

PRINTED CIRCUIT BOARD RECYCLING IN AUSTRALIA

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ABSTRACT

Electronic printed circuit boards (PCBs) are complex assemblies which embody numerous materials and which require quite large quantities of energy and other materials to manufacture. They also include significant quantities of metals such as lead, copper and nickel some of which are toxic to life and all of which are valuable resources. Large volumes of printed circuit boards are imported into Australia every year in television receivers, computers etc. and these must eventually be disposed of. Recovery of the valuable materials and their diversion from landfill where leaching of toxic materials may occur, is an expensive process because of the complexity of the product and the relatively small quantities present on each printed circuit board.

This paper uses an LCA approach to examine the value of recycling various grades of PCB. It compares various scenarios from complete landfill to recycling of most metallic components for a range of different PCBs from complex (such as in computer boards) to more simple (such as found on computer CRT monitors) and includes the shipping of PCBs overseas for processing. The study suggests that recycling is very worthwhile from the point of view of material recovery but only marginally worthwhile on other measures. It also reveals that the logistics of collection arrangements are critical and must avoid dedicated vehicle trips to deliver small quantities of end-of-life product.

Keywords: printed circuit boards, recycling, landfill, life cycle assessment

1. GENERAL INFORMATION

Large quantities of electronic equipment are manufactured every year around the world. Australia's share is almost entirely imported in the form of consumer items such as television receivers, computers and mobile phone handsets. The quantities of the most significant items are shown in figure 1.

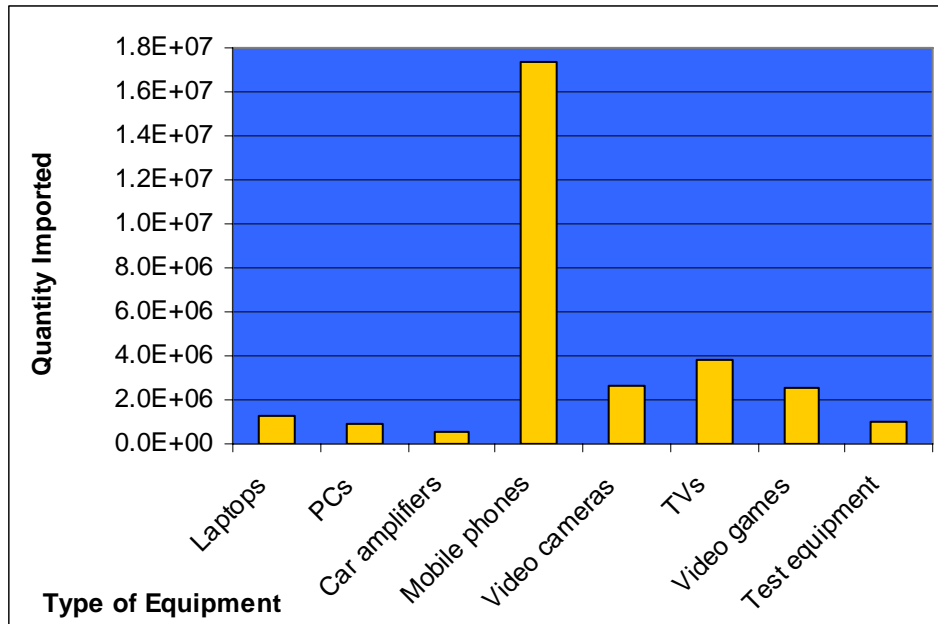


Figure 1. Quantity of items of electronics imported to Australia in 2004.
Source: Australian Bureau of Statistics, 2005

2. INTRODUCTION

Almost every piece of electronic equipment has its electronic components mounted by soldering onto a fibre-based epoxy printed circuit board (PCB) or similar with the interconnecting wiring provided by tracks of copper on that board. The solder is usually a mixture of lead and tin. The components themselves are a mixture of often quite sophisticated construction and include the components listed in table 1.

Table 1. Typical printed circuit board components and their major compositional components

| Electronic Component | Majority Composition |
|-----------------------------|---|
| Resistors | Ceramic, carbon |
| Capacitors | Aluminium, electrolyte, plastic etc, copper leads |
| Inductors, Transformers | Steel, copper |
| Integrated circuits | Plastic cases, copper leads, silicon |
| Transistors, diodes | Plastic cases, copper leads, silicon |
| Connectors | Various plastics, steel, copper |
| Wires | Copper, plastic |
| Mounting brackets | Aluminium, steel |
| Heat sinks | Aluminium |

All this results in quite a large variety of materials being part of the whole assembly, with the possibility of significant environmental impacts arising from both the material resources use and the effects of disposal. These possibilities when multiplied by the quantities outlined in table 1 suggest that minimising the impacts may be a worthwhile activity. Specifically, a significant proportion of the embodied materials are metals which are worth recycling as shown by the data in table 2.

Table 2. The energy benefits of recycling materials commonly found in printed circuit boards.
Source: Cui & Forssberg [1]

| Material | Energy savings over virgin materials (%) |
|----------------|--|
| Aluminum | 95 |
| Copper | 85 |
| Iron and steel | 74 |
| Lead | 65 |
| Zinc | 60 |
| Paper | 64 |
| Plastics | >80 |

Currently some small proportion of the printed circuit boards from items such as computers and television sets are recycled from Australia, mainly (if not entirely) by exporting them to a distant location such as Korea or Europe. The purpose of this paper is to evaluate the extent to which such recycling efforts are worthwhile. The common alternative to recycling is to simply land fill.

3. LAND-FILLING PRINTED CIRCUIT BOARDS

There are however significant issues with land filling of obsolete printed circuit boards. While such boards comprise only about 3 % by weight of the mass of general consumer electrical and electronic waste [2], their environmental impact may be significant for several reasons. Some of these reasons are related to the manufacturing of integrated circuits and the printed substrate itself which are not relevant to this present study. Others relate directly to the embodied materials of the boards. For example, such boards contain significant amounts of copper in the tracks and cables and lead in the solder, both of which are toxic materials (and both of which required significant energy to extract from ore initially). Land-filling of these metals is thus not only a waste of valuable resources, but also a potential hazard. There is evidence that leaching of lead occurs from land-fill sites into water tables [3], [4]. Table 3 shows estimates of the amount of leaching from landfill for various materials.

Table 3. Estimated leaching of materials in a controlled landfill.
Source: Huisman 2003 table 3.3 [5]

| Element | to soil | to air | to water |
|---------|---------|---------|----------|
| Hg | 0,0004% | 0,0000% | 0,0071% |
| Cd | 0,0001% | 0,0000% | 0,0026% |
| As | 0,0001% | 0,0000% | 0,0022% |
| Cr | 0,0001% | 0,0000% | 0,0019% |
| Cu | 0,0002% | 0,0000% | 0,0045% |
| Pb | 0,0001% | 0,0000% | 0,0016% |
| Zn | 0,0000% | 0,0000% | 0,0006% |
| Cl | 0,2933% | 0,1035% | 1,4373% |
| Ni | 0,0002% | 0,0000% | 0,0040% |

In addition, there may be small amounts of more valuable metals such as gold (used for contacts) and silver (used in some solders and in sensors etc), and in some cases it is the economic value of these materials which drives the recycling effort. The quantity of these materials is however decreasing over time. Small amounts of other hazardous materials may also be present in many different details of the printed circuit boards.

The quantities of materials in typical printed circuit boards varies widely depending on the application and age. Some representative figures are given in table 4 for four different printed circuit boards. This data is sourced from literature where detailed analysis of composition was done and from general observations and estimates by the author [6], [7], [8], [9], [10]. Only those materials relevant to the current study are included in table 4.

Table 4. Material composition of selected printed circuit boards by weight (%), excluding materials in very small quantity not relevant to the present study.

| Material | Board 1 FR4 (less copper and ICs) | Board 2 FR4 (more copper & ICs) | Board 3 Phenolic board (TV, monitor) | Board 4 FR4 (more copper & ICs, lead free solder) |
|------------------------------|--|--|---|---|
| | % | % | % | % |
| Copper | 7 | 27 | 36 | 27 |
| Iron | 12 | 2 | 10.7 | 2 |
| Glass fibre & SiO2 filler | 23.8 | 15 | 13 | 15 |
| Plastics | 23 | 5 | 7 | 5 |
| Ferrite | 5 | 0 | 3 | 0 |
| Epoxy | 7 | 8 | 0 | 8 |
| Phenolic | 0 | 0 | 6 | 0 |
| Gold | 0.03 | 0.1 | 0 | 0.1 |
| Bismuth | 0.005 | 0.05 | | 3.45 |
| Chromium | 0.002 | 0.1 | | 0.1 |
| Lead | 0.3 | 3 | 0.2 | 0 |
| Nickel | 2.3 | 0.2 | 0.1 | 0.2 |
| Silver | 0.3 | 0.04 | 0 | 0.1 |
| Tin | 0.3 | 3 | 0.2 | 2.5 |
| Zinc | 3 | 0.5 | 0 | 0.5 |
| Aluminium | 7 | 1 | 22 | 1 |
| ICs complex equiv | 9 | 35 | 1 | 35 |

4. RECYCLING PRINTED CIRCUIT BOARDS

There are many different processes for recycling printed circuit boards and many more being proposed as time goes on, but difficulties arise with the economics of such processes [2] and with the very large mix of materials contained in the boards. However a typical process is [1], [11], [5]:

- Partial disassembly by hand to remove hazardous materials such as batteries and other large components.
- Shredding to reduce particle size to a few mm or smaller.
- Separation of different materials
 - Magnetic separation for ferrous metals
 - Magnetic separation for some copper alloys
 - Eddy current separation for non-ferrous metals
 - Triboelectric or density based separation for plastics
 - Jigging to separate light and heavy non-ferrous metals
 - Smelting to refine out small fractions of valuable metals such as gold

This would seem to be a complex process given the relatively small volume involved. Indeed, it is argued in [12] that disassembling printed circuit boards has a relatively low environmental benefit relative to some of the other activities such as collection of metal dominated products (refrigerators and washing machines) and CRT glass recycling currently being mandated in Europe. The purpose of this study is to assess to what extent recycling may be worthwhile in Australian conditions.

5. LIFE CYCLE ANALYSIS

A life cycle assessment study was undertaken on the range of typical printed circuit boards described in table 4, above starting from the time of their disposal in the commercial or domestic premises where they have been used. Each of the four different boards was assessed according to two scenarios both of which are currently practiced in Australia, namely simple

disposal in landfill or partial disassembly and shipping overseas for recovery of certain materials. The integrated circuits were omitted from the analysis because their contribution was very significant and tended to mask the other results and, since it was assumed that no recycling of integrated circuits was practical, they were not relevant to this end-of-life study.

According to [13], the mass of electronic equipment needing recycling in the USA is of the order of 0.8 kg per person per year with an average household comprising 2.5 people. However [2] gives much higher figures for Europe of 4 to 9 kg per person per year. For this study, therefore, the following assumptions were made about quantity and collection from households:

- Quantity 4 kg per person or 10 kg per household per year
- Printed circuit boards comprise 3 % of electrical and electronic equipment waste by mass

The landfill scenario began with the transport of the entire equipment by waste pick up, a distance of 15 km to a transfer station and then a further 130 km by train to a landfill site.

The recycling scenario began with the delivery of the entire equipment a distance of 5 km by a dedicated trip by private car to the collection point once per year. This was followed by transport 30 km to a disassembly plant where it remained in storage for 4 weeks, was disassembled with all components except the printed circuit board going to landfill. Australian data was used for all transport, energy costs etc.

The printed circuit boards alone were then packed, transported by road to the wharves, by ship to Korea (as a typical destination) followed by further transport by road. At the processing plant, boards were shredded and materials separated by eddy current or magnetic processes using typical energy input data and percentages of recovery data from [5] as shown in tables 5 and 6. Some energy was also recovered by burning the fibre board itself. For this part of the study, the functional unit was chosen to be 170 g of waste printed circuit board, a typical weight for a computer card or similar. In this analysis, all metals and glass, plastics and paper are recycled.

Table 5 Typical energy consumption of shredding and separation.
Source: Huisman (2003) table 3.1 [5]

| Process | Energy consumption (kWh/ton) |
|---------------------|------------------------------|
| Shredder 1 | 20 |
| Shredder 2 | 40 |
| Magnetic Separation | 0.6 |
| Eddy Current | 5 |
| Total | 65,6 |

Table 6 Average recoveries of metals at a copper smelter
Source: Huisman (2003) table 3.4 [5]

| Metal | Recovery rate |
|-------|---------------|
| Cu | 95% |
| Ag | 97% |
| Au | 98% |
| Pd | 98% |
| Ni | 90% |
| Pb | 90% |
| Sn | 90% |
| Cd | 90% |
| Hg | 90% |

A model of the amount of leaching of potentially hazardous substances was also incorporated as given in table 7.

Table 7 Estimated leaching of materials in a controlled landfill
Source Huisman (2003) table 3.3 [5]

| Material | To soil | To air | To water |
|----------|---------|---------|----------|
| Hg | 0.0004% | 0.0000% | 0.0071% |
| Cd | 0.0001% | 0.0000% | 0.0026% |
| As | 0.0001% | 0.0000% | 0.0022% |
| Cr | 0.0001% | 0.0000% | 0.0019% |
| Cu | 0.0002% | 0.0000% | 0.0045% |
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6. RESULTS

The eight possible scenarios outlined above were analysed using SimaPro, predominantly Australian data and the Eco-Indicator 99 (E) method. An overall comparison of the eight different boards and disposal cases is given in figure 2, however this raw data includes production impacts etc for the boards and thus does not help answer the question about whether recycling of printed circuit boards is worthwhile.

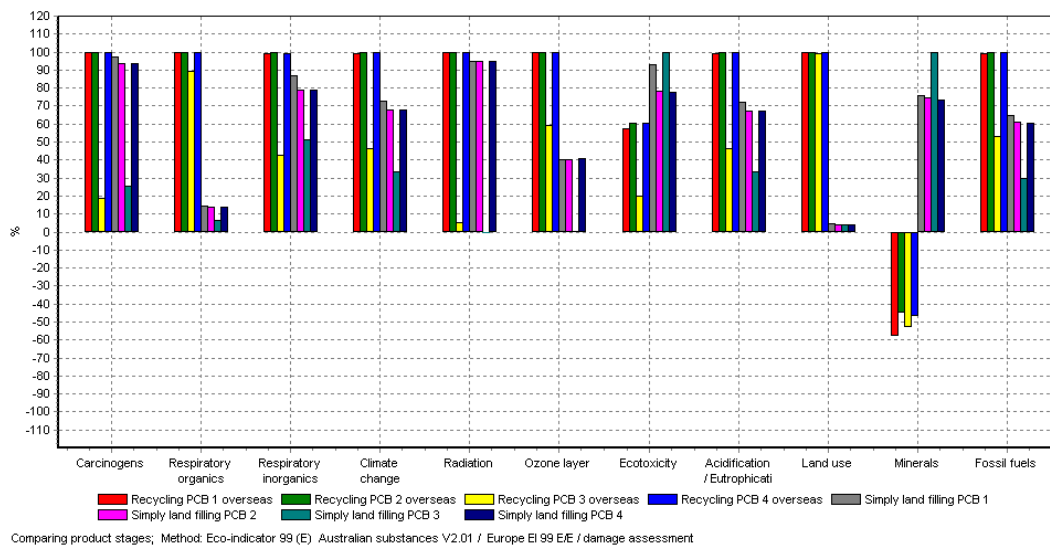
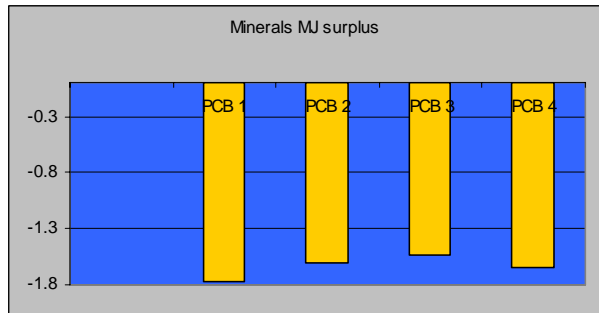
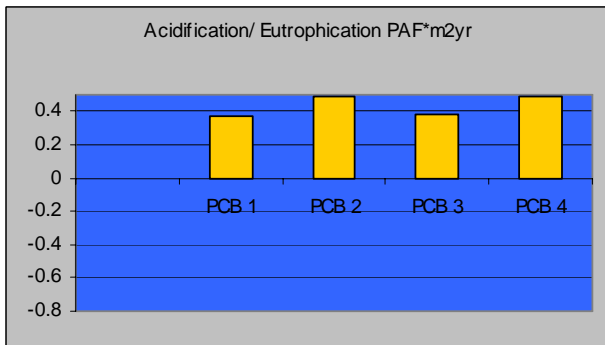
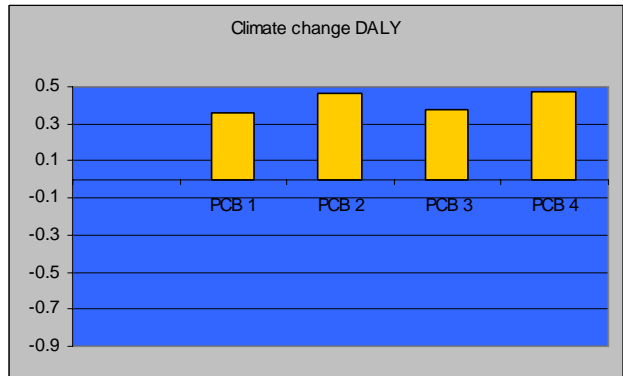
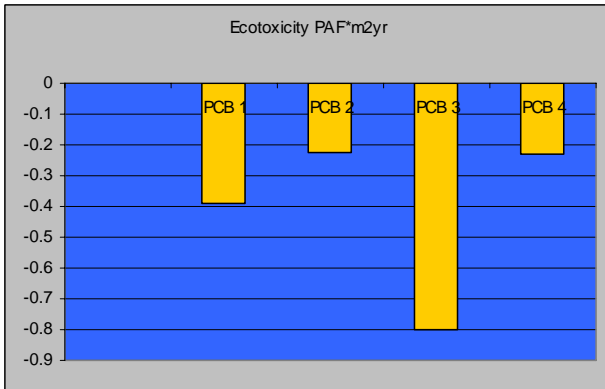
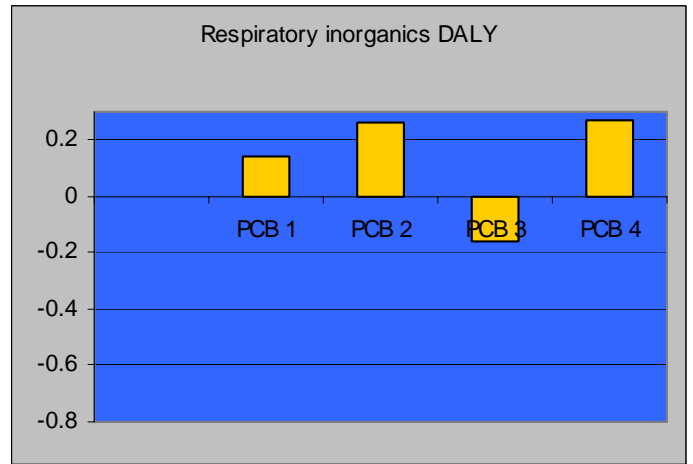
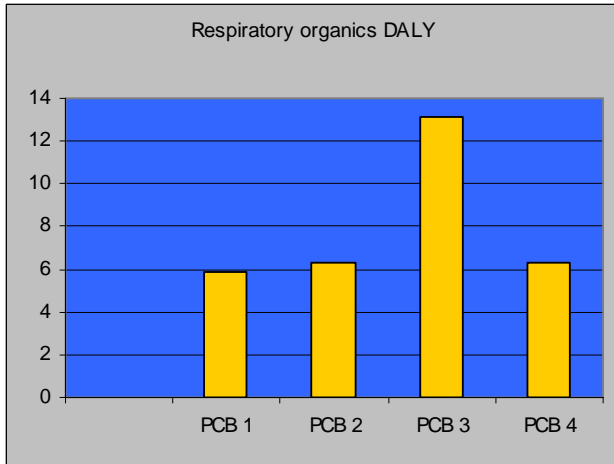


Figure 2. Total impact scores for eleven characteristics of environmental damage due to eight different printed circuit board scenarios.

The data of figure 2 can however be used initially to draw some conclusions about the impact of the different types of printed circuit boards. Board 3 is the simpler type commonly found in monitors and television receivers, and the board itself is commonly phenolic in construction rather than epoxy based and its electronic components are somewhat simpler overall than those found for example on computer boards. These boards cause less damage than epoxy boards in all of the characteristics analysed in figure 2 except ecotoxicity and minerals where they cause the most damage because of the large amount of aluminium assumed and the releases by the high energy demand of that process. The aluminium is used as brackets to hold the bulky components needed for displays.

Board 4 is the same as board 2 except that the former uses lead-free solder, so some less damage is to be expected at least for the land-fill case in the light of worldwide moves to ban lead based solder. According to figure 2 however there is very little difference between the two boards on any characteristic, because the impact of lead is less than the impact of other factors such as those caused by energy use or by the production of the epoxy boards.

The analysis in figure 2 also suggests that the only category where shipping printed circuit boards overseas and recovering metals from them is environmentally beneficial is in the mineral category. All other categories including fossil fuel use and toxicity show that it is better to landfill. However in order to more precisely determine the impact of recycling boards relative to the simple alternative of land-filling them, the difference in damage scores between the recycled cases and the corresponding land-filled cases were taken and expressed as a fraction of the land-filled case. Figure 3 shows the difference in damage scores between the scores for recycling and those for land-filling, expressed as a fraction of the land-filling case. They thus represent the damage caused by recycling as opposed to land-filling with positive scores indicating more damage due to recycling.



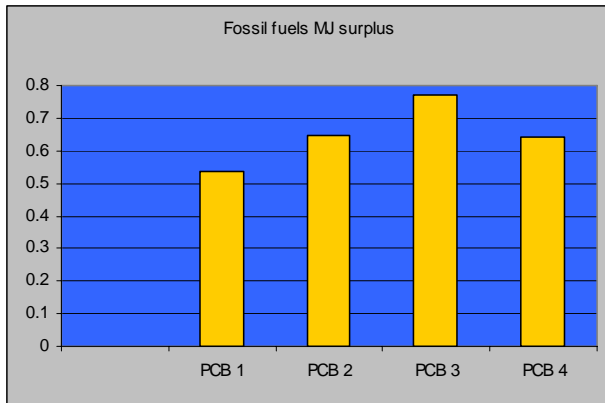


Figure 3. Damage characterisation due to recycling compared to land-filling four different printed circuit boards. The vertical axis is damage expressed as a fraction of damage caused by land-filling the same board – positive scores indicate more damage due to recycling.

On each of the characteristics analysed, the results suggest the following conclusions:

- Respiratory organics: It causes more damage to recycle than to landfill by factors from 6 to 14 for the various printed circuit boards, with the phenolic board being the worst. This impact is predominantly from car petrol with some from oil refinery waste. This impact thus occurs mainly in Australia.
- Respiratory inorganics: More respiratory organics are released by recycling the epoxy boards than by land-filling but only by a relatively small margin typically 30%. For phenolic boards, there is less release. These impacts are mainly due to the use of a car to deliver the boards to the recycling depot but there is also a significant impact from the electricity used for the recycling process.
- Ecotoxicity: There are some relatively small advantages to recycling in this area because it avoids putting some copper into the environment in Australian landfill sites.
- Climate change: The impact of recycling here is negative. It would be better not to recycle because of the emissions due to car petrol and to electricity for processing the boards.
- Acidification/Eutrophication: The impact of recycling is again negative because of the emissions due to car petrol and to electricity for processing the boards.
- Minerals: As might be expected, recycling allows recovery of some materials and is thus beneficial. The benefit would occur at the site of metal refining.
- Fossil fuels: More fuel is used to recycle because of the energy needed for transport and processing so from this point of view recycling is not worthwhile.

Perhaps not surprisingly, the use of a car to deliver small quantities of printed circuit boards to the recycling depot is a source of significant and sometimes dominant environmental impact. Consequently, the analysis was repeated under the assumption that no car transport was needed, and that collection could be arranged via normal council garbage collection. Figure 4 shows the results of this analysis using the same method as for the data of figure 3.

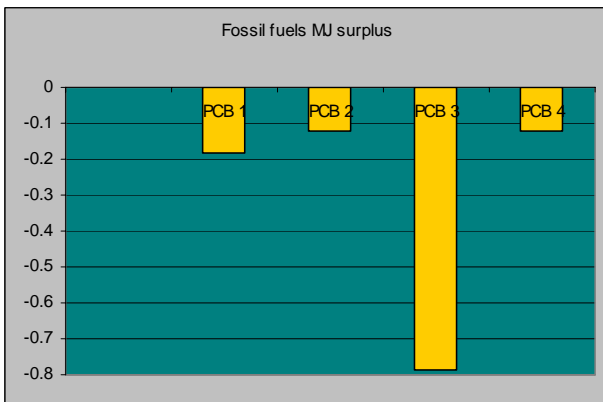
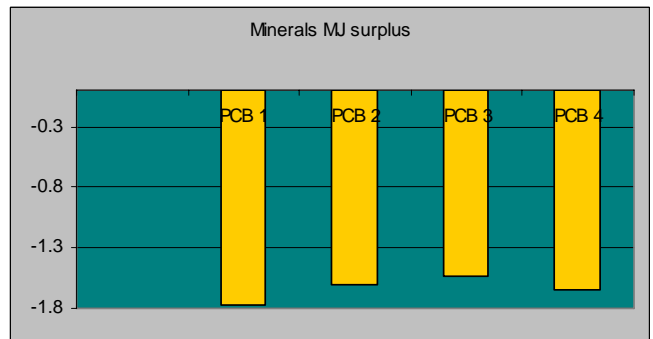
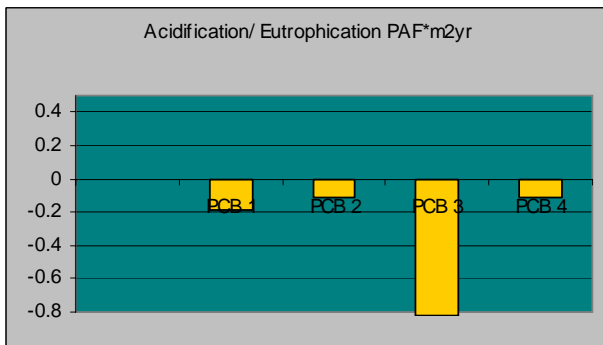
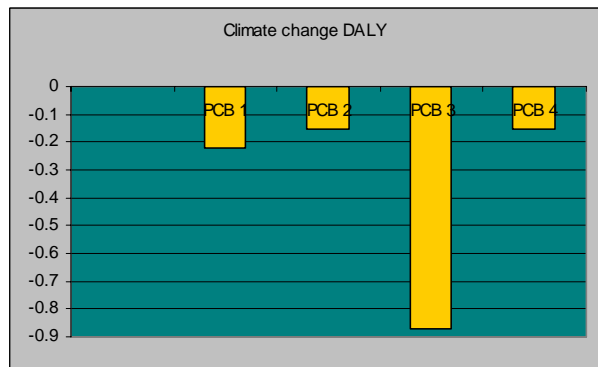
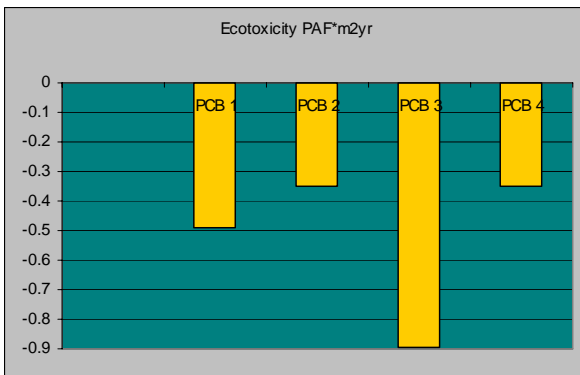
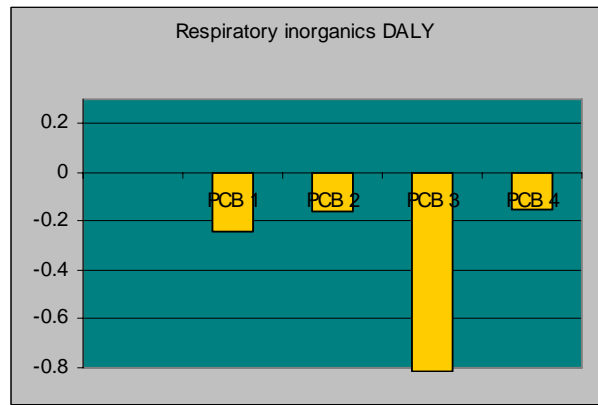
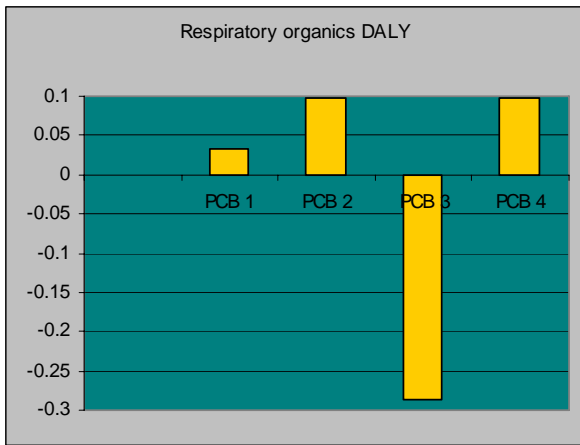


Figure 4. Damage characterisation due to recycling compared to land-filling four different printed circuit boards, but without the use of a car for collection. The vertical axis is damage expressed as a fraction of damage caused by land-filling the same board – positive scores indicate more damage due to recycling.

On each of the characteristics analysed in figure 4, the results suggest that recycling is worthwhile on almost every criteria. This result indicates that the collection arrangements for any recycling system are critical and must avoid dedicated trips in small vehicles to collect small quantities of material for recycling. Considering each criteria in turn, the following more detailed conclusions may be drawn:

- Respiratory organics: A dramatic improvement in this measure is achieved by avoiding car transport to deliver the boards to the recycling depot. The remaining dominant damage factor in this case becomes the energy cost associated with storage of the boards while awaiting shipping.
- Respiratory inorganics: The net outcome in this area is now positive mainly because of the reduced burning of fossil fuels achieved by recycling materials rather than producing virgin materials. However the energy used in transport is significant although less than that saved.
- Ecotoxicity: Minor improvements are achieved here, mainly due to the avoidance of copper in the environment by it being recycled.
- Climate change: Elimination of the car transport results in a net benefit to climate change as a result of recycling because of the reduced emissions by recycling materials.
- Acidification/Eutrophication: Again there is a turn around from net damage in this category to net benefit because there is a net reduction in the use of electricity related to production of virgin materials.
- Minerals: As might be expected, eliminating the car transport cases little change to this measure.
- Fossil fuels: The consumption of fossil fuels is reduced overall by recycling printed circuit boards because of the energy saved in avoiding production of virgin materials.

7 DISCUSSION

Australian data was used for most critical parts of the study such as energy sources and mineral supply because of its availability and presumed correctness. However some of the processes involved such as copper refining, some transport and recycling machinery use may well occur in other places with greater or lesser impacts. There are relatively small differences between the impact scores for the various scenarios considered in this study which must be interpreted in the light of the possibility of the variations outlined above.

If it is assumed that collection can be arranged to avoid minimise dedicated car usage, then the results above suggest that recycling of printed circuit boards is generally worth doing irrespective of the type of board. The main reason for this appears to be the avoidance of the energy costs associated with producing virgin materials, which is of course the fundamental reason for considering recycling. In this context, the issues which cause significant damage to the environment which might be improved are the transport costs, particularly if shipping overseas is involved and storage costs if delays are involved before shipping occurs. The costs associated with processing the printed circuit boards do not appear to be highly significant although of course efforts to reduce these would also be worthwhile.

[5] reports that in Europe, even with state of the art processing, benefits of only from 2% to 13% of total environmental impact are obtainable from end-of-life processing. These conclusions are based on a single score method which has been avoided in this paper. However the data in figure 4 suggests that, over all the characteristics of damage, the reduction in damage from recycling is about 0.5 to 1 times the actual damage caused by land-filling the same printed circuit board. This would seem to be a benefit significantly greater than the results of [5].

8. CONCLUSIONS

Recycling of electronic printed circuit boards can be an environmentally beneficial activity provided the logistical details are appropriately designed. Primarily, the delivery of small quantities of equipment for recycling using dedicated trips in vehicles such as private cars must be avoided if recycling is to be environmentally worthwhile. The scale of the benefit however is typically quite small being about 20% to 30% of the damage caused by the same product if it were simply land-filled, except for a major benefit in recovery of materials.

The differences in impact between the three epoxy printed circuits boards analysed was not very great overall, suggesting that differentiation between board types would depend on detailed knowledge of specific composition, which would be difficult to achieve in a general recycling situation. There is however evidence that the phenolic boards may be worth treating differently, but again such a decision depends on knowledge of detailed composition.

Some details of printed circuit board composition are significant in the above results, one example being the use of large amounts of aluminium in support brackets in larger printed circuit boards such as those used in television monitors which should be minimised. On the other hand, lead-free solder is not significant in the overall end-of-life damage caused by

printed circuit boards, although the arguments for its elimination may rest on more specific or localised criteria such as its emission at the site of landfill.

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