Evaluation of the environmental impact within semiconductor packaging materials

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***Abstract*—This paper reports the sustainability of materials and components required for PCB manufacturing, namely the substrate material, die-attach method and IC chip design. Electronics manufacturing processes are generally decided by the technical and economic requirements, and not sustainability, resulting in poor practices and unintended outcomes. Alternative methods could be used and this paper reviews some of the drivers and opportunities for sustainable PCB manufacturing. A life-cycle assessment (LCA) was performed on simple Printed Circuit Boards (PCB) and a comparison of the manufacturing approach using FR-4, polyimide and paper-based substrates is made. The impacts of different processing steps were considered, all scored using the ReCiPe Endpoint. The results found solder material has a significant influence, with lower-temperature solders reducing the overall environmental impact. However, it has been found that the component that has the biggest environmental impact overall is the IC. We discuss how die size, technology node and packaging formats effects this rating, and also show how the move towards alternative materials can reduce the environmental impact of electronic products.**

***Index Terms*—LCA, degradable electronics, additive printing, PCB**

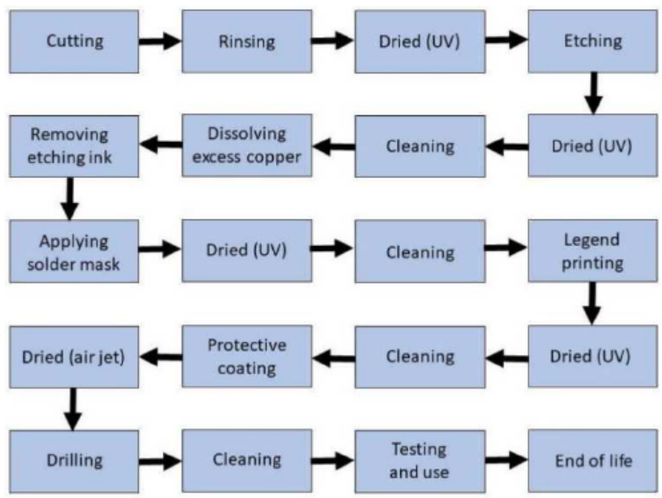


Fig. 1: Fabrication process flow of a standard PCB board. Also, the flow used for the substrate comparison LCA calculations in this work.

I. Introduction

Electronic waste (e-waste) is quickly becoming a major, global problem. In 2020, 53.6 million tonnes of e-waste was generated, and only less than 20 % of that was collected for recycling. [1] The amount of e-waste generated is only growing [2]. On top of the end-of-life waste, there is a significant amount of greenhouse gas emissions produced during the production of electronic components - throughout the supply chain.

Current technologies used in printed circuit board assemblies (PCBA) have evolved over more than 50 years to maximise the performance of the electronics, with little consideration for the sustainability and environmental impact of the product. [3] Conventional PCB substrates utilise composite materials that cannot easily be recycled, as well as a number of critical rare Earth elements that have underdeveloped recycling processes. [4]

This paper evaluates the environmental impacts of each part of the PCBA separately. The widely used FR4 substrate is compared to alternative flexible substrates, which have clearer recycling pathways. Secondly, the current most popular, high-energy-use solder material is discussed and compared to silver conductive adhesives with lower energy processing requirements. The final part of the PCBA is the integrated circuit. Although this is a small percentage of the PCBA by weight, it is a large part of the required input energy and raw materials.

II. Methods

Our model is based on the work of Grant *et al.* [5]. Using this, an initial model was created in a commercial software packaged ”GaBi” from Sphera, Germany. The results were scored using the ReCiPe Endpoint. The initial material inputs into the PCB manufacturing process include an epoxy based polymer (representing FR-4), copper, glass fibre, and additional resin to model the four key layers of a printed circuit board. ICs data was sourced from the GaBi database. Solder matrials were gernated form in-house or from the GaBi database.

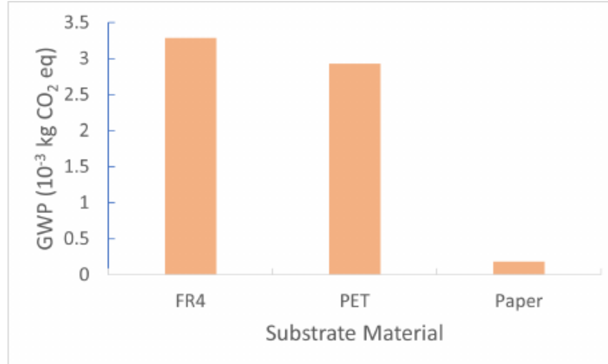
III. Substrate

The most-used, conventional manufacturing approach to make a PCB is with FR4, which uses a combination of glass fibre, epoxy resin and copper. The standard manufacturing flow for an FR4-based PCB is shown in figure 1. This manufacturing flow starts with an FR4 board and the other input materials and transforms it into a finished PCB board.

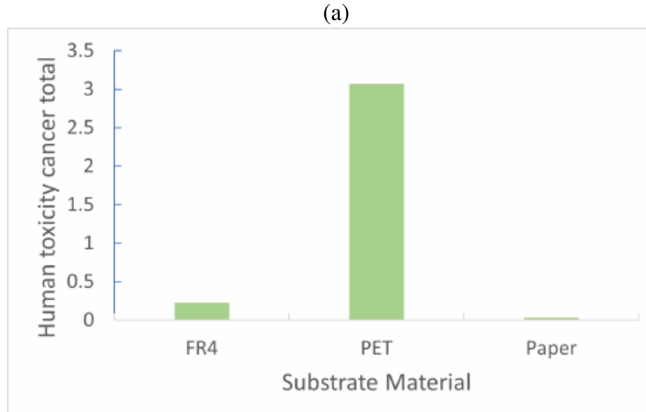
There are alternative materials that could replace FR4 in the future and are currently commercially available. Polyethylene terephthalate (PET) is one material that has been reported to be enzymatically degradable. [6], [7] Other alternatives include fluorinated ethylene propylene (FEP), Poly ether ether ketone (PEEK), flexible glass (CMG) and paper. A key parameter for the usability of these materials within the manufacturing processes is the glass transition temperature of the material. For PET the value is quite low, less than $70\,^{\circ}\mathrm{C}$, which might cause the material to be incompatible with many of the common manufacturing processes that require heating, e.g. soldering. For FEP, PEEK, CMG and paper the glass transition temperature is significantly higher, at more than $200\,^{\circ}\mathrm{C}$.

To evaluate the environmental impact of some of the alternative substrates, a life cycle assessment has been carried out on the conventional PCB, as well as PET and paper alternatives. The standard manufacturing flow was used to compare each of the substrate materials. Modelling was carried out using GaBi software from Sphera and utilised the inbuilt database, as well as custom-built processes. For the FR4 PCB, the processes were designed based on values from Ozkan *et al*. [8] For the PET and paper substrates input materials from the GaBi database were used, 'EU-28: Polyethylene terephalate fibres' for PET, and 'EU-28: Corrugated board' for paper.

The substrate materials are compared using the ReCiPe life cycle impact assessment method. Figure 2a shows the global warming potential (GWP) of the three materials and indicates a clear decrease in GWP could be made by swapping FR4 for paper within the PCB. There is a smaller decrease in GWP to be gained from swapping from FR4 to PET, but this benefit is offset by a much higher human toxicity cancer potential for the PET material - figure 2b. The source of this high toxocity cis primarily contributed by the production of the raw materials of terephthalic acid and ethylene glycol.



(a)



(b)

Fig. 2: a) Global warming potential of the FR4, PET and paper within a $25\,\mathrm{cm}^2$ PCB. Results using the ReCiPe method. b) Human toxicity cancer total of the same materials.

IV. Solder and Die Attach

The material used to attach components to the PCB is another area where a move to less energy-intensive materials reduces the environmental impact of the final, populated PCB. In the past, lead-based solders were most commonly used within the electronics industry, but currently, lead-free solders are dominant after the harmful effects of lead were realised. The most commonly used solder alloy is tin-silver-copper (SnAgCu or SAC) which is considered to have lower human toxicity than lead-based solders.

From the perspective of the global warming potential of the materials, a significant parameter of the solder alloy is the required reflow temperature. As an example, the melting point of lead-based SnPbAg solder is $179\,^{\circ}\mathrm{C}$, whereas for the lead-free SnAgCu the melting point is much higher at $217\,^{\circ}\mathrm{C}$. So, the energy input required for the lead-free solder is consequentially higher. This energy input for the soldering process is usually significantly higher than the embodied energy from the production of the solder.

Figure 3 shows the global warming potential for each solder material. Both production and soldering process are taken into account for soldering a 100-pin IC to a PCB. The GWP due to solder production is dependent on the constituent components of each solder paste and the processes used in production. The GWP due to the energy consumption is majority dependent on the temperature required to melt the solder; a standard solder oven requires about $8\,\mathrm{W}/^{\circ}\mathrm{C}$.

To reduce the overall GWP of the die-attach process it is important to reduce the required reflow temperature of the adhesive material. This will result in a direct reduction in the process energy consumption and could be a significant reduction in the overall energy consumption as well. One option that has been explored is silver conductive adhesive. This adhesive is epoxy based, with silver nanoparticles as the conductive material. The curing temperature is $140\,^{\circ}\mathrm{C}$, much lower than the reflow temperature of lead and tin-based solder pastes. Figure 4 compares the energy consumption of the silver conductive adhesive to that of SAC solder paste - the current most used die attach material.

The embodied energy cost of the silver ICA production is actually slightly higher than for the SAC solder, however,

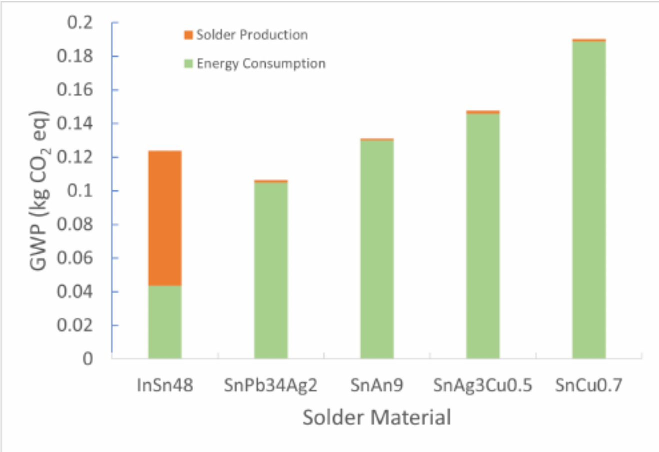


Fig. 3: Global warming potential for the production of solder and energy consumption for soldering. All measurements are for soldering an IC with 100 pins.

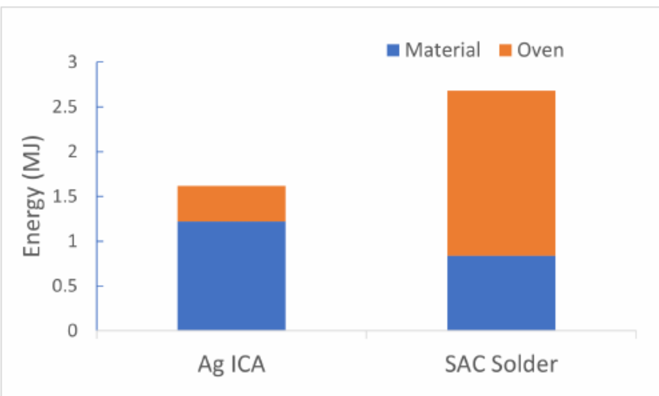


Fig. 4: Energy requirements for production and process use of both standard SAC solder and alternative silver conductive adhesive. Data from A. S. G. Andrae *et al.* [9]

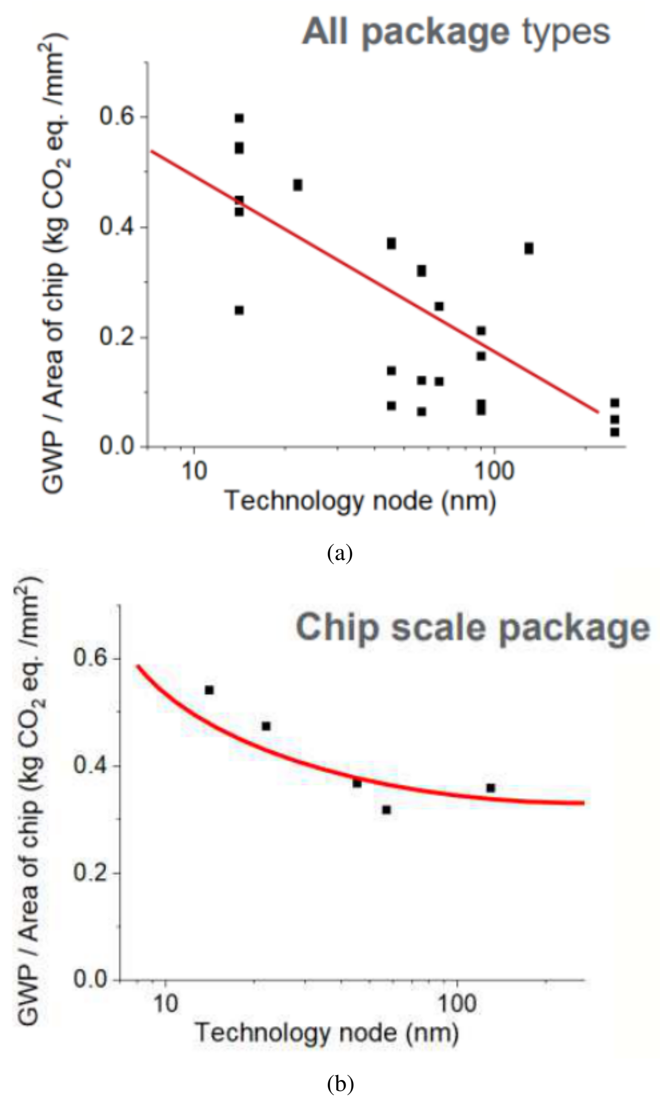


Fig. 5: Comparisons of the global warming potential by area of IC chip for all ICs in the GaBi database. a) chip-scale packages. b) all types of packages.

the overall energy required is significantly lower. The curing energy required is only $22\,\%$ of the solder process energy. The overall energy saving is $40\,\%$ for this material combination, although a higher energy saving could be achieved by reducing the embedded energy of the silver ICA. This could be done through improved production processes or changes in the composition of the adhesive to minimise energy use during production. There are many ways of fabricating the required silver nanoparticles, which could be investigated from an energy usage viewpoint.

V. IC Layout

The final part of a populated PCB is the integrated circuits that are attached to the PCB. The layouts that underpin the IC design have been decreasing in size as fabrication technology has evolved. However, a smaller scale doesn't equate to fewer resources used in the manufacturing process. In fact, by chip area, the GWP increases as node size decreases. This is shown to be the trend for all the ICs in the GaBi database, see figure 5. The results shown here are plotted by area, but this is affected if a different parameter is used. For example, if GWP per megabyte on the IC is considered the results are more favourable to the lower technology node lengths. It is worth noting that, in general, as node size has decreased, the size of the dies has increased. So, GWP per die shows a similar trend to the GWP per area shown in the figure.

One limitation of the results discussed here is the lack of data from current and recent generations of ICs. The fabrication process data is considered proprietary and of high value by chip manufacturers. Therefore, the available doesn't include the recent technology node sizes and the smallest size shown in the results is $14\,\mathrm{nm}$. The current lowest technology node size is $3\,\mathrm{nm}$. Clearly further research is needed in this area.

VI. CONCLUSION

The increasingly urgent need to reduce emission and electronic waste requires all aspects of PCBAs to be optimised for sustainability. To this end, alternative materials for each of the major components have been evaluated. Life cycle assessments of substrate materials have shown that a paper-based substrate can reduce the global warming potential by $94\,\%$ compared to the standard FR4 material. Similarly, the total energy consumption for the die attach process can be almost halved through the use of a silver conductive adhesive instead of the most popular SAC solder paste in use today. Finally, the current trend of IC designs has been shown to be increasing global warming potential with each technology advancement. Since the IC is the most significant part of the PCBA from a global warming perspective, alternative designs to combat this trend is an important goal.

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