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Improving the sustainability of printed circuit boards through additive printing

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***Abstract*— A life-cycle assessment (LCA) was performed on Printed Circuit Boards (PCB) made using the traditional manufacturing approach with FR-4 substrates. The scope was cradle to grave, including embodied impacts, transportation, energy used during manufacturing, waste material generated and disposal. The impact of different processing steps were considered, all scored using the ReCiPe Endpoint. Results show that consideration should be given to PCB design, including number of layers used in multilayer boards. Furthermore, the study investigated the impact of changing the manufacturing methodology by considering an additive printed circuit board. A significant reduction in environmental impact is seen by moving to either polymeric or paper based substrates.**

Keywords—Printed circuit boards, PCB, sustainability, life cycle assessment, printed electronics, large area electronics, additive printing

I. INTRODUCTION *(HEADING 1)*

For more than 50 years, advances in electronics have revolutionized all socioeconomic sectors. Electronics underpin the digital transformation that affects all businesses, industries and value chains and are critical to delivering the UN Sustainable Development Goals [1]. There is little doubt that the modern world will continue to rely heavily on smart technologies, and with this reliance comes a phenomenal demand for more products and energy to power such products. However, in pursuit of this goal, the industry has evolved whereby the materials and manufacturing processes are decided by the technical and economic requirements, and not sustainability, resulting in poor practices and unintended outcomes [2]. These technologies are major greenhouse gas (GHG) emitters in households and industries, especially when one considers the Information and Communications Technologies (ICT) such as lighting, food and heating that underpin these technologies. With the threats of climate change more impactful than ever before, extensive changes need to be made to the way these new technologies are developed and consumed in order to procure a sustainable future and meet net zero targets.

The Waste Printed Circuit Board (WPCB) makes a major part of WEEE. However, the material composition varies tremendously with application, design, functionality, manufacturing route, and application. The most common material is based on the composite material FR-4 and planar printed circuit boards (PCBs) are seen in most electronic devices, but emerging applications, such as wearable electronics, vehicles with interactive interiors, and robotics, require conformable and flexible PCBs (FPCBs) [3,4]. Typically, WPCBs comprise a mixture of materials that can be grouped into nonferrous and ferrous metals and plastics and ferrous metals tend to constitute the largest proportion of WEEE in size and weight, followed by plastics [5].

This paper will first review some of the drivers and opportunities for sustainable PCB manufacturing, and then target specific areas of processing to changes to improve the sustainability. Process modelling has been undertaken, and environmental assessment conducted, to support the final recommendation to improve the sustainability of the product. The paper presents a method to accurately model the life cycle of a printed circuit board (PCB), and this can be used to review the environmental impact at each key stage of the life cycle. Furthermore, the paper provides scope for further investigation into the use of alternative materials in PCB manufacturing as a step to improve their sustainability; as well as provide a potential gateway for research into other types of electrical component manufacturing. The move towards additive manufacturing (or “printed electronics”) shows how alternative material and processes can reduce the environmental impact of electronic products which is validated through Life Cycle Assessment (LCA) calculations.

II. METHOLODOLOGY

A. *Goal and scope*

The goal of this study is to assess the environmental impact across the life cycle of a PCB, and from these findings propose changes which will reduce the environmental impact. The scope of this research will cover an initial model based on current PCB manufacturing processes and materials, and a revised model with a lower environmental impact. Analysis of materials and the processes needed to make them suitable for PCB manufacturing will be at the centre of the study, with an emphasize on the solder paste material, substrate material and end of life scenario. A selection of soldering and substrate materials will be explored based on the inventory of materials available on the commercial databases. The quantities of the materials will be scaled appropriately to simulate a single layered 25cm^2 PCB. The environmental impact assessments cover the global warming potential over one-hundred years, acidification potential, human toxicity cancer total, Ozone layer depletion, particulate matter, metal depletion and water depletion using the EcoInvent database. Global differences in energy mix and landfill procedure will have an impact on the results. This study will constrain the PCB life cycle to within Great Britain (GB) as keeping manufacturing local minimises transportation emissions, therefore, the work has applied the GB energy mix and utilised GB and European standard procedures for landfill.

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B. *Implementation*

Our initial modelling is largely based on previous studies from Babuna et al [6]. Using this, an initial model was created in a commercial software packaged “GaBi” from Sphera, Germany. GaBi models are derived from the inputs and outputs that go into each phase of the simulation. This is done by using “flows”. There are three main flows that GaBi uses to build an accurate representation of the model: elementary, non-elementary (waste), and non-elementary (tracked). The first is used to depict the flow between natural resources, the second flow is that of an unnatural resource that is no longer used in the processes and thus can be considered waste. Lastly, the third flow type is non-elementary, but these resources are valuable and can be moved through the simulation to be used elsewhere. Whilst GaBi boasts an impressive database, it does not house every process, and so custom-made processes were built to accommodate the diversity of the manufacturing stages. This process consisted of the process to manufacture an FR-4 based PCB. This model made use of custom designed processes based on the values obtained from the study by Ozkan et al. [7] and the described manufacturing stages.

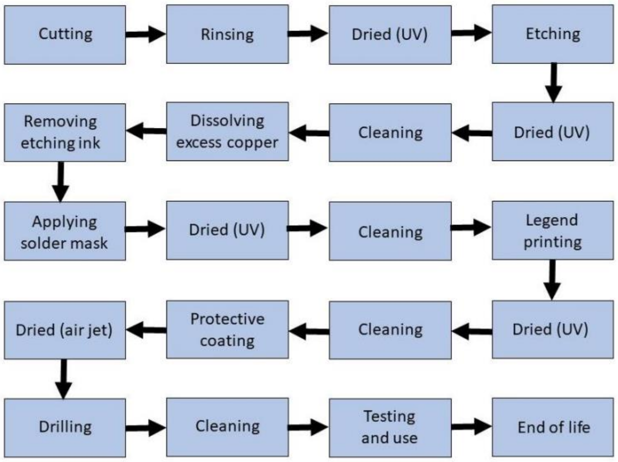


Figure 1; Process flow used for the LCA calculations in this work

The initial material inputs into the PCB manufacturing process (Figure 1), 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. This model has then been implemented into a larger system which includes the soldering and integrated circuit processes to complete the inputs for the initial model for manufacturing a PCB with an integrated circuit. The comprehensive model has been used to review the environmental impacts associated with the manufacturing of the product using the aforementioned standard procedure for PCB manufacturing and subsequent materials, solder paste, and landfill as the end-of-life process for the product. Based on the results of the ‘Initial Model’ simulation, deeper analysis has been conducted on the soldering and substrate materials as well as how these changes will affect the end-of-life procedure. From the analysis carried out on these environmental impact assessments, a recommendation has been made that will reduce the overall environmental impact of the ‘Initial Model’. This has been verified by comparing the global warming potential of the ‘Initial Model’ with that of the modified model with the improvement recommendation. Improving the sustainability of PCBs using LCA. The results were scored using the ReCiPe Endpoint.

III. RESULTS

A. *Life cycle of the PCB*

From the results of the process depicted in Figure 2(a), the manufacturing process is shown to be the largest contributor to the overall Global Warming Potential (GWP) impact, when compared to the end-of-life processes; note, incineration and depositing into landfill were considered. This trend was continued across all other environmental impact assessments, although the data is not shown. “Use stage” was also not modelled in this work as such a wide variety of use cases are seen in electronics depending on application, all of which uses varying amounts of electricity. These results indicated a need to more deeply investigate the aspects of the PCB which contribute to environmental degradation. The GWP results from the investigation into PCB manufacturing are as shown in Figure 2(b).

The results from the Standard PCB analysis indicate that the epoxy resin is the largest contributor to the GWP. This tends to be the largest material present in PCBs substrates in terms of mass, which is one of the primary reasons it contributes the most in terms of overall GWP. However, it is worth noting that the copper, glass fibres and the manufacturing process itself all contribute significantly to the overall effect.

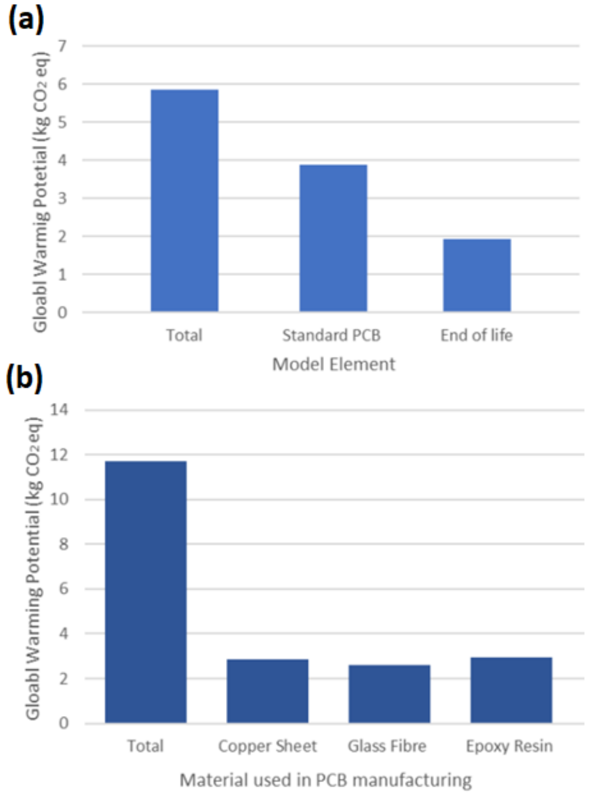


Figure 2(a) and (b) Global Warming Potential (GWP) of the PCB considering manufacturing and End-of-Life via landfill and (b) breakdown of how materials in PCB impact on the GWP

Results from the studies in figures 2(a) and (b) showed that the several materials and manufacturing steps of PCBs contributed significantly to the GWP of the PCBs. Therefore, alternative substrate materials have been investigated to determine which substrate will lower the environmental impact of the product. Using data from the GaBi database, analysis was conducted on how the GWP varied with the number of layers used within a 'Printed Wiring Board', made with rigid FR-4 and with a HASL finish (Subtractive method). The results, as shown in Figure 3, show a strong linear correlation between an increasing number of layers and an increase in the GWP impact. Within electronics, there is an increasing trend to move towards multilayer PCBs; this saves space, enables high speed operation and can reduce cost [8]. However, it is clear that using the minimum number of layers possible would be beneficial in reducing the overall GWP, unless savings in power consumption or improved recycling resulted.

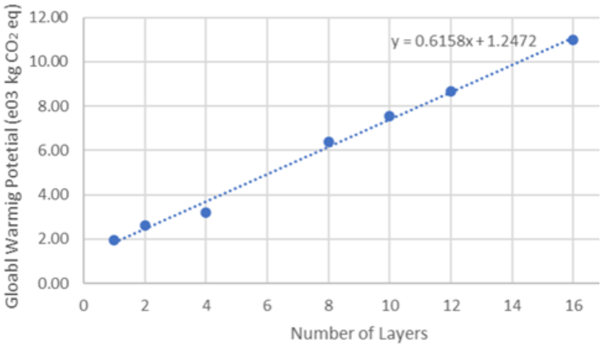


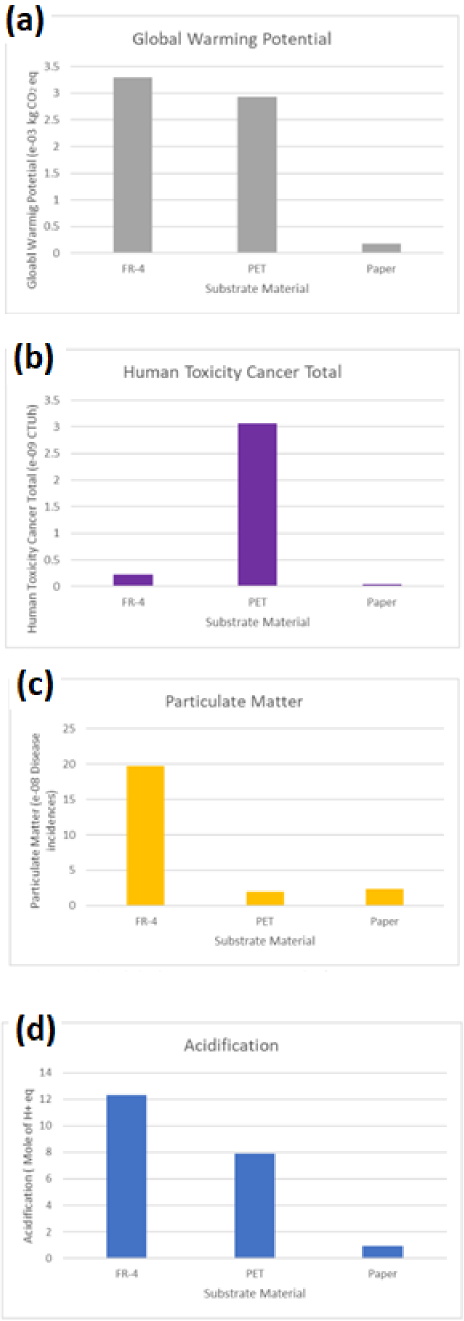
Figure 3 Global Warming Potential (GWP) of the PCB considering different numbers of layers on a multilayer PCB substrate

B. *Comparison against printable substrates*

In addition to the standard FR-4 substrate, alterative substrate materials such as Polyethylene terephalate (PET) and paper-based substrates were considered. PET can be recycled, and recent studies indicate that it can also degrade enzymatically [9]. As such, the FR-4 substrate results were compared against 'EU-28: Polyethylene terephalate fibres' (PET), and 'EU-28: Corrugated board' (paper-based) to review how changing the substrate material will impact the GWP of standard single-layer-PCB manufacturing using the model seen in Figure 1.

The results indicate that using FR-4 as the substrate in the PCB has the worst impact upon GWP, whereas using a paper-based substrate contributes the least to GWP (Figure 4). The corrugated board substrate shows a significant decrease in environmental impact compared to both FR-4 and PET results, with the exception of impact categories involving land use (as clearly commercial forestry is needed to produce large volumes of paper). However, the results also highlight the benefits of using PET as the substrate in place of FR-4. Whilst the impact levels do not have the same significant drop compared to the paper-based substrate, the material and mechanical similarities between PET and FR-4 make it an ideal step towards a more sustainable model for PCB manufacturing. Its main drawback exhibited is its extremely high human toxicity cancer total but implementing this substrate into standard PCB manufacturing would be much more manageable at the moment than implementing a paper-based substrate due to the mechanical similarities between FR-4 and PET [10].

However, manufacturing PCBs using paper and PET are still conceptual or used in niche application and the technologies haven't made significant commercial in-roads owing the reliability, cost, and new technology adoption challenges [11]. Additional challenges are related to the type of solder paste that is used, which must have a lower melting point than the glass transition temperature of plastic substrates or avoid burning the paper-based substrate. Fortunately, In-Sn based material or electro conductive adhesives have melting points under 118ºC and could be suitable for PCBs made onto PET or a paper-based substrate [12].



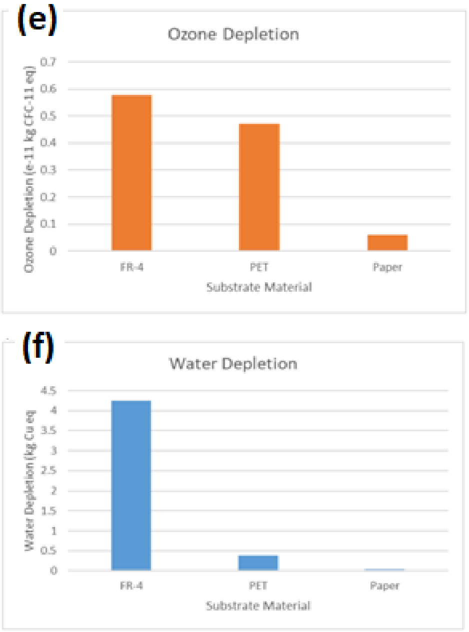


Figure 4 (A) Global warming potential of FR-4, PET, and 'EU-28: Corrugated board' (paper); (B) Acidification for each substrate; (C) Human Toxicity Cancer Total; (D) Ozone Depletion; (E) Particulate Matter (F) Water Depletion for each substrate

As mentioned prior, using a paper-based substrate would require altering the material used in the conductive layer. Printed silver ink would be a viable option for the conductive layer of the PCB. On this basis, an additional model was run using the paper substrate and silver as the conductive layer to verify the practical implications of using the supposed environmentally beneficial substrate. The results of this study are shown in Figure 5 found that using silver as the conductive layer in conjunction with a paper-based substrate will cause the GWP to decrease from 2.87 kg CO_2 eq. to 2.83 kg CO2 eq. This is an excellent step towards sustainability within PCB manufacturing as using the silver ink with the paper, and using In-Sn solders for soldering, paper-based substrates can produce a significantly more sustainable product.

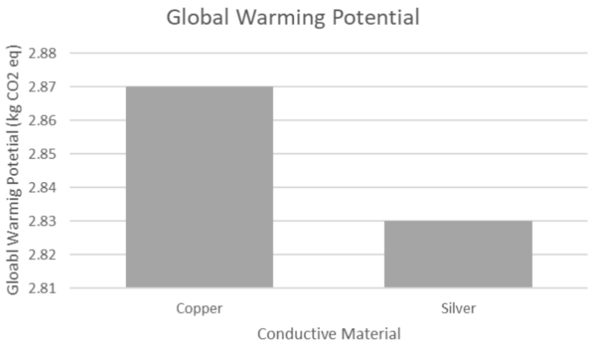


Figure 5 Global warming potential of copper and silver-based PCB conductive layers

CONCLUSIONS

With the increasing use of electronics in everyday life and the emergence of mass product such as Internet of Things (IoT), there is a greater need to improve the sustainability of PCBs. In this work, a life-cycle assessment (LCA) was performed on Printed Circuit Boards (PCB) made using the traditional manufacturing approach which uses FR-4 substrates and subtractive etching of copper tracks. The impact of different processing steps were considered in order to identify 'hotspots' in the manufacturing process and were scored using the ReCiPe Endpoint. Results show that consideration should be given to PCB design, including the minimization of materials (e.g. thinner PCBs) and also designing for operation by keeping the number of layers used in multilayer boards to a minimum. Furthermore, the study investigated the impact of changing the manufacturing by considering an additive printing of PCBs. A significant reduction in environmental impact is seen by moving to either polymeric or paper based substrates.

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