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Life Cycle Assesment of Electronics. Ugelstad-particles Ball Grid Array and Chip Scale Packaging.

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Vestlandsforsking rapport

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Samandrag
Notatet oppsummerer eit prosjekt som har hatt som mål å vurdere miljøbelastning fra livsløpet til elektronikk, med spesiell vekt på Ugelstad-kuler brukt i sammenkoblingsteknologiene Ball Grid Array (BGA) og Chip Scale Packaging (CSP).

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Preface

This report is about environmental aspects of electronics. The objectives are to provide knowledge of the use of life cycle analysis for assessment of environmental impacts of electronics, as well as to provide insight into the environmental implications of using monodisperse polymer particles, so-called Ugelstad particles, in microelectronics, specifically in Ball Grid Arrays (BGA) used in Chip Scale Package (CSP) manufacturing.

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1 List of abbreviations and acronyms

ACA	Anisotropic Conductive Adhesive
ADSL	Asymmetric Digital Subscriber Line
ALCA	Attributional LCA
BGA	Ball grid array
BOM	Bill of materials
CLCA	Consequential LCA
CSP	Chip scale package
Eco–Indicator’99 (H)	Indicator from weighting of 3 main impact categories: 1) reduction in ecosystem quality, 2) damage to mineral and fossil resources and 3) damage to human health. Developed by PRé Consultants.
EFSOT	Environment-Friendly Soldering Technology (http://www.efsot-europe.info)
GWP100	Global warming potential (GWP) relative to that of CO_2 over a 100 year long period
ICs	Integrated circuits
IPCC	The Intergovernmental panel for climate change
LCD	Liquid Crystal Display
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFBGA	Low–profile Fine–pitch Ball Grid Array
MEEuP	Method for the Evaluation of Energy using Products
MPP	Monodisperse Polymer Particle
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PEU	Primary energy usage
PGA	Pin Grid Array
PWB	Printed wiring board
Si die	Silicon die
TQFP	Thin Quad Flat Pack
WCSP	Wafer Level Chip Scale Package

2 Summary

During the last decades the electronics industry has undergone tremendous changes due to intense research leading to advanced technology development. Multiple life cycle assessments (LCA) have been performed on the environmental implications of consumer electronics. The aim of this report is to provide knowledge of the use of LCA for assessment of environmental impacts of electronics, as well as to provide insight into the environmental implications of using monodisperse polymer particles, so-called Ugelstad particles, in microelectronics, specifically in Ball Grid Arrays (BGA) used in Chip Scale Package (CSP) manufacturing.

In the review of LCAs we wanted to assess the consistency between different LCA studies for desktop computers, laptop computers, mobile phones, and televisions. A literature study was thus conducted covering some key LCA contributions to the consumer electronics field. The focus is primarily on GWP100 efficiency in different life cycle phases, and secondarily on primary energy usage/electricity usages which are normalized per year to find inconsistencies.

The LCIA GWP100 results for consumer electronics over the years suggest that most studies are of comparable quality, however, some studies are neither coherent nor transparent. Published LCAs for mobile phone and TV sets are consistent, whereas for laptop and desktop computers the studies occasionally give conflicting messages.

The inconsistencies appear to be rooted in subjective choices and different system boundaries and life time, rather than lack of standardization. If included, the amounts of emissions of sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) are crucial to the GWP100 in the various life cycle phases for a desktop using LCD screen. The GWP100 of SF_6 is 22,800, while that of NF_6 is 17,200. Another important observation is that the MEEuP Methodology report/tool underestimates the GWP100 of electronic component manufacturing processes.

Between 1997 and 2010, the ISO 14040/44 standards have ensured a rather consistent set of GWP100 results for the studied products. However, the lack of transparency for consumer electronics LCAs sometimes makes benchmarking difficult. It is nevertheless possible to compare new LCA calculations to existing studies. It is also possible to reveal which product studies are consistent with studies of sub–materials and sub–components. In most cases, the GWP100 results for consumer electronics are consistent. Based on the survey of published work, recycling and other end–of–life processes have a tiny share of the total GWP100 score for consumer electronics. It is important for Conpart to know this, in order to focus on areas with the largest impact.

Few studies have been published on the micro/nanosystems technologies providing same benefit. Nano structured polymer particles are produced to be used in ball grid array (BGA) and chip scale packaging (CSP). The technology could replace conventional BGA and CSP metal balls and the hypothesis is that the shift will be eco-efficient as polymer core particles might increase reliability. For the first time these particles are environmentally evaluated in their system perspective.

The relative impact share of BGA balls in a BGA package was estimated. Moreover, change in environmental loadings when replacing traditional component packaging, here Quad Flat Pack (QFP) to BGA/CSP, was explored both on component and printed circuit board assembly (PCBA) level. This was followed by LCI comparisons between BGA packages using different types of metal plated polymer balls and conventional balls, respectively. On top of this LCIs were explored for GWP100 and Eco–Indicator'99 (H) single weighting scores in order to estimate eco–efficiencies.

For BGAs the silicon (Si) die dominates CO_2e emissions, but Eco–Indicator'99 (H) scores for solder balls are not negligible. Excluding the Si die and component assembly, changing a Thin Quad Flat Pack (TQFP)–64 for a Low–profile Fine–pitch Ball Grid Array (LFBGA)–84 would reduce CO_2e by about 4% and increase Eco–Indicator'99 (H) by about 25%. Changing the LFBGA–84 to WCSP–64 would reduce CO_2e by about 98% and Eco–Indicator'99 (H) by about 90%. Overall for BGA–256 using same size balls, gold plated ball technology decreases the Eco–Indicator'99 (H) score by about 25% compared to Pb based or Pb–free balls. Excluding all sub–parts of BGA–256 components, except the balls, showed that gold production dominated the environmental impact, as expressed by the GWP100 and Eco–indicator'99 (H), for the gold plated alternative.

This research has conservatively demonstrated how to quantify the environmental change induced by miniaturization of specific electronic components. Not all BGAs will reduce the environmental footprint from the package materials alone. Each micro-system is unique and new environmental impact estimations must be done for the sub–structures of each electronics device. Even though the metal mass per ball is greatly reduced, it is a weak indicator of environmental impacts, which are driven by each materials specific environmental characteristics.

The ball share of the BGA–256 GWP100 and Eco–indicator'99 (H) scores are small and the BGA/CSP producers can only marginally improve the environmental performance by focusing on the balls. On PCBA level the contribution from BGA balls is negligible. Results for metal plated monodisperse polymer particles (MPP) BGA balls suggest that gold usage is the key environmental performance indicator of interest. The eco–efficiency of using gold makes up for it to a certain degree. Especially metal plated MPP balls of reduced size and identical functionality, could demonstrate eco–efficiency by being more reliable. For metal plated MPP balls, the eco–efficiency scores increase with decreasing ball diameter.

Screening LCA is a good method for identifying environmental improvement possibilities in technology development. The off–set effect of CSP miniaturization, driven by more and more PWB layers, must be included in further electronics micro-system expansions. For LCA in general, it is necessary to update all LCIA methods which include ozone depletion, with the latest results for nitrous oxide (N_2O).

3 Introduction

During the last decades the electronics industry has undergone tremendous changes due to intense research leading to advanced technology development. Multiple LCA studies have been performed on the environmental implications of consumer electronics. For assessing the usefulness of LCA in determining the environmental implications of advances in electronics, we found it necessary to conduct a review of LCA studies on consumer electronics products. This would provide valuable knowledge for assessment of the consistency between such studies of desktop computers, laptop computers, mobile phones, and televisions.

Between 1997 and 2010, the ISO 14040/44 standards have ensured a rather consistent set of GWP100 results for the studied products. However, the lack of transparency for consumer electronics LCAs sometimes makes benchmarking difficult. It is nevertheless possible to compare new LCA calculations to existing studies. It is also possible to reveal which product studies are consistent with studies of sub–materials and sub–components.

Few studies have been published on the environmental implications of different micro/nanosystems technologies providing same benefit. Nano structured polymer particles, based on the Ugelstad process, are produced by Conpart AS to be used in ball grid array (BGA) and chip scale packaging (CSP). The technology can have the potential to replace conventional BGA and CSP metal balls. The hypothesis is that the shift will be eco-efficient as polymer core particles might increase reliability. It has never before been conducted LCA-studies on these particles, for evaluating their life cycle environmental impacts within their electronics system.

For the purpose of clarifying the basic concepts of the methods applied in this research we have included in this report a chapter with a short introduction to life cycle assessment. The intention is that this can serve as an introduction for those readers who are not familiar with the LCA method.

4 Short introduction to Life Cycle Assessment

Life cycle assessment (LCA) is a technique for assessing the potential environmental impacts associated with a product or service. ISO standards exist for LCA, the so called ISO14040s. An LCA consists of four different phases': goal and scope, inventory, impact assessment and an interpretation phase.

It is common to distinguish between an attributional LCA (ALCA) that tries to answer questions such as "What environmental impact can this product be held responsible for?" and a consequential approach (CLCA) where the aim is to assess environmental burdens due to change in demand. Consequential LCA requires an economic-causal way of thinking; i.e., which processes are affected when a change in demand for a product under study occurs. In CLCA marginal data are used to calculate the technologies that are most affected, such as which electricity plant will be installed as a result of increase in demand for electricity.

The objective of an LCA is to estimate the potential environmental loadings associated with the manufacturing, use, and disposal of a product. It is a holistic approach that compares alternatives with respect to their environmental impacts. In solving one problem we generate another process with its associated impacts.

The goal and scope definition of an LCA provides a description of the product system in terms of the system boundaries and a functional unit. The functional unit is the important basis that enables alternative goods, or services, to be compared and analysed. The functional unit is not usually just a quantity of material. Practitioners may compare, for example, alternative types of packaging on the basis of 1 m^3 of packed and delivered product—the service that the product provides. The amount of packaging material required, termed the reference flow, can vary depending on the packaging option selected (paper, plastic, metal, composite, etc.).

Life cycle inventory (LCI) is a methodology for estimating the consumption of resources and the quantities of waste flows and emissions caused by or otherwise attributable to a product's life cycle. The processes within the life cycle and the associated material and energy flows as well as other exchanges are modeled to represent the product system and its total inputs and outputs from and to the natural environment, respectively. This result in a product system model and an inventory of environmental exchanges related to the functional unit. In the life cycle inventory the data for each unit process within the scope are collected. It is the most time-consuming and most important phase of an LCA. Basically it is mass and energy balances that are set up.

Life cycle impact assessment (LCIA) provides indicators and the basis for analyzing the potential contributions of the resource extractions and wastes/emissions in an inventory to a number of potential impacts. The result of the LCIA is an evaluation of a product life cycle, on a functional unit basis, in terms of several impacts categories (such as climate change, toxicological stress, noise, land use, etc.) and, in some cases, in an aggregated way (such as years of human life lost due to climate change, carcinogenic effects, noise, etc.

Interpretation is the phase of LCA in which the result from the inventory analysis and the impact assessment are considered collectively. The interpretation phase ought to bring results that are consistent with the defined goal and scope phase of the study. In this phase the LCA practitioner should reach conclusions, explain limitations and present recommendations (ISO 1440).

5 LCA of electronics products

5.1 Background, aim and scope

It is well–known that the research of environmental problems should be carried out using a multidisciplinary approach, using appropriate tools. As such, LCA has the potential to point out the important issues from an environmental point of view. LCA is e.g. useful for rather small and distinct product systems or technologies. Recently, this has been shown for as different systems as as polyols (Helling & Russel, 2009), toys (Muñoz et al., 2009), and mountain huts (Goymann et al., 2008).

During the last few decades the electronics industry has undergone tremendous changes from intense research leading to advanced technology development. LCA requires large amounts of data when applied to complex electronic products involving many technologies. Even so LCA has been used successfully to develop eco–design strategies in the electronics industry (Alonso et al., 2003; Gurauskiene & Varzinskas, 2006; Yung et al., 2009).

Many studies have been conducted on the environmental implications of different consumer electronic technologies with the same function, but no comparison of the different studies have so far been carried out. In this report we present an overview of LCA results for some common consumer electronics products. The focus is mainly on results for CO_2 equivalents (CO_2e) expressed as the global warming potential during 100 years (GWP100). Other indicators, such as primary energy usage (PEU), are usually not covered in detail in literature contributions. GWP100 is an indicator that is easy to communicate. It is however strongly related to energy usage. Therefore, we have performed a normalization the results to the same electricity mix to facilitate a better comparison of the studies. CO_2 emissions are moreover very important, as in addition to being the prime greenhouse gas, they are one of the factors enhancing the acidification of the oceans (Rockström et al., 2009). The problems of LCA in general, pointed to e.g. by Reap et al. (2008), is in the report discussed in light of LCA results for consumer electronics.

5.2 Literature review

This section is an overview of LCA results from studies of certain electronics products produced in high volumes. In order to facilitate a comparison, the GWP100 expressed as CO_2e is used.

5.2.1 LCA case studies of laptop and notebook PCs

We have included five LCA studies of laptop and notebook computers in this review. A comparison of the results of their main parameters are shown in Table 1. The five studies were:

Study 1.1: Lu et al. (2006)

The study assessed the economic and environmental implications of notebook computer recycling in China (Taiwan). It was estimated that during its life cycle a typical laptop computer emits 51 kg CO_2, 120 g methane, and 240 mg N_2O during. This translates into 54 kg

CO_2e. The weight of the laptop was 2.3 kg, of which 10 % were integrated circuits (ICs), while printed wiring board (PWB) constituted 15 %. It is of relevance for this report that the part of the LCD that consists of “Gel (epoxy resin 1)” only makes up 0.38 % by weight. 54 kg for GWP100/p seems rather small and it is not possible to derive the distribution between life cycle phases. Due to the fact that SimaPro version 5.0 was used for the modelling, there is a lack in transparency for the basis for these results.

Study 1.2: Tekawa et al. (1997)
The study by Tekawa et al. (1997) presented LCA results, mixing personal usage and office usage, for a notebook (laptop) computer indicating that emission of greenhouse gases in production and use phases were similar (44 % and 53 % respectively). The GWP100 of the emissions from the production of the main circuit board was approx. 85 kg CO_2e in the life cycle of a notebook computer. In this study it is assumed similar weight and share of printed wiring boards (PWB) and integrated circuits as for the Taiwanese laptop in Study 1.1. The NIRE–LCA software program version 2.1 was used for the modelling and the GWP100 for the 1996 Japanese average electricity mix was applied. The GWP100 index of sulphur hexafluoride (SF_6) was not included.

Study 1.3: Ecoinvent (2008a-c)
The Ecoinvent database contains LCI data modules for manufacturing, usage, and end–of–life of a typical laptop computer with the weight of 3.2 kg. In our report, these modules have been combined for a whole life cycle, by the use of SimaPro ver. 7.1. Then the total emissions of CO_2e is 660 kg per computer, of which only about 7% is from the use phase. The reason for this is the high emissions during the manufacturing of the LCD, particularly in the form of nitrogen trifluoride (NF_3) emissions, with a GWP100 of 17,200. during the assembly of the LCD module . The use phase was assumed to be 4 years and the total electricity consumption in this phase was 190 kWh. This calculation of the applied electricity was based on a mix that in total emits 0.59 kg CO_2e/kWh. The production of the main board was assessed to emit 55 kg CO_2e per notebook.

Over the years, for GWP100, the IPCC has increased the number of gases included. Bearing in mind that NF_3 lacked a GWP100 value in IPCC version 2001, the calculation was redone with NF_3 set to zero. Even so the use phase contribution only increases to 15%, explained by SF_6 emissions from LCD module assembly and magnesium production.

Study 1.4: PE International (2008)
The study by PE International published in 2008 schematically showed, mixing office and personal usages, that a small laptop of 1.5 kg emits about 410 kg CO_2e during its four year life cycle. It was assessed that the contribution from the use phase is about 2/3 of the total life cycle emissions. The main circuit board emits about 70 kg CO_2e during the life cycle of the notebook computer. Even though the literature reference is a presentation with little transparency it is reasonable to assume that GaBi LCA software and GaBi databases corresponding to 2008 was used.

Study 1.5: IVFa (2007)
From a comprehensive study for the European Commission several useful facts were reported about laptop computers. This included bill of materials (BOM), electricity consumption, as

well as LCA results. It was assessed that 251 kg CO_2e is emitted in the life cycle. The contribution from the use phase was about 64 %. The EuP EcoReport tool was used for the calculations (European Commission, 2005).

Comparison of the studies of laptop and notebook computers
For comparison, the LCA results for laptop PCs are summarised in *Table 1*. The negative signs in front of some figures in the end-of-life column are caused by materials recycling, assumed to offset primary material extraction and manufacturing.

Table 1 Comparison of the studies of laptop and notebook computers

Study #	1.1	1.2	1.3	1.4	1.5
Regional relevance	Taiwan	Japan	Switzerland	Global	Europe
Mass per piece (kg)	2.3	2.3	3.2	1.5	2.5
Emissions per piece (kg CO_2e)	54	260	660	410	251
Emissions per mass (kg CO_2e/ kg)	23	113	206	273	100
% in various life cycle phases:					
Production & transport	n.a.	44	93	41	36
Use	n.a.	53	7	63	64
End-of-life	n.a.	3	0.1	-5	-0.4
Life time (years)	n.a.	n.a.	4	n.a.	5
Electricity usage in use stage, office [kWh]	n.a.	n.a.	190	n.a.	580
PEU in use stage, office [kWh]	n.a.	n.a.	610	n.a.	1,600
Electricity usage in manufacturing [kWh]	n.a.	n.a.	170	n.a.	66
PEU in manufacturing [kWh]	n.a.	n.a.	840	n.a.	350

We have identified some major inconsistencies between the results of the different studies.

First of all it is clear that in Study 1.1 the value of 23 kg CO_2e/kg for the life cycle emissions of the laptop is likely to be too low. This is not consistent with the fact that in this PC, where the integrated circuits alone makes up about 10 % of the total weight of 2,3 kg, integrated circuits typically having life cycle CO_2e emissions in the area of thousand kg CO_2e/kg (Table 6.

Study 1.3 and 1.4 shows much larger CO_2e emissions per kg, respectively 206 kg and 273 kg. Study 1.3 is however very different from the others regarding the share of the emissions in the various life cycle phases. The main amount is emitted from the manufacturing (including transport) phase, while for most of the others the use phase is contributing the most.

Study 1.2 and 1.5 provide more moderate values for CO_2e emissions per kg, respectively 113 kg and 100 kg in the laptop life time.

5.2.2 LCA case studies of computer monitors

Three different LCA studies of computer monitors, two CRT and one LCD have been assessed. They were:

Study 2.1: Kim et al. (2001)
The study by Kim et al. (2001) provided useful figures concerning the material content of a CRT monitor, but unfortunately the absolute figures were not disclosed. They reported that

the “Use stage–operating mode” was contributing 63%, “Use stage–passive mode” 10%, “CRT assembly” 10%, “PCB assembly” 7% and “others” 10% of the total life cycle emissions of CO_2e.

Study 2.2: Socolof et al. (2005a)
A comparative LCA of display technologies was originally performed by Socolof et al. (2005), and analysed further by Zhou and Shoenung (2007). The PWB and electronic components made up 4 % of the total weight of 21 kg for a 17 inch CRT monitor.

Study 2.3: Socolof et al. (2005b)
For a 15 inch LCD monitor weighing 5.7 kg the PWB and components made up 6.5 wt %.

The collected primary and secondary data in Study 2.2 and 2.3 were imported to the LCA software program “Life–Cycle Design Software Tool”. An effective life of 13,547 hours (1.5 years) was estimated for both monitors.

Comparison of the studies of computer monitors
The LCA results for computer monitors are summarised in Table 2.

Table 2 Comparison of results from LCA studies of computer monitors

Study #	**2.1**	**2.2**	**2.3**
Regional relevance	S.Korea	US	Japan
Display type	CRT	CRT	LCD
Mass per piece (kg)	23	21	5.7
Emissions per piece (kg CO_2e)	n.a.	690	590
Emissions per mass (kg CO_2e/ kg)	n.a.	33	100
% in various life cycle phases:			
Production & transport	25	34	71
Use	75	66	29
End-of-life	0	0.2	0.1
Effective life time (years)	6	1.5	1.5
Electricity usage in use stage, office [kWh]	n.a.	630	240
PEU in use stage, office [kWh]	n.a.	2300	850
Electricity usage in manufacturing [kWh]	n.a.	n.a.	n.a.
PEU in manufacturing [kWh]	n.a.	5200	580

The BOM for this study enables a benchmarking with LCI data for PWBs, ICs and other components.

The LCD module manufacturing emits SF_6 which partly explains the difference in life stage shares of CO_2e emission for CRT and LCD. As noted earlier, Ecoinvent has NF_3 emissions in their LCD assembly LCI model, giving similar effect as SF_6.

5.2.3 LCA case studies of desktop PCs

Quite many LCAs studies of desktop computers have been conducted. In this review we have looked at 10 studies. They were:

Study 3.1: Tekawa et al. (1997)
One of the earliest LCA studies of desktop PCs was a Japanese study by Tekawa et al. (1997).

No "key" product data were presented such as power usage, weight or BOM.

Study 3.2: Atlantic Consulting/IPU (1998)
Atlantic Consulting/IPU has presented much cited results for a desktop PC system consisting of monitor, control unit, and keyboard. One PC system used 1,000 kWh of primary energy for manufacturing and 880 kWh electricity during its lifetime.

Study 3.3: Williams (2004)
In the study by Williams (2004) it was estimated that for a computer (weight 24 kg) the total energy use of the production is more important, 81%, than the usage, 19%. It was calculated that a desktop computer using a 17–inch CRT, during 3 years of usage at home, consumed 420 kWh of electricity. For the production, the usages of electrical energy and direct fossil energy were 430 kWh and 920 kWh, respectively. 920 kWh energy extraction from direct fossil corresponds to around 360 kg CO_2e. For the life cycle, using 0.6 kg CO_2e/kWh electricity, this suggests that the CO_2e emissions are around 870 kg per computer and 36 kg CO_2e per kg computer.

Study 3.4: Choi et al. (2006)
In this South Korean study it was argued that the component manufacturing was of more importance than use for a Pentium IV PC. However, their study did not present absolute numbers which limits the value of their estimations. The functional unit was four years of usage in South Korea and manufacturing in the same nation. The monitor (display) was not included, so eventual SF_6 and NF_3 emissions from LCD module must be added to the result.

Study 3.5: Ecoinvent (2008d–l)
The Ecoinvent database contains LCI data modules for manufacturing, usage, and end–of–life of desktops. Assuming 4 years of office use, it is possible to make LCA calculations of desktops using a 17 inch CRT screen (weight 20 kg).

Study 3.6: Ecoinvent (2008d,f-k,m-n)
Same as Study 3.5, but with a 17 inch LCD screen (weight 5.1 kg). The GWP100 for laptops using LCD screens becomes 140% higher than for CRT laptops. The reason is LCD manufacturing loadings and particularly NF_3 emissions from assembly of the LCD module.

Study 3.7: Duan et al. (2009)
The first Chinese LCA study on desktop PCs was published in 2009 by Duan et al. Their assumptions were based on computers where 50% had CRT screens and 50% LCD screens. The life time was 6 years and they were assumed used mostly in China, but also to a certain degree in other parts of the world. The paper unfortunately avoided to publish any inventory results, but only aggregated Eco–Indicator'99 scores, which limits the transparency. The CO_2e distribution of manufacturing, use, and end–of–life is approximately 30%, 65%, –5%, respectively. This is similar to the Ecoinvent desktop using 100% CRT screen.

Study 3.8: IVF (2007b)
The study by IVF, described above in Study 1.5, also encompassed desktop computers. This study of desktop computers with CRT monitors gives as result a high impact from the use phase with a contribution of 82 % of the total life cycle. The desktop computer alone without the display contains around 1.4 kg electronics and the total life cycle emissions were

calculated to 96 kg CO_2e, i.e. 69 kg/kg.

Study 3.9: IVF (2007c)
There was also a laptop computer with a 17" LCD monitor in the IVF study. For the manufacturing phase of this computer the results were emission of 7.5 kg CO_2e/kg.

Study 3.10: Apple (2009)
Apple har published LCA results for a 20-inch iMac. With its low weight, only 8.3 kg this is the lightest of the desktop computers assessed. There is almost equal contribution to the total life cycle emissions from the production and the use phase.

Comparison of the studies of desktop computers
The LCA results for desktop PCs including monitors are summarised in *Table 3*. As in the tables above, a negative sign in front of a figure in the End-of-life column are caused by materials recycling, assumed to offset primary material extraction and manufacturing.

Table 3 Comparison of results from LCA studies of desktop PCs including monitors

Study #	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	3.10
Monitor type	CRT	CRT	CRT	CRT	CRT	LCD	CRT/LCD (1:1)	CRT	LCD	LCD
Regional relevance	Japan	Europe	USA	South Korea	Switzerland	Switzerland	China	Europe	Europe	USA
Mass per piece (kg)	n.a.	22	24	n.a.	33	18	n.a.	27	17	8
Emissions per piece (kg CO_2e)	750	650	870	n.a.	1,300	3,300	n.a.	1,400	1,100	870
Emissions per mass (kg CO_2e/ kg)	n.a.	30	36	n.a.	41	180	n.a.	52	65	105
% in various life cycle phases:										
Production & transport	18	29	81	91	36	97	30	18	22	49
Use	89	68	19	8	64	3	65	82	78	50
End-of-life	0	3	0	1	0	0	-5	0	0	1
Life time (years)	n.a.	3	3	4	4	4	6	6	6	n.a.
Electricity usage in use stage, office [kWh]	n.a.	880	420	305	1,460	860	n.a.	1,300	600	n.a.
PEU in use stage, office [kWh]	n.a.	2,800	1,100	n.a.	5,200	2,500	n.a.	3,600	1,700	n.a.
Electricity usage in manufacturing [kWh]	n.a.	n.a.	430	n.a.	410	340	n.a.	44	44	n.a.
PEU in manufacturing [kWh]	n.a.	1,000	2,100	n.a.	2,400	2,200	n.a.	270	270	n.a.

The results in study 3.3 are remarkable in terms of the low share of use phase emissions considering the "general idea" of desktops with CRT having relatively high electricity consumption during use. These two on one hand, and five others obtain rather different conclusions for the emissions in the different life cycle stages for the (in general) same type of computer.

5.2.4 LCA case studies of mobile phones

We have assessed five studies of mobile phones. They were:

Study 4.1: Nokia (2005)
Nokia performed a LCA of a 3G mobile phone. The raw material acquisition and processing together with all the production steps for the populated PWB (including IC production) contributed to about 60 % of the total life cycle primary energy usage (PEU) which was around 300 MJ. The life cycle emitted 14 kg of CO_2e per phone. The electronic components

contributed 48 % to the life cycle CO_2e emissions. The “unpopulated” PWBs using AuNi surface treatment contributed 40% of the life cycle CO_2e alone. The ICs contributed only 2.9% of the life cycle CO_2e for this mobile phone. The PEU results were very similar to the CO_2e emissions results, in terms of shares between life cycle stages.

Study 4.2: Park et al. (2006)
In the South Korean study by Park et al. it is claimed that the manufacturing of the raw materials constituted 59%, the assembly of components and phone 2%, the use stage 38% and the end–of–life 1% of the life cycle CO_2e emissions.

Study 4.3: PE International (2008)
PE International showed overview results for a 250 g handheld mobile phone in 2008. The system boundaries were global, e.g., component manufacturing in Asia and transports to the US and Europe. The manufacturing phase was responsible for 80% of the life cycle CO_2e emissions.

Study 4.4: Bergelin (2008)
Bergelin presented a comprehensive LCA in Gabi software for Sony Ericssons W890, which is a 3G mobile phone.

Comparison of the studies of mobile phones
The results of the LCA studies on mobile phones are summarised in *Table 4*.

Table 4 Emission of CO2e from the life cycle of mobile phones.

Study #	**4.1**	**4.2**	**4.3**	**4.4**
Regional relevance	Finland	South Korea	Global	Sweden/ China
Mass per piece (kg)	0.08	n.a.	0.25	0.08
Emissions per piece (kg CO_2e)	14	n.a.	30	20
Emissions per mass (kg CO_2e/ kg)	180	n.a.	120	250
% in various life cycle phases:				
Production & transport	71	61	93	80
Use	29	38	13	20
End-of-life	~0	1	-7	~0
Life time (years)	2.5	n.a.	n.a.	3.5
Electricity usage in use stage, office [kWh]	7.1-9.3	n.a.	n.a.	6.2
PEU in use stage, office [kWh]	28	n.a.	n.a.	23
Electricity usage in manufacturing [kWh]	n.a.	n.a.	n.a.	12
PEU in manufacturing [kWh]	42	n.a.	n.a.	64

The results for life cycle CO_2e emissions in the assessed studies of mobile phones are rather consistent in terms of life cycle stage shares, compared to the studies of desktops and laptops. However there are large differences between the absolute figures for the emissions, particularly on a per kg basis.

5.2.5 LCA case studies of TVs

We have looked at a total of four different LCA of television sets. They are:

Study 5.1-3: Aoe (2003)
In the attempt by Aoe it was presented life cycle greenhouse gas emissions from comparing three types of 32 inch TV technologies; Cathode Ray Tube, Liquid Crystal Display and Plasma Display Panel.

Study 5.4: Feng and Ma (2009)
A recent LCA study of TVs was done in China by Feng and Ma (2009). Their functional unit was 10 000 units of colour TVs. Although this was a very detailed and transparent LCA, it is not clear how the electronic components were modelled. The authors used Dodbiba et al. (2008) to estimate the material shares, e.g., electronics 3.0 wt%. The study contains many recent Chinese LCI data for electricity, steel, copper, aluminium, and glass production.

Comparison of the studies of TV sets
A summary of the above case studies on TV sets are given below in *Table 5*.

Table 5 Emission of CO2e from the life cycle of TV sets

Study #	**5.1**	**5.2**	**5.3**	**5.4**
Display type	CRT	LCD	PDP	CRT
Regional relevance	Japan	Japan	Japan	China
Mass per piece (kg)	59	28	21	30
Emissions per piece (kg CO_2e)	1000	1600	1100	1100
Emissions per mass (kg CO_2e/ kg)	17	57	52	36
% in various life cycle phases:				
Production & transport	20	29	28	32
Use	80	71	72	68
End-of-life	~0	~0	~0	0.5

Another study of TVs that is worth mentioning is that of Dodbiba et al. (2008), who used LCA to indicate whether the plastic part of a TV should be mechanically recycled or incinerated. They provided a material content declaration for a TV of unknown type in which the share of the “circuit board” was 3.0wt%.

6 Emissions of climate gases from electronics components

A comparison of the life cycle climate emissions from various electronics components were done.

The results are shown in Table 6.

Table 6 Emission of CO2e from the life cycle of some electronics components

Device and technology, nation, reference, system boundary	Mass per unit (kg)	Emissions per unit (kg CO_2e)	Emissions per mass (kg CO_2e/ kg)
Wafers			
Wafer, 200 mm diameter, layer complexity, EU Commission (2005), gate–to–gate	0.044	300	6 818
Wafer, DRAM, 200 mm diameter, 1,100 dies/wafer, 0.2 mm thickness, Liu (2009), cradle–to–gate	0.014	150	10 714
Wafer, thyristor, 125 mm diameter, 4,200 dies/wafer, 0.2 mm thickness, confidential (2000), cradle–to–gate	0.006	110	18 333
Wafer, Switzerland, 200 mm diameter, 0.2 mm thickness, Ecoinvent (2008o), cradle–to–gate	0.014	2 300	164 286
Wafer, 130nm node, 300 mm diameter, 0.775 mm thickness, 490 dies/wafer, US/China, Boyd et al. (2009), cradle-to-gate	0.13	2 900	22 308
Microchips			
Die (sub-part of processor microchip), 130 nm node, US/China, Boyd et al. (2009), cradle-to-gate	2.0×10^{-4}	6	30 000
Microchip (IC), SOD6, thyristor, confidential (2000), cradle-to-gate	8.7×10^{-5}	0.058	667
Microchip (IC), DRAM, TSSOP66, China, confidential (2008), cradle–to–gate	5.4×10^{-4}	0.54	1 000
Microchip (IC), DRAM, plastic ball grid array, memory, Switzerland, Ecoinvent (2008p), cradle–to–gate			509
Microchip (IC), DRAM, plastic ball grid array, logic, Switzerland, Ecoinvent (2008q), cradle–to–gate			1 020
Printed Wiring Boards			
PWB, EU Commission (2005), cradle-to-gate	3.8	64	17
PWB, Malaysia, Sirim (2005), cradle-to-gate	0.29	29	100

The CO_2e emissions per mass of microchip is dominantly decided by the area (=mass) of the die inside the chip. The papers studied in Section 5 do not contain enough information about the functional die areas to facilitate benchmarking. This prevents a benchmark against the figures for wafers and dies in *Table 6*.

7 Environmental trends for integrated circuit packaging technologies-the case of metal plated polymer particles

7.1 Background, aim and scope

Even thought the electronics industry has changed much the last decades, only a few studies (Liu et al., 1999 and Nissen, 2001) have been published on environmental implications of different micro/nanosystems packaging technologies providing same benefit. A possible reason is the large amounts of data required by the LCA tool of complex electronic products using many technologies. For micro/nanoelectronics packaging it could be more worthwhile quantifying smaller systems, however having the larger perspective in mind.

Packaging technology is here divided into five levels, 1) the wafer, 2) the integrated circuit (IC), 3) the multichip module, 4) the printed board assembly, 5) the motherboard and 6) the system (e.g., a laptop) (Andersson, 2007). Referring to levels 2–4, nano–structured polymer particles are produced especially for usage within Anisotropic Conductive Adhesive (ACA) used at level 2 and 4. Interconnection materials are strongly connected to this research as they are almost identical to solder balls, in turn possible to replace with metal–plated polymer balls (Andrae, 2009).

ACAs are one of three major groups of electrically conductive adhesives, the two other being isotropic and non conductive adhesives. ACA pastes usually consist of diglycidyl ether of bisphenol F or diglycidyl ether of bisphenol A as polymer matrix, imidazoles as curing agents, and different types of Ag powders or Au–coated polymer spheres as conductive particles. ACA technology is capable of finer pitch interconnect which can reduce Si die and component size. Traditionally ACA has been used to attach chips to package leadframes and chips directly to the printed wiring board, so called flip chip technology (Cao et al., 2005).

Metal plated MPPs can be customised for applications such as ball grid array (BGA) and chip scale packaging (CSP). BGA is a surface–mount package that utilizes an array of metal spheres or balls as means of providing external electrical interconnection, as opposed to the pin grid array (PGA) which uses an array of leads for that purpose. The balls are composed of solder, and are attached to a laminated substrate at the bottom side of the package. The Si die of the BGA is connected to the substrate either by wire bonding or flip–chip connection. At packaging technology level 2 (described above), metal plated MPP ball technology could replace conventional metal balls for BGA and CSP applications and the hypothesis is that the shift will be eco–efficient for several reasons: the polymer core particles increase the reliability by improving the interconnection compliance compared to compact metal cores (He et al., 2007), smaller sized MPP balls can achieve even higher reliability in BGA/CSP (He et al., 2008). A key issue is that smaller particles are less flexible than larger ones. Moreover, it has been predicted that by introducing polymer cores, the heavy metal use, for the same size balls, can be reduced by a factor of 3–7 (Whalley & Kristiansen, 2008).

We present here, for the first time, an exploration into the possible life cycle eco–efficiency aspects of polymer core solder balls, from their product system perspective. We also propose guidelines for evaluation of similar systems.

7.2 Approach

The cradle–to–gate carbon footprint varies considerably for different silicon wafers. The deciding parameters are roughly yield, amount of Si die per wafer, and wafer volume. A recent Taiwanese study reports of an 8 inch memory wafer emitting 146 kg CO_2 (Liu et al., 2010). Another study reported emissions of 6 kg CO_2/Si die for a 300 mm wide, 0.78 mm thick 45 nm node CMOS wafer with 590 gross silicon die (Boyd et al., 2009). The study by Liu et al. did however exclude silicon wafer production and infrastructure, which was included in the study by Boyd et al. The carbon footprints per mass of Si die are 9,800 and 30,300 kg CO_2/kg respectively for Liu et al. and Boyd et al.

In this report we present an approach which combines the well published results for silicon die masses of specific ICs, with 0.34 kWh electricity/cm^2 in the final assembly of the circuit (MCTC, 1993) and 147 mg Si/cm^2 (Liu et al., 2010).

Ecoinvent's data set for "Electricity, production mix CN/CN U" was used to model the electricity extraction. The study by Nissen (2001, p. 90) applied a value of 110 kWh electricity/kg, which is similar order of magnitude as the value used in our study.

7.2.1 Relative share of different parts of Ball Grid Array microcircuits

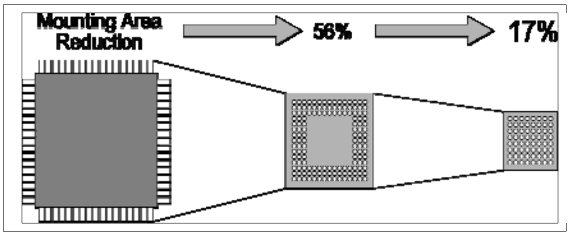
The relative environmental impact share of BGA balls compared to other parts of a BGA package was estimated by calculating screening cradle–to–gate LCA scores for a Metal BGA (Xilinx, 2007) using balls made of 63Sn–37Pb and 95.5Sn–3.9Ag–0.9Cu alloy. In the material content declaration the *Si die attach* part (75wt% Ag) was 0.23 wt % and *solder balls* (made of 63Sn–37Pb) were 16 wt % of the total weight 11 g. No primary data for manufacturing of sub–parts were collected in that study, for the comparison between Pb and Pb–free BGA–560 packages. The manufacturing of metal solder balls is described in paragraph 7.2.4 .

A value for electricity use of 1 kWh (+/– 0.1 kWh) per kg was assumed for the simple processes such as "heat spreader production". Metal plated MPP ball production is also described in paragraph 7.2.4 . It is likely that raw material production is more important than material processing for the sub–parts (except the Si die) of present IC components. The GWP100 and Eco–indicator '99 results are shown in Figure 5.

7.2.2 Consequence of miniaturization from TQFP to LFBGA to WCSP

It is commonly assumed that the miniaturization of packaging concepts will lead to environmental benefits. Component packaging concepts can only be compared if an identical Si die is "stored" inside the package. Microchips are comparable if they can contain the same Si die size (Nissen, 2001). The Si die size determines how many input–output connections are possible and those cannot be proportionally different if the comparison shall be valid. Here follows a micro controller example from OKI Semiconductor of "older" and "newer" packaging concepts. But what is the potential environmental gain from such a component miniaturization? In *Figure 1* we show an illustration of the mounting area reduction.

Figure 1 Miniaturization on package level



Source: OKI Semiconductor

For this comparison the Si die has the same mass for the old and new concept, but the amount and composition of additional packaging materials differ.

The example concerns reported material content declarations for Thin Quad Flat Pack 64 (TQFP–64) (OKI, 2009a), Low–profile Fine–pitch Ball Grid Array (LFBGA–84) (OKI, 2009b), and Wafer CSP–64 (WCSP–64) (OKI, 2009c) (equal Si die mass of 16.9 mg). Examples of GWP100 and Eco–indicator '99 results are shown in Figure 6 and Figure 7.

7.2.3 Consequence of miniaturization for the environmental impact of printed board assemblies

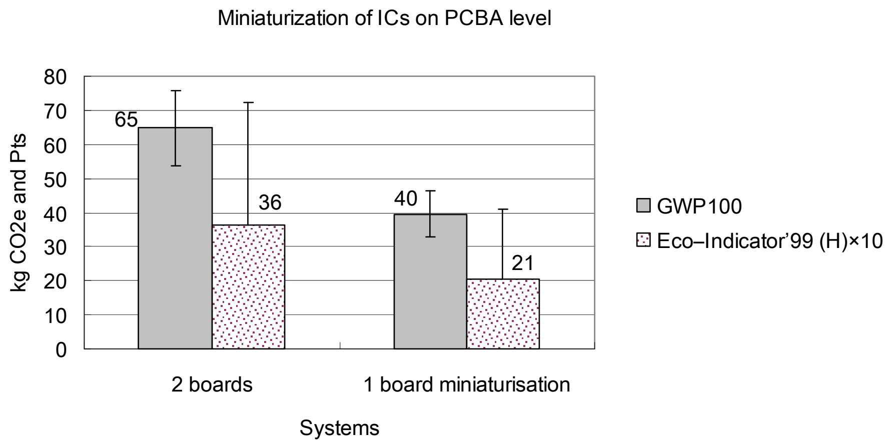
According to Toshiba, The PCBA footprint could be reduced for a specific product by around 50% by resource saving design (Toshiba, 2010). Here follows another example in which the IC miniaturization effect is explored for an Asymmetric Digital Subscriber Line (ADSL) product (Confidential source, 2010). Between product generations two 32 port PCBAs could be integrated to one 64 port PCBA whereby several QFPs were naturally replaced by BGAs, components were omitted and integrated to higher density BGAs. *Table 7* shows the key data and *Figure 2* the CO_2e results for ICs.

Table 7 Inputs for ADSL PCBA miniaturization calculation

	ICs [#]	Mass ICs ~[g]	Si dies, mass ~[g]	Si dies, area ~[cm2]	Gold, ~[g]	I/Os [#]
Before	96	93	1.6	8.7	0.3	9,268
After	56	56	0.98	5.5	0.14	5,812

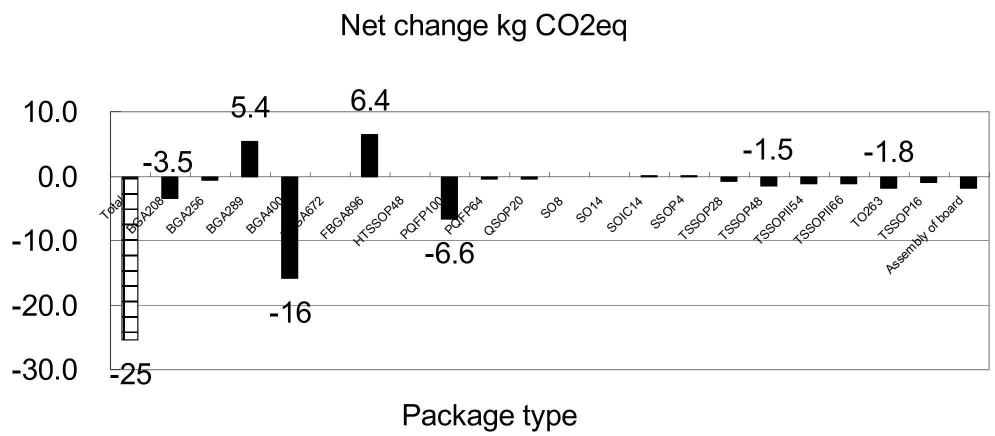
Although two PCBAs were replaced by one, the above indicators were not reduced by 50%, and subsequently were not the carbon footprint and Eco–indicator linearly reduced according to number of PCBAs. The explanation is to be found on IC component level.

Figure 2 Estimated effect of IC miniaturization on environmental impacts on ADSL board level



Monte Carlo simulations in SimaPro showed that the probability is 100% (for all GWP100 gases) that the miniaturization is beneficial. The uncertainty of GWP100 indices would cancel each other and would not change the probability much. *Figure 3* shows the package type contributions for GWP100.

Figure 3 Net change in CO_2e for different IC package types on ADSL board level

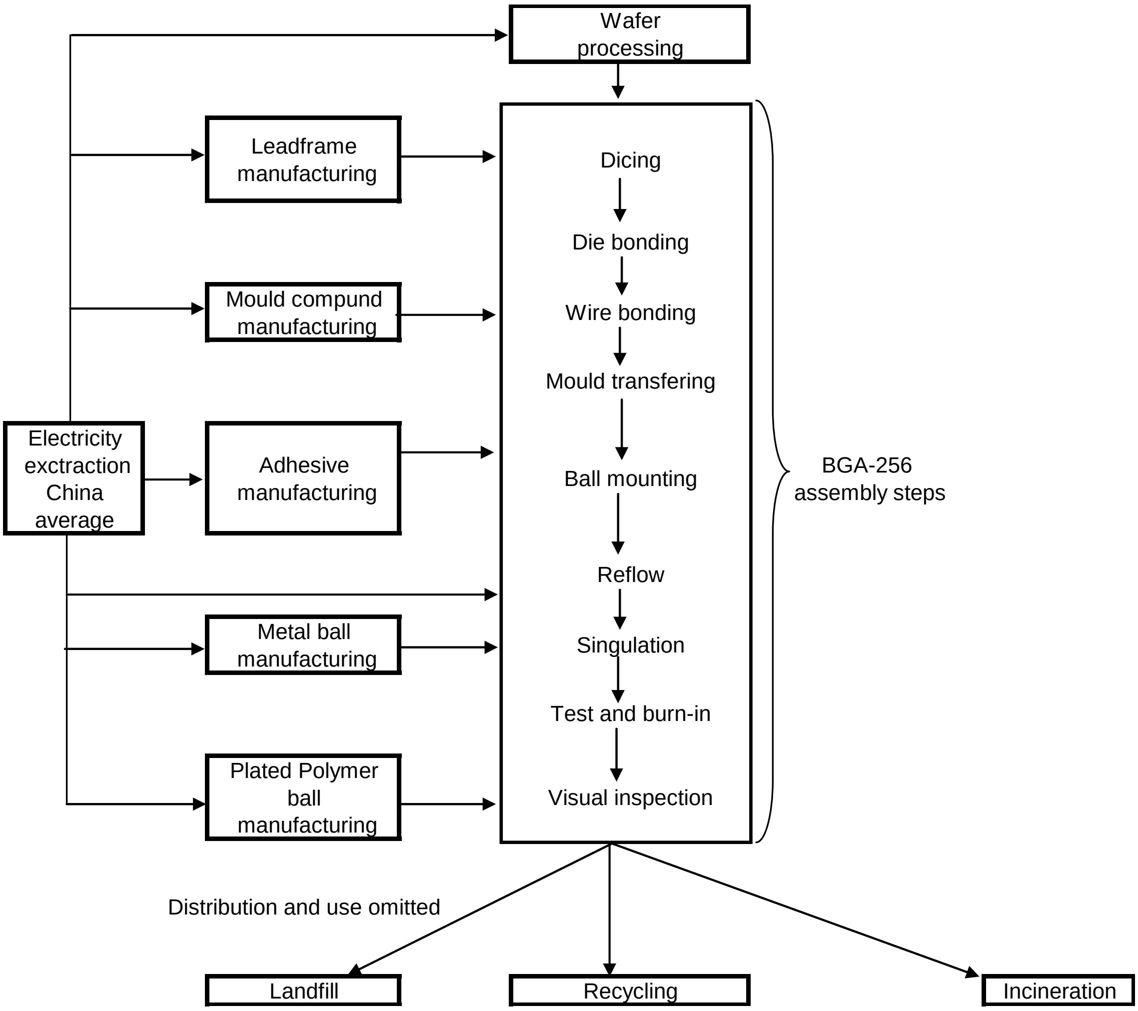


Note that the CO_2e in Figure 3 is limited to ICs, with no other electronic components.

7.2.4 Consequence of different BGA ball materials: BGA–256 example

Here follows a section where BGA–256 by NXP® (package code SOT1018–1 and ball diameter 500µm, NXP Semiconductor, (2010)) is explored for different types of ball materials. Five major parts constitute the BGA–256; Adhesive (0.029 wt%), Mould compound (31 wt%), Si die (2.5wt%), Lead frame (53wt%), and the (Pb–free) Balls (13wt%). All manufacturing including metal plated MPP balls are assumed to take place in China. These polymer balls will only constitute 3.8–5.8 wt% of the BGA–256 and lower its weight by 11%, but how eco–efficient is this advantage? The scope is shown in *Figure 4*.

Figure 4 Scope of BGA–256 screening LCA



The conventional balls (Metal Ball production China) are produced by the Uniform Droplet Spray process in which metals are melted and forced through an orifice, creating a laminar jet which is broken into uniform droplets (balls) (Williams, 1996, Yu et al., 2008). In Yu et al. (2008) for each experiment about 200 g of solder alloy was filled into the crucible for spraying. Every experiment started with evacuating the chamber to 10 Pa and backfilling with pure nitrogen three times. The chamber pressure was maintained at 70 kPa after which the crucible was heated to 300 °C, holding this temperature for 15 minutes. Anyway, the latest information is that the procedure uses a few kW and takes less than an hour (Personal communication, Chun, 2009). The assumptions are summarized in *Table 8* and *Table 9*.

Table 8 Assumptions for manufacturing of metal solder balls

		Unit	Amount	2σ NORM
Output				
	Production of metal solder balls	g	200	
Inputs				
	Electricity	kWh	2.7	0.27

Metal plated MPP balls are produced (Plated Polymer ball manufacturing) by first preparing the polymeric microspheres via the Ugelstad process, and then metallization of the polymeric spheres. Per ball these emulsion polymerization processes are very energy efficient compared to the Uniform Droplet Spray process.

The differences between "One BGA package using metal plated MPP balls" and "One current BGA package using conventional balls" is for starters the weight of the balls and the materials from which they are made. Also ancillary chemicals and transportation differ, however these two differences are omitted here due to lack of data. The volume of the metal plated MPP balls is assumed identical to the Pb based and Pb free solder balls. For this research four ball types, used in the same BGA, are reported.

Table 9 Assumptions for manufacturing of metal coated polymer balls

		Unit	Amount	2σ NORM
Output				
	Production of metal coated polymer balls	g	1,000	
Inputs				
	Ugelstad process, Electricity	kWh	11	1.1
	Plating processes, Electricity	kWh	94	9.4

The electricity usage for the Ugelstad process is composed of the amount needed to heat water and keep it warm for a few hours.

The electricity usage for plating processes per kg are calculated by the number of plated layers (3), ball area including platings (7.9×10-3 cm^2), electricity usage per area (2.7×10-4 kWh/cm^2, Ecoinvent, 2009, Electroplating Nickel I) and ball mass (6.9×10-8 kg).

The mass of one Acrylate Cu SnPb ball is 0.22 mg. The acrylate Cu AuNi ball weighs 0.14 mg. *Table 10* below shows the input values for arriving at these weights. The density of polyacrylate is approx. 1.2 g/cm^3.

Table 10 Basis for weight calculation of balls of total diameter 0.05 cm

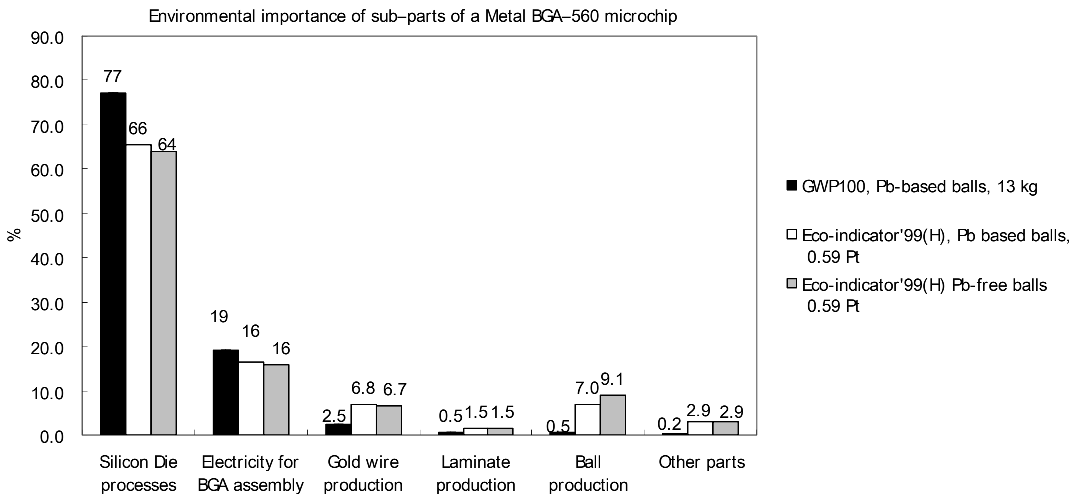
Ball type	Radius polymer (cm)	Thickness (cm) copper layer	Thickness (cm) 63Sn–Pb37 layer	Thickness (cm) gold layer	Thickness (cm) nickel layer
Acrylate Cu SnPb	2.4×10-2	1.0×10-3	2.0×10-3	n.a.	n.a.

Acrylate Cu AuNi	2.4×10-2	1.0×10-3	n.a.	1.0×10-5	1.0×10-5

Pb based (63Sn–Pb37) and Pb–free balls (96.5Sn–3Ag–0.5Cu) weigh 0.62 and 0.54 mg, respectively, as 256 Pb–free balls weigh 140 mg. The densities of 63Sn–Pb37 and 96.5Sn–3Ag–0.5Cu alloys around 8.4 and 7.3 g/cm^3, respectively.

Transports, losses and ancillary materials are left out in this study due to knowledge gaps. The Ecoinvent database has been used for all materials. Electricity extraction power is Chinese power mix for all processes. The results of the calculations are shown in Figure 5.

Figure 5 Environmental importance of production stages of a metal BGA–560 microchip



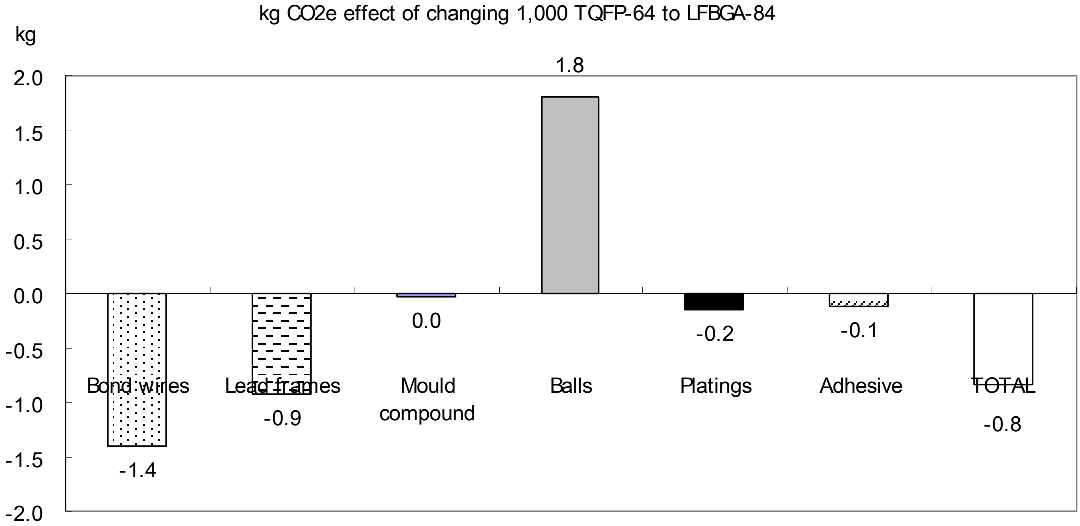
From the results of GWP100 and Eco–indicator'99 (H) shares of BGA–560 constituents a preliminary conclusion can be drawn that solder balls have small environmental impact for metal BGA–560 microchip packages. The shift to Pb–free ball material does not necessarily lead to environmental improvement.

In 52 % of the Monte Carlo runs Pb–free BGA–560 was worse than Pb–based BGA–560, i.e, no significant difference. The Si die production model from Boyd et al. was used. The electricity for BGA assembly was calculated as follows: Si die mass, 320 [mg] × 0.34 [kWh/cm^2]/51 [mg/cm^2] = 2.1 kWh.

7.2.5 The miniaturization effect

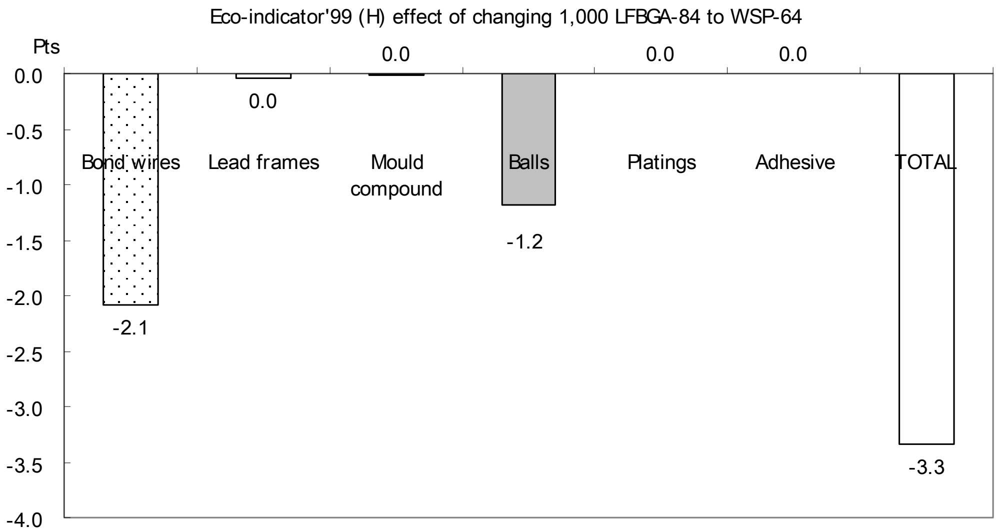
In *Figure 6* is shown the GWP100 reduction effect from miniaturization from TQFP–64 to LFBGA–84 to WCSP–64 (OKI Semiconductor, 2009a-b).

Figure 6 Miniaturization effect on GWP100 of changing 1,000 TQFP–64 to corresponding LFBGA–84 and WCSP–64



The effect on Eco–indicator '99 (H) of changing 1,000 LFBGA–84 to the same number of WCSP–64 is shown in *Figure 7*.

Figure 7 The miniaturization effect on Eco–indicator'99(H) of changing 1,000 LFBGA–84 to 1,000 WCSP–64

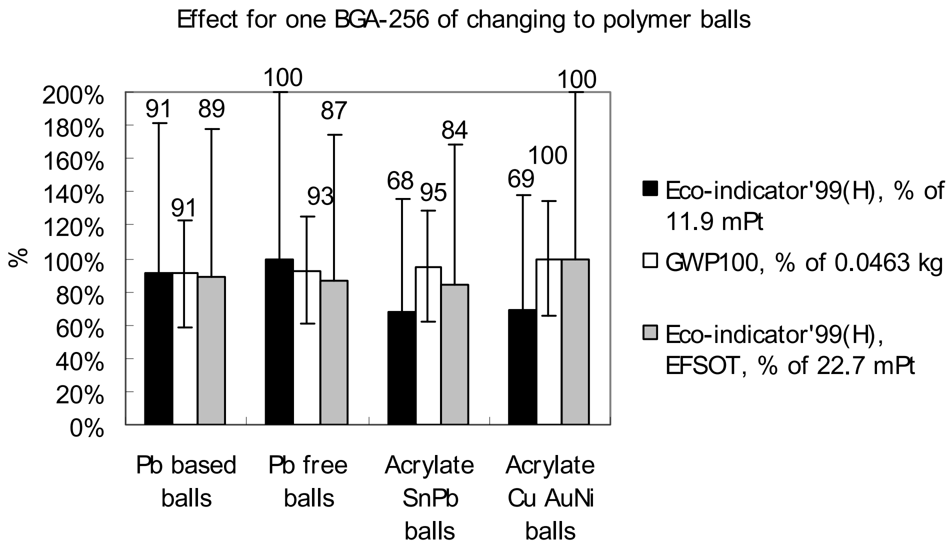


From this it can be concluded that it would be advantageous, from a component packaging material viewpoint, to change to WCSP technology.

7.2.6 The solder ball vs. metal coated polymeric ball life cycle comparison

The environmental benefits of changing from solid metal balls to metal coated polymeric balls are shown in *Figure 8*.

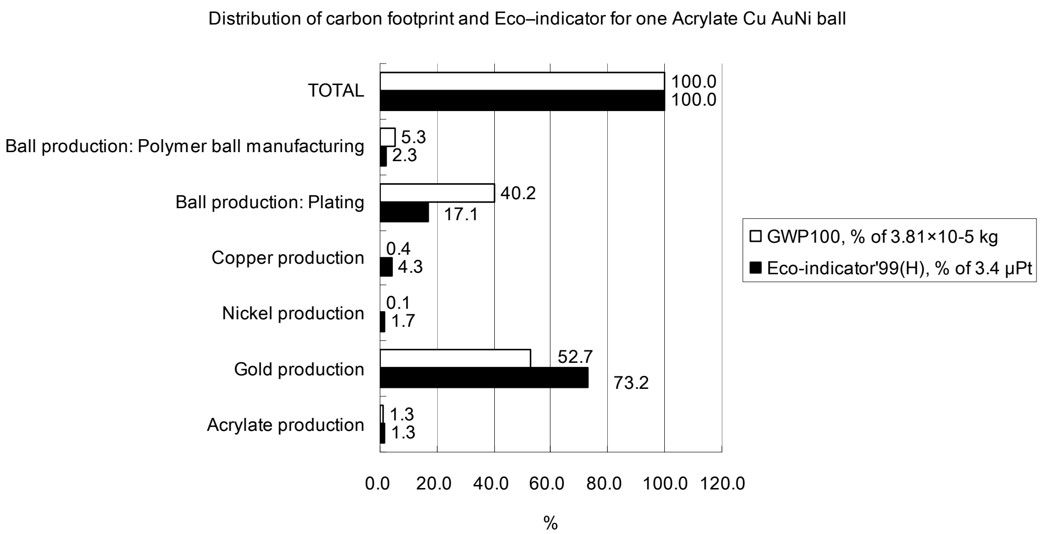
Figure 8 Environmental gain per BGA–256 life cycle of changing metal balls to metal coated polymeric balls



The acrylate Cu AuNi balls gave as result more detrimental environmental impact, as expressed with the indicator GWP100, compared with the acrylate Cu SnPb balls, in 95% of Monte Carlo runs.

The distribution of environmental impact in the various production stages for acrylate Cu AuNi balls are shown in *Figure 9*.

Figure 9 Distribution of GWP100 and Eco–indicator'99(H) results in the various production stages of acrylate Cu AuNi balls



8 Discussion

8.1 LCA case studies of consumer electronics

The many consumer electronics product groups studied in this report have different functions and cannot strictly be directly compared. They are moreover produced and used in different geographical locations, and are thus not equal. The use phase can occasionally be compared by using a common electricity mix, and the manufacturing phase can be normalized per year if the life time assumption is known. However, few studies allow such comparison.

It is therefore difficult to judge whether the life cycle emissions of CO_2e per product or per mass are reasonable. Moreover, it is important to understand if the published LCI/LCIA results of electronic components are reasonable in comparison to the electronic product LCI/LCIA results and vice versa.

The CO_2e emissions per mass of microchip is dominantly decided by the area (=mass) of the die, m_{die}, inside the chip. The following algorithm, expresses the (global average) carbon footprint for any IC:

$$m_{die}\ [mg] \times 0.0308\ [kgCO_2e/mg] + m_{die}\ [mg] \times 0.0066\ [kWh/mg] \times 0.6\ [kgCO_2e/kWh].$$

The first factor is based on Boyd et al. (2009). However, most of the studies contain too little information about functional die areas or die masses preventing a comparative analysis.

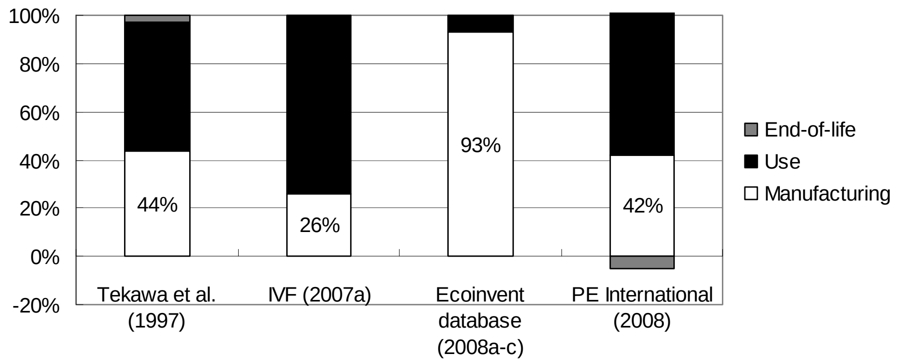
8.1.1 Inconsistencies

In the comparison of the data presented, several major inconsistencies were found and some can partly be analysed by normalizing electricity/energy usages and by checking CO_2e flows.

First, the laptop PC from Taiwan (Study 1.1) seems suspiciously low in CO_2e, 54 kg/piece. ICs were 10 wt% alone and they typically have CO_2e intensities of at least 1,000 kg CO_2e/kg. The Japanese notebook (Study 1.2) on the other hand has a reasonably CO_2e score per piece, 260 kg/p. This assumes similar weight and share of PWBs and ICs as for the Taiwanese laptop.

Second, the Ecoinvent laptop (Study 1.3) is inconsistent with IVFs laptop (Study 1.5) regarding CO_2e emissions in the various life cycle phases, as shown by Figure 1. This is clarified by normalizing the electricity or PEU in Error: Reference source not found. The PEUs are pointing in different directions for the manufacturing and use phases.

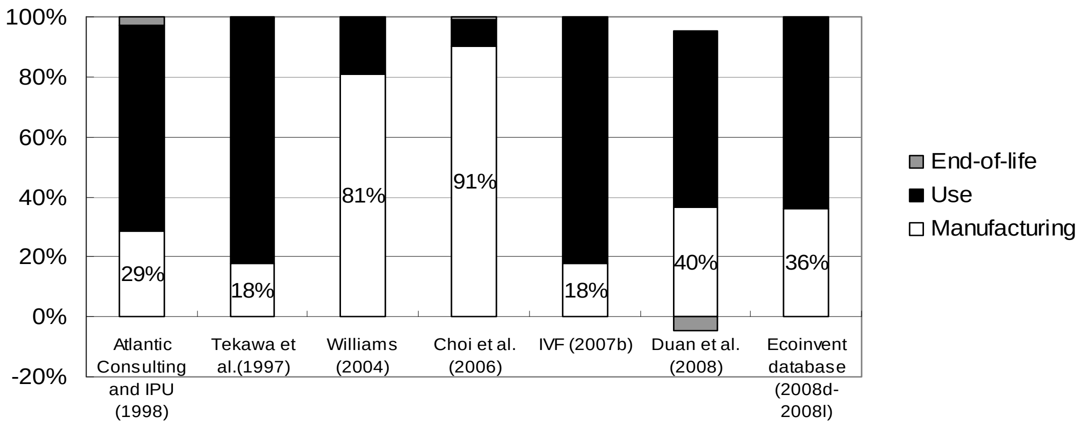
Figure 10 CO2e shares of life–cycle phases for laptop computers



Third, for CRT desktops, Choi et al. (2006) claim that the “pre–manufacturing”, even when the monitor is excluded, is by far the most important life cycle phase for a desktop in South Korea (Study 3.4).

Forth, having a global perspective, Williams (Study 3.3) arrived at the same conclusion as Choi et al. (Study 3.4). These two differ from the other CRT desktop case studies, as shown in *Figure 11.*

Figure 11 CO_2e shares of life–cycle phases for desktop computers using CRT screen

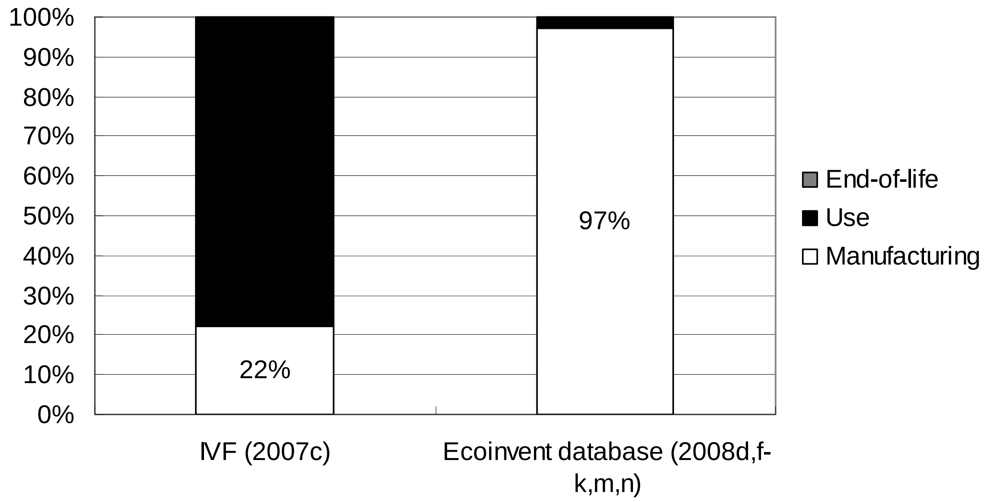


This is awkward as it could give the impression that LCA cannot be used to support eco-design. But on the other hand the improved understanding of the magnitude of manufacturing impacts, together with generally decreased power usages, could have changed the share of CO_2e -emissions from the individual life cycle phases. Nevertheless, the two later analyses by IVF (Study 3.9) and Ecoinvent (Study 3.5), contradicts that trend as they clearly point out the large share of total CO_2e -emissions from the use phase for CRT desktops. This is also evident from normalization per year for PEU/electricity.

The fifth is the Ecoinvent desktop using LCD screen (Study 3.6), which has a much higher share of manufacturing GWP100 than IVF (Study 3.9). For the Ecoinvent LCI data set "Assembly, LCD module/GLO U", the amounts of emissions of SF_6 and especially NF_3 are crucial to the overall GWP100 result and the distribution between life cycle phases for a desktop using LCD screen. The GWP100 of SF_6 is 22,800, while that of NF_6 is 17,200. As a result, for computer sub–parts, the Ecoinvent LCD screen manufacturing (4,400 kg CO_2e/p) is inconsistent with the LCD screen manufacturing results by Socolof et al. (Study 2.3), 590 kg CO_2/p. The main reason is the NF_3 emissions from LCD assembly.

Figure 12 shows the inconsistency of two desktop computers using LCD screens.

Figure 12 CO2e shares of life–cycle phases for 2 desktop computers using LCD screen



Sixth, the PEUs for the manufacturing stage of the desktop PCs with LCD monitors (Table 3) are dramatically different in IVF (Study 3.9) and Ecoinvent (Study 3.6). This underlines that the MEEuP Methdology report/tool (European Commission, 2005) underestimates electronic component manufacturing processes.

Seventh, the LCA by Socolof (Study 2.2) of a CRT computer monitor is not consistent with results of LCAs for desktop computers with CRT monitors. The PEU for CRT monitor manufacturing is more than twice as high as the highest result for complete CRT computer systems.

8.1.2 Consistencies

For CRT PCs, Williams (Study 3.3) and Ecoinvent (Study 3.5) have similar PEU per year for the manufacturing stage.

For LCD PCs, the PEUs in Socolof (Study 2.3) for the LCD unit is consistent with the Ecoinvent results (Study 3.6) for a whole PC system with LCD monitor.

8.1.3 Electronic component checks

If the material content information in Dodbiba et al. (2008) is added into the LCA software

SimaPro7 and assuming the same length of use phase as in Study 5.1-3 (8 years) and same weight as in Study 5.1 (59 kg/TV), then the result would be 880 kg CO_2e per TV set. This is not very different from the results of Study 5.1 with 1,000 kg CO_2e per TV set.

From those studies that provide data on the life cycle's share of CO_2e emissions, e.g., around 11% for Chinese TV in Study 5.4 (Feng and Ma, 2009) for “PWB and electric components”, this will be higher than their weight share, e.g. 3wt% in Study 5.4. This is true for all products in the present study. Providing a kind of validation, electronics, in form of the average of 34 advanced populated PWBs for telecom products, could have a CO_2e load of around 140 kg CO_2e/kg (coefficient of variance 48%) and a Cumulative Energy Demand of 695 MJ/kg. This was calculated in SimaPro7 LCA software. That is, 0.9 kg “PWB and electric components” would emit around 130 kg CO_2e.

Study 3.8 (IVF, 2007b) presents an office desktop PC (excluding display) containing approx. 1.4 kg electronics and 96 kg CO_2e emissions, i.e. 69 kg CO_2e/kg . Microchips emitted at the most 420 kg CO_2e/kg and using the previously mentioned algorithm, 1,700 kg CO_2e/kg IC. This indicates again that MEEuP methodology underestimates component manufacturing. Moreover, IVF’s 17 inch LCD–display manufacturing in Study 3.9 (IVF, 2007c) seems underestimated with 7.5 kg CO_2e/kg compared to 71 kg CO_2e/kg in Study 2.3 (Socolof et al., 2005b). Also CRT–display manufacturing by IVF in Study 3.8 is noticeably lower than Ecoinvent in Study 3.5 (Ecoinvent database, 2008e) and Socolof in Study 2.2.

For mobile phones and TVs the LCAs seem to be more consistent than the case is for personal computers. However, the Ecoinvent database version 2.1 lacks unit processes, which does not make it possible to conduct LCAs on mobile phones and television sets in the same way as for desktop PCs and laptop computers. It is therefore an unanswered question whether there is consistency between LCAs of mobile phones and TVs, carried out with the MEEuP methodology (European Commission, 2005) and the Ecoinvent database.

8.1.4 LCA harmonisation

Reap et al. (2008) discuss the selection of functional units and unit process boundaries in the goal & scope phase of an LCA. For LCI the major controversial issues are to what degree allocation, cut-off, and local technical uniqueness affect the precision of the analyses. We have commented on the lack of unit process and the local technical uniqueness exemplified by how in the Ecoinvent database and the MEEuP methodology this affects the results. A properly conducted LCA should as a minimum identify similar hot–spots for similar technologies if the functional unit is the same.

The LCA method in itself cannot be criticised for the inconsistencies. The explanation is rather connected to the subjective choices that are being made. E.g., the choice of effective life, manufactured life, and operating pattern for computers, can to a large extent affect the relative importance of each use phase. The choice of LCI database also affects the consistency.

Also Scharnhorst (2008) identified the necessity of a well–balanced LCI for assessing the life cycle environmental impact of electronics products. Well-defined product categories are essential. Choi et al. (2006) used non–balanced LCI of desktop PCs by excluding the

(CRT/LCD) monitor, which earlier LCAs (Socolof et al., 2005) had shown the importance of. It is necessary, but not sufficient, to have transparent and unit–process based LCI datasets.

Standardisation for product groups would not make LCA results from two different studies exactly comparable, but it would probably eliminate the risks of omitting important unit processes (Choi et al, 2006).

8.1.5 Polymeric balls in BGAs

The electronics package can be resembled to a storage box in which the same Si die is stored. Consequently there is a myriad of different ways in which the "storage box" can be designed; DIP, SOP, TSOP, QFP, BGA, CSP, flip–chip, etc.

The Ecoinvent database presents two models for IC manufacturing; one for memory type and one for logic type. The CO_2e results are 500 and 1,000 kg CO_2e/kg, respectively. This indicates that the benchmark intensity GWP100 results, for BGA–560 (1,174), BGA–256 (972 to 1,103), TQFP–64 (2,577), LFBGA–84 (3,345), and WCSP–64 (20,932), are fairly reasonable.

Nevertheless, it can be argued how eco-design of BGA circuits can be done. One approach is to exclude the Si die and put the focus on the other parts, and at the same time evaluate the package using other impact categories than GWP100, as well as single indicators.

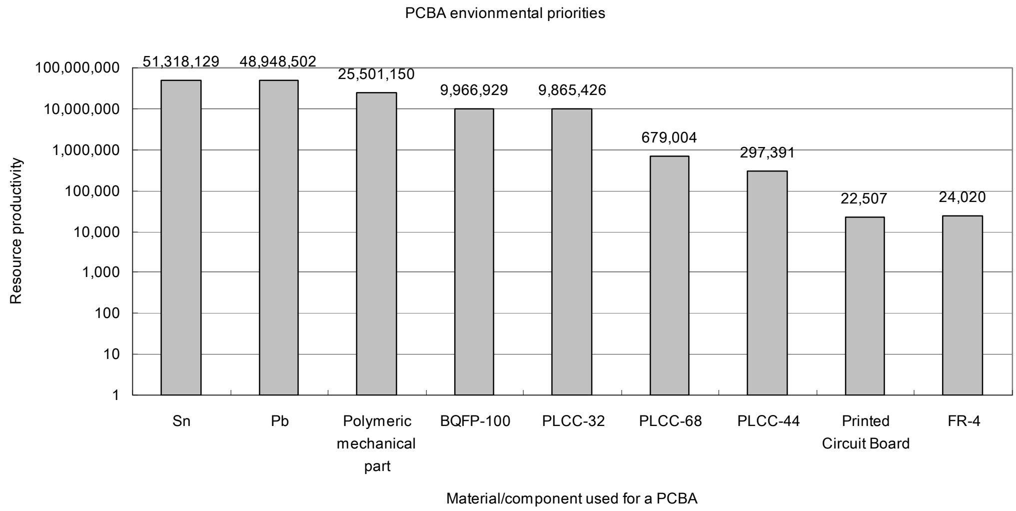
As shown in Figure 5 the share of CO_2e impacts in (GWP100) of solder balls is very small compared to other parts of the BGA. It does not matter if Pb–free or Pb–based balls are used; the Si die is the dominating part.

However, it is not certain what the experimental details found about the Uniform Droplet Process means for industrial production of solder balls. Both electricity and nitrogen gas is used which could be significant per ball, but not likely per BGA. For the ball fabrication process, the emulsion polymerization followed by metal plating, is probably much less energy demanding. Over usage of gold which is wasted is not significant either. The gold used in lead–frames is much more important than the gold used in BGA/CSP balls. However, as shown in *Figure 9*, the ball plating process is a potential driver of impacts.

The solder balls, Pb or Pb–free, are a very small fraction (~1%) of the cradle–to–gate CO_2e impact for a Metal Based BGA of 560 balls. However, there exist several types of BGA packages; metal based, plastics based, low profile fine pitch etc. The weight share of the solder balls fluctuates depending on BGA package type. Philips Semiconductors has reported that for plastic and low–profile fine–pitch BGAs, the share of the solder balls was 0.020 and 11wt%, respectively. For BGA–256 (NXP Semiconductor, 2010), the balls and Si die shares were 13 and 2.5 wt%, respectively.

Figure 13 shows the result of resource productivity (RP) analysis for a specific PCBA (Alcatel-Lucent, 2008). RP is defined as "annual unit production" divided by the "combined aggregated and dimensionless environmental impact between 0 and 1" (Luo, et al., 2001). As e.g., ICs and Printed Circuit Boards have a high environmental impact compared to annual usage, they get a lower RP than, e.g., Sn for specific PCBAs.

Figure 13 Resource productivity of different materials and components used on a PCBA



Alcatel–Lucents RP approach does not necessarily give different conclusions for PCBAs designers than plain process sum LCA. Most PCBA LCAs also show that the PCB and the ICs have a similar relation as in *Figure 13*.

Using EFSOTs updated version of Eco–indicator'99(H) which includes, e.g., gold and silver resource indices, does not change any conclusions on BGAs shown in *Figure 8*. This EFSOT version of Eco–Indicator also include an impact category called "Human Toxicity" for which indices have been derived for several metal emissions to air, soil and water, including gold, silver, Pb, and tin. Here gold emissions (mainly from lead frames) could possibly be a concern counting with maximum possible emissions to water. That is, emissions from polymer balls are of no concern as far as the current knowledge situation as 81wt% of the gold used in the BGA–256 using Acrylate Cu AuNi balls origins from the lead frame.

The size of metal plated MPP balls can be decreased whereby the reliability of the BGA/CSP package is increased. This means that the higher eco–efficiency of metal plated MPP balls is valid. Per same size ball the life cycle calculation showed that the metal mass can be reduced by 67–88%, but this study indicates that the correlation to environmental effects is low.

It is difficult to judge how much of the BGA/CSP will be recycled and the issue is out of reach for IC Tier 2 manufacturers.
Weighting methods such as the Eco–indicator'99 are based upon many assumptions. Recently US scientists estimated a new ozone depletion potential, 0.017 kg CFC11 equivalents/kg, for nitrous oxide (N_2O) (Ravishankara, et al. 2009). Their estimation would roughly translate to 1.4×10^{-5} DALY/kg. However, the ozone depletion is weighted too low in the Eco–indicator'99 for the N_2O to have effect on this research. Anyway, for the ozone layer category, from now on N_2O will probably dominate many LCA studies.

9 Conclusions

The lack of transparency of LCA studies of different consumer electronics makes comparison of the environmental impacts of the various products difficult. It is however still possible to relate new LCA results to some of the existing studies. When BOMs are available, it is also feasible to reveal which product studies are incoherent with other LCA studies of sub–materials and sub–components. All in all, published GWP100 results for televisions and mobile phones seem to be consistent to a larger degree than desktops and laptop computers. Based on the survey of published work, recycling and other end–of–life processes have a very small share of the total GWP100 score for consumer electronics.

Public LCAs of electronic and other products have been accused of being biased and inadequately transparent, leading to limited use in improving the communication of environmental impacts. The major difficulty appears to connected to the multitude and magnitude of the flows involved in the production and supply chains, as well as rapid changes in the industry. Areas with importance for obtaining a wider consensus are: i) functional units, ii) allocation and iii) system boundary selection.

It might be advisable that LCA practitioners review the technical systems to establish trends, proportions and relations. This is necessary as to comprehend the consistency and robustness of the result. When the LCA results are used for decision support, these system reviews should also be taken into consideration. Further improving the ISO14040/44 LCA standards could also increase the LCA consistencies.

The International Electronic Manufacturing Initiative (iNEMI) in USA is developing a non–competitive process, software program, and electronics components database for conducting LCA, with the aim of reducing the current redundancies. The idea behind this is that several industrial companies agree on the ranges and algorithms, procedures for update, and for carbon footprints of the most important LCI modules in the life cycle of ICT products.

Moreover, there is an initiative in Europe (within European Telecommunications Standards Institute, ETSI) along these lines, suggesting LCA standards for telecommunication equipment. These harmonisation efforts have the potential to improve the quality of LCAs for complicated electronic products.

The ball share of the BGA–256 GWP100 and Eco–indicator'99 (H) score is small and the BGA/CSP producers can marginally improve the environmental performance by focusing on the balls. On PCBA level the contribution from BGA balls is negligible. Results for metal plated MPP BGA balls suggest that gold usage is the key environmental performance indicator of interest. The eco–efficiency of using gold makes up for it to a certain degree. Especially metal plated MPP balls of reduced size and identical functionality, can be argued to be more eco–efficient through being more reliable. For metal plated MPP balls, the eco–efficiency scores increase with decreasing ball diameter.

Screening process–sum LCA is a good method for a sub–sub IC supplier company to find the best ways to environmentally improve their technologies. However it must be emphasized that all LCIA methods which include ozone depletion should updated be with the latest scientific agreements on factors. This is also important the case for assessment of climate gas emissions, where the amounts of emissions of sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) are crucial to the GWP100.

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These are similar papers published after Andrae & Andersen (2010), as they are reviews of many consumer electronics LCAs.