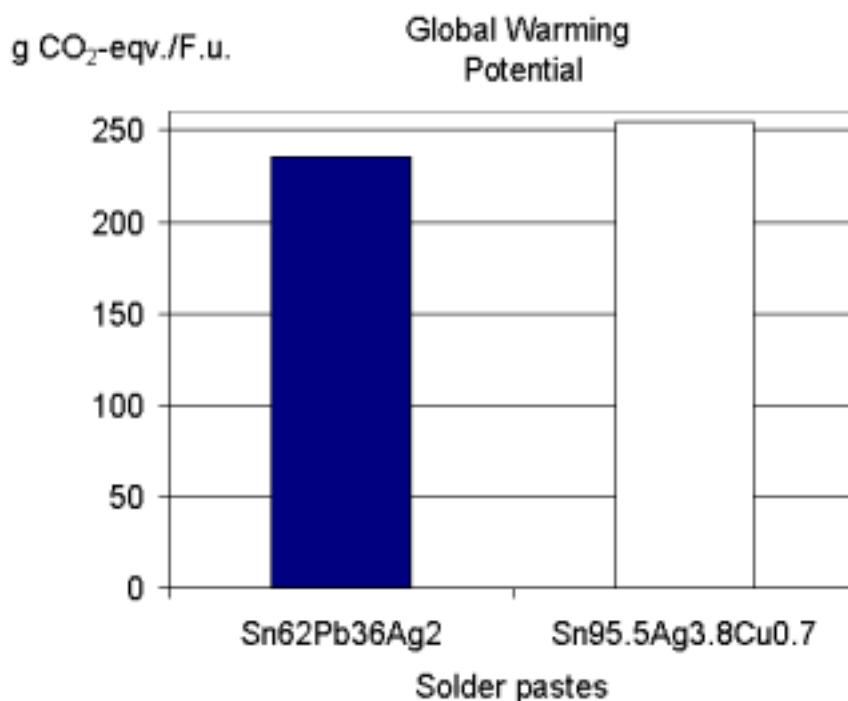
#### 4. Impact assessment

The impact category selected in this study is  $GWP_{100}$  as it has been found robust and reliable in earlier studies.

Table 3. List of impact categories for  $GWP_{100}$  included in this study, the equivalence factors and the units for characterisation factors<sup>25</sup>.

Substance	Equivalence factor	Relative contribution in Sn62 and Sn95.5 system	Units for characterisation factors
CO <sub>2</sub>	1	91	g CO <sub>2</sub> -equivalents/g
CH <sub>4</sub>	23	7	g CO <sub>2</sub> -equivalents/g

The characterised results for the solder pastes Sn62Pb36Ag2 (TL) and Sn95.5Ag3.8Cu0.7 (LF) are provided by Fig. 3. In figure 4 is shown the contribution from different life-cycle stages of LF. All results are presented per functional unit (F.u.).



<sup>25</sup> Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis*, Cambridge, UK, Cambridge University Press, Technical Summary of the Working Group I Report, Table 3, p. 47, 2001.

Fig. 3. Total GWP<sub>100</sub> results for solder pastes Sn62Pb36Ag2 (TL) and Sn95.5Ag3.8Cu0.7 (LF).

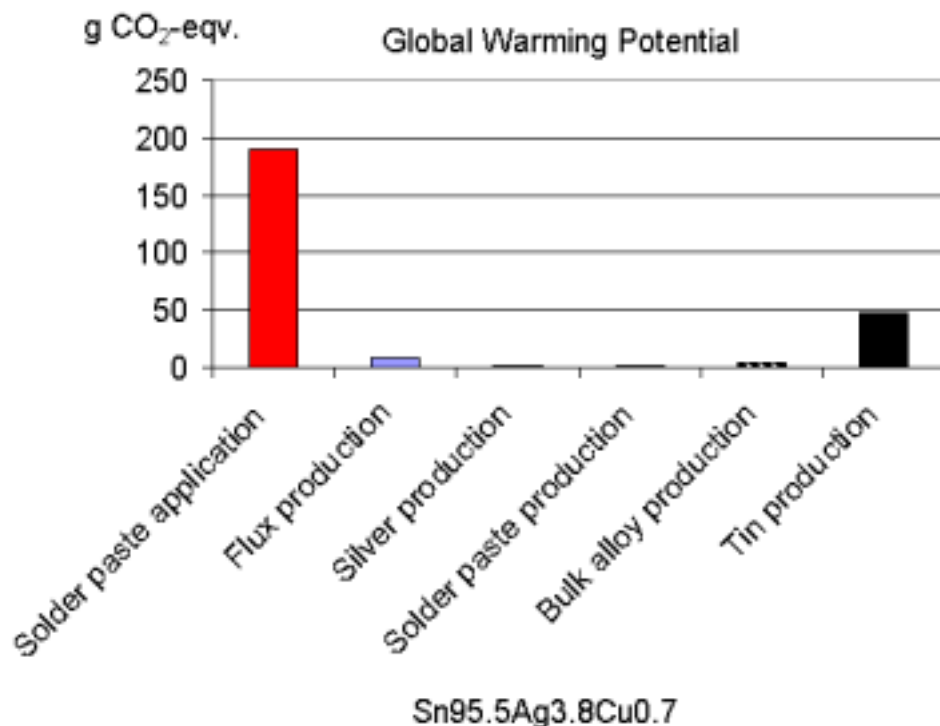


Fig. 4. Contribution from different life cycle phases to GWP<sub>100</sub> for solder paste Sn95.5Ag3.8Cu0.7 (LF). Solder paste application dominates the picture because it requires large quantities of electricity.

## 5. Interpretation

Based on global warming considerations, reflow soldering energy was considered as the most significant aspect for both solder pastes.

Silver production may have a larger global warming burden than modelled, considering that silver production was modelled as a by-product of copper production<sup>26</sup>. Actually, silver is globally produced to 31 % from zinc sources, 28% from virgin silver sources and to 25% from copper sources<sup>27</sup>. A more precise model would have been to use a weighted average of the sources from which silver is globally produced. That model also holds for the metals copper, tin and lead. The metal data used is as follows; the copper production is modelled using nickel production where copper is by-product, the tin production is modelled as primary tin production and lead production too. The main reason, for the end-of-life stage turning out

<sup>26</sup> "Ecoprofile of Primary Copper Production" A Report for the International Copper Association, I Boustead & S G Panvalkar, January 1998. Boustead Consulting Ltd. pp. 71-73. Tables 92-99. Recovery of silver from copper production

<sup>27</sup> <http://www.silverinstitute.org/supply/production.php>

to be of low global warming importance, is that the landfill and incineration plants maintenance energies are a relatively small share of the total life-cycle energy. Pb emissions to air mainly occur at the waste incineration of printed board assemblies (PBAs) containing Sn62Pb36Ag2 solder. The largest contributor of Pb water emissions is the Pb production from cradle-to-gate.

The attributional LCA describes the obvious fact that the shift from TL to LF means that lead is essentially eliminated from the solder life cycle. A consequential LCA can describe to what extent the shift means that the total use of lead is reduced, to what extent it means that the use of lead will increase in other life cycles, and, hopefully, in what products the use of lead increases when the metal is eliminated from the solder paste. It is yet an open question if a shift of lead use from solders to other products reduces or increases the risks to human health and ecosystems.

## 6. Conclusions and discussion

The following preliminary conclusions are based on results from the attributional study:

- Except for lead emissions and waste, the environmental impact of Sn95.5Ag3.8Cu0.7 (LF) solder paste compared to Sn62Pb36Ag2 (TL) is slightly higher for the LF.
- The results predominantly reflect energy use (combustion of fossil fuels), mainly for electricity production.
- The solder application stage and the tin production stage give the largest impact for both solder pastes.
- The end-of-life stage contributes little (<1%) to the total GWP<sub>100</sub> impact for TL and LF. However, the end-of-life-stage for TL may have significant toxicological impact due to Pb emissions to air from waste incineration.

Although the consequential study has only been initiated, it can still be used to illustrate the fact that attributional and CLCI give complimentary knowledge.

It appears to be difficult to find price elasticity estimates for the supply and demand of specific metals in the literature. Such estimates seems to be available for a few goods only. It might be difficult also to identify the marginal use of specific goods. The cumbersome collection or generation of economic data means that fewer flows can be traced upstreams in a CLCI compared to an ALCI. The decision regarding what flows to follow upstreams in a CLCI can be based on accumulated experience. In this case, we had little relevant experience when the project started. Instead, we used the GWP<sub>100</sub> results from the attributional study to identify the most important flow expect for lead. Using attributional results as a basis to identify the aspects to investigate in a consequential study entails a risk. Flows that are important in an ALCI might be less important in a CLCI, or the other way around.

## 7. Acknowledgement

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