Techniques for Recovering Printed Circuit Boards (PCBs)

Demonstrating the economic benefits of different techniques for the recovery of printed circuit boards

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Executive Summary

Within the waste electrical and electronic equipment (WEEE) recycling industry, recyclers use a variety of methods for extracting printed circuit boards (PCBs) from WEEE. This report provides an overview of the principal recovery techniques used in the UK, including a description of each and the rationale behind why a company decides to use one technique over another.

The project was completed using a combination of primary and secondary research. UK WEEE recyclers were interviewed to gain a detailed understanding of their process for recovering PCBs. End market PCB refiners in the UK and EU were also contacted to gather information about end markets.

The research found that there are four key techniques used in the UK for the recovery of PCBs:

- **Fully manual segregation** – segregation of target items from other WEEE streams, followed by manual dismantling of equipment;
- **Fully manual segregation, including re-use** — as above but incorporates the recovery of specific PCBs/processor chips for re-use;
- **Semi-automated with commercial shredding** – Mechanical shredding of WEEE for size reduction and separation of saleable ferrous and non-ferrous metals, with manual downstream picking operations to recover PCBs and other components. This process is best suited for recovering PCBs from items which are not cost effective to manually sort or items where the PCBs are physically attached, e.g. welded, and cannot be manually removed; and
- **Semi-automated with commercial smashing** – manual removal of streams requiring manual recovery. Spinning and smashing of the remaining WEEE into smaller components followed by magnetic separation; and finally manual picking lines.

The project identified that the technique used is dependent on the type of WEEE being processed and the value of the PCBs. Manual recovery techniques are typically used for extracting high grade PCBs, mainly from IT and communications equipment as well as flat panel displays (FPDs), whereas automated recovery techniques are typically used for large domestic appliances (LDAs) and small mixed WEEE, where it is not cost effective to use manual techniques.

The grade of PCB is dependent on the quantity of precious metals it contains such as gold and silver, which can vary between the category of WEEE and its age. Sophisticated IT equipment such as computers, telecommunications equipment, and flat panel displays will often contain high grade PCBs with good quantities of precious metals, however PCBs from cathode ray tubes (CRTs), other small mixed WEEE and white goods will typically be low grade (or not cost effective to recover manually).

As PCBs are recovered for their precious metal content, their value is influenced by global prices. PCBs are considered a commodity and the value that UK operators receive is dependent on the prevailing market price of gold and other precious metals.

In order to identify the value of recovering PCBs to a UK WEEE recycler a financial assessment was conducted which took into account treatment costs, technique recovery...
efficiencies, grade of PCB recovered by WEEE stream and value of PCB. A summary of findings is in Figure ES1.

**Figure ES 1 Financial Assessment of PCB Recovery Techniques**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream A (LDA)</td>
<td>N/A</td>
<td>N/A</td>
<td>£1,139</td>
<td>£498</td>
</tr>
<tr>
<td>Stream C (Display)</td>
<td>£1,100</td>
<td>£8,283</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Stream E (SMW)</td>
<td>£7,480</td>
<td>£11,425</td>
<td>£2,463</td>
<td>£1,038</td>
</tr>
</tbody>
</table>

This shows that manual recovery with re-use captures most value from PCBs. The main advantage of using a manual technique is that it ensures that the PCBs can be recovered whole, minimising the potential loss of precious metals. The net benefit of using manual recovery is approximately £7,480 per tonne for small mixed WEEE and £1,100 per tonne for displays.

Another key benefit of recovering PCBs/processor chips whole is that they can be sold individually for re-use where appropriate, which can achieve a value several times greater than for recovery. This work identified the net benefit of using manual recovery with re-use is approximately £11,425 per tonne for some products within small mixed WEEE (mainly IT equipment) and £8,283 per tonne for display equipment.

The work also identified that when using technologies for recovering PCBs they will often be accompanied by a manual process to target the higher value PCBs, using the technology to recover low grade PCBs and other material streams.

The figure above highlights the benefit of recovering PCBs particularly with sufficient end markets in the UK, EU and Far East.
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Glossary

Abbreviations commonly used in this report are listed below.

**AATF** – Approved Authorised Treatment Facility  
**BATRRT** – Best Available Treatment Recovery and Recycling Techniques  
**CRM** – Critical Raw Material  
**CRT** – Cathode Ray Tube  
**EEE** – Electrical and Electronic Equipment  
**EfW** – Energy from Waste  
**ELV** – End of Life Vehicles  
**EU** – European Union  
**FPD** – Flat Panel Displays  
**kt** – Thousand tonnes  
**M** – Million  
**PC** – Personal Computer  
**PCB** – Printed Circuit Board  
**SCP** – Sustainable Consumption and Production  
**WEEE** – Waste Electrical and Electronic Equipment

Definitions of key terminology used throughout the report are provided below.

“**Re-use**” means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived

“**Recycling**” means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations

“**Recovery**” means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II sets out a non-exhaustive list of recovery operations

“**Pre-processing**”, for the purpose of this report refers to the activity of recovering circuit boards from waste products, such as waste electrical and electronic equipment

“**End-refining**” for the purpose of this report refers to the activity of recovering materials from printed circuit boards

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Acknowledgements

This study has been funded by WRAP (Waste and Resources Action Programme) and carried out by Valpak, who would both like to thank the organisations that contributed to the study by sharing their knowledge and expertise.
1.0 Introduction

1.1 Introduction

Within the WEEE recycling industry, recyclers use a variety of methods for extracting printed circuit boards (PCBs) from WEEE. This report provides an overview of the principal techniques used in the UK, including a description of each technique and the rationale behind the choice of usage.

A financial assessment of each technique is also included, taking into account the recovery of different grades of PCBs from each relevant WEEE category, PCB recovery rates, operating/capital costs and end market value.

1.2 Context

In 2012, 1.4M tonnes of household electrical and electronic equipment (EEE) were put onto the UK market, of which 505kt was recorded as being recycled4, with the remainder being sent to EfW or landfilled. It is estimated that between 0.2% and 14% of waste electrical and electronic equipment (WEEE) is made up of Printed Circuit Boards (PCBs)5, which typically contain the following CRMs and precious metals (by weight)6:

- Non-metallic e.g. glass-reinforced polymer 70%
- Copper 16%
- Solder (containing tin) 4%
- Iron, ferrite (from transformer cores) 3%
- Nickel 2%
- Silver 0.05%
- Gold 0.03%
- Palladium 0.01%
- Other (bismuth, antimony, tantalum etc.) <0.01%

Figure 1 provides two examples of PCBs and their components.

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Figure 1 PCB Components
Defra’s Sustainable Consumption and Production (SCP) Evidence Programme and report on ‘Future Resource Risks’, explores the issue of scarcity of resources from the perspective of the challenges for the UK economy as well as identifying critical raw materials (CRMs), which are becoming increasingly important to the UK. This is due partly to the growth of industries such as the renewable energy and electrical automotive sectors, which use rare metals such as indium.

In order for the UK to become less dependent on imports of these resources and precious metals it must source them from within its borders where possible. The Recast WEEE Directive also highlights the importance of PCB recovery by requiring the removal, recovery and separate recycling of PCBs, principally from devices where the surface of the PCB is greater than 10cm². The list of recoverable materials above highlights the potential for recovering CRMs and precious metals from PCBs within the UK, and the section below presents the viability of metal recovery, discussing the position of each key metal as a world commodity within the global market.

1.3 Global Material Value

The key materials of commercial value contained within PCBs are the precious metals detailed above. With the exception of the trace metals indicated and rare earth elements, these are actively traded commodities across the world.

The dominant market for base metals (copper, tin and nickel) is the London Metal Exchange and for precious metals (gold, silver and palladium) is Comex, based in Chicago. Both of these markets provide exchange traded hedging opportunities through futures and options derivative contracts. They also provide internationally accepted benchmark prices against which bilateral physical transactions in these metals are priced.

The prices quoted on these exchanges change constantly. Normal commercial activity drives these fluctuations as participants hedge or are involved in the physical delivery of these metals. However, the prices also reflect underlying supply and demand factors relevant to the physical metal, such as stock levels and demand.

These factors are in turn driven by prevailing macro-economic considerations and perceptions. For example, gold is known to be a safe haven for investors when other assets such as cash and equities are perceived to have an increased risk. Therefore factors beyond the immediate supply/demand balance can affect the prices of these commodities.

Figure 2 provides a snapshot of the relative values of the metals typically found in PCBs.

---

**Figure 2** Value of Metals in PCBs

<table>
<thead>
<tr>
<th>Metal Type</th>
<th>Composition of PCB (by weight)</th>
<th>Price / Troy Ounce</th>
<th>Price / Tonne</th>
<th>Value / PCB Content</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LME</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>16.00%</td>
<td>$6,716</td>
<td>$1,075</td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td>3.97%</td>
<td>$22,855</td>
<td>$908</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>2.00%</td>
<td>$15,135</td>
<td>$303</td>
<td></td>
</tr>
<tr>
<td><strong>Comex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td>0.03%</td>
<td>$1,370.50</td>
<td>$44,062,598</td>
<td>$13,219</td>
</tr>
<tr>
<td>Silver</td>
<td>0.05%</td>
<td>$21.34</td>
<td>$686,065</td>
<td>$343</td>
</tr>
<tr>
<td>Palladium</td>
<td>0.01%</td>
<td>$776.95</td>
<td>$24,979,523</td>
<td>$2,498</td>
</tr>
<tr>
<td>Other (bismuth, antimony, tantalum etc...)</td>
<td>0.01%</td>
<td>$776.95</td>
<td>$24,979,523</td>
<td>$2,498</td>
</tr>
</tbody>
</table>

**Notes**
- Comex Prices – settlement prices for COB 11 March 2014 – April delivery.
- Tin – assumed content in lead free solder 99.3%.
- Value of ‘Other’ assumed to be COMEX palladium.
- Grams per Troy Ounce 31.1035.

This shows the price of gold has the biggest effect on the value that can be obtained from PCBs due to its high price, despite its low content.

The figures below illustrate how the prices of some of these metals have fluctuated since the financial crisis of 2008.

**Figure 3** Copper (LME)
This shows that the price of Copper hit a low in 2008, however has recovered since to levels similar to pre-financial crisis.

**Figure 4 Gold (Comex)**

![Gold Price Chart](chart)

Figure 4 shows the price of Gold had increased since the start of the financial crisis, which is due to Gold being a more stable investment when there is instability within the stock markets. This is reflected by a decrease in value since the end of 2012.

**Figure 5 Silver (Comex)**

![Silver Price Chart](chart)
Silver has followed a similar pattern to Gold in that it peaked in value in 2011 and has largely slowly decreased since then.

The volatility in value of these commodities shows how the value of PCBs can vary significantly. WEEE recyclers must be aware of the potential value of PCBs (and precious metals they contain) and ensure they use the most cost effective technique for recovering them.

This report identifies the key techniques used in the UK for recovering PCBs and when each technique should be used to maximise value achievable.

1.4 Methodology

Industry Engagement

The project was completed using a combination of primary and secondary research. The primary research involved conducting site visits and interviewing UK WEEE recyclers (who recover PCBs from WEEE). End market refiners, who recover precious metals from PCBs (facilities outside the UK), were also interviewed.

The identity of UK WEEE recyclers that contributed to this report has not been disclosed due to the sensitive nature of the information provided.

Secondary research was also conducted to investigate end market refiners operating in the UK, as none were available for interview at the time of writing.

Information gathered included:

- PCB recovery technique used;
- PCB recovery rates;
- Grades of PCB reclaimed;
- End markets (UK, EU or beyond);
- Value of PCB grades;
- Key benefits/disadvantages of each technique; and
- Capital and operating costs.

To gain an understanding of the recovery levels of precious metals/CRMs from each grade of PCB, international end market treatment facilities (refiners) were also interviewed as part of the study, including:

- Umicore, a global materials technology group based in Belgium;
- Boliden, a mining and smelting company focusing on production of copper, zinc, lead, gold and silver based in Sweden; and
- Galloo, based in Belgium recycling metals, plastics and electronics.

8 A copy of the full questionnaire can be found in Appendix I
For overseas smelters, the following information was gathered⁹:

- PCB grades accepted;
- Sources of PCBs;
- Materials recovered from PCBs; and
- Value of PCB grades.

**Financial Assessment**

A financial assessment was also conducted to provide an auditable comparison of the different recovery techniques. The results are presented in Section 6.

Company data have been used in an aggregated form to allow for anonymisation of individual company figures. These have then been analysed in a dynamic Microsoft Excel model, providing the platform to analyse the differences between techniques. For comparison, the streams have been assessed against each other to provide a value per tonne of PCB processed. Each different recovery technique was split into three sections:

- Inputs;
- Processes; and
- Outputs.

Examples of these are shown for each technique in Section 6. The financial assessment concludes with a sensitivity analysis based on the input grades and the point at which one technique becomes more economically viable than another.

**It should be noted that the robustness of the results is dependent on the accuracy of the data provided by participating companies, which neither Valpak nor WRAP can verify.**

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⁹ A copy of the full questionnaire can be found in Appendix II
2.0 UK Recovery of PCBs

2.1 Overview

The research found that methods used by UK recyclers to extract PCBs from WEEE could be grouped into four key techniques:

- Fully manual segregation for recycling/recovery;
- Fully manual segregation, including re-use;
- Semi-automated with commercial shredding; and
- Semi-automated with commercial smashing.

The following table summarises each technique.
<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
<th>WEEE Category</th>
<th>Typical PCB Grade¹⁰</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully manual segregation</td>
<td>Manual segregation from other streams, followed by manual dismantling of equipment. Grading of PCBs.</td>
<td>IT and Communications Equipment (Category 3)</td>
<td>Grades 1,2,3, and 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FPDs and CRTs (Displays, Category 11)</td>
<td></td>
</tr>
<tr>
<td>Fully manual segregation, including re-use</td>
<td>As above but incorporates the recovery of specific PCBs/processor chips for re-use – visual checks and functionality testing is used. This is followed by cleaning and packaging ready for sale, being stored and advertised for sale on electronic auction sites or sold in bulk to a third party retailer.</td>
<td>IT and Communications Equipment (Category 3)</td>
<td>Grades 1,2 and 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FPDs and CRTs (Displays, Category 11)</td>
<td></td>
</tr>
<tr>
<td>Semi-automated with commercial shredding</td>
<td>Mechanical shredding of WEEE for size reduction and separation of saleable ferrous and non-ferrous metals, with manual downstream picking operations to recover PCBs and other components. This process is best suited for recovering PCBs from items which are not cost effective to manually sort or items where the PCBs are physically attached, e.g. welded, and cannot be manually removed.</td>
<td>Large domestic appliances (Category 1)</td>
<td>Grades 3 and 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small mixed WEEE (Category 2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carcasses remaining (after manual segregation) from separately collected I.T and communications equipment</td>
<td></td>
</tr>
<tr>
<td>Semi-automated with commercial smashing</td>
<td>Manual removal of streams requiring manual recovery. Spinning and smashing of the remaining WEEE into smaller components followed by magnetic separation and finally manual picking lines. QZ 2000 (MeWa) tool used by respondents.</td>
<td>Small mixed WEEE</td>
<td>Grades 3 and 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large domestic appliances</td>
<td></td>
</tr>
</tbody>
</table>

¹⁰ See Section 3 for definition of PCB grades
NOTE: No organisations using a fully-automated technique for the recovery of PCBs from all WEEE categories were identified during this project. All had some form of manual picking line, targeting PCBs from WEEE containing higher value boards, prior to any automation for those containing lower value ones. All respondents indicated that this is due to the value of PCBs justifying their recovery in the best possible condition and in the greatest quantities.

2.2 Disadvantages and Advantages of each Technique

2.2.1 Fully manual segregation

Advantages of a manual process for extracting PCBs from WEEE
- Achieves a high recovery rate of PCB with minimal material loss;
- A fully manual process means that other valuable components or those which are legally required to be removed and separately treated from WEEE can be extracted with minimum material loss. The WEEE regulations in the UK enact the requirement in Article 8(2) and Annex VII of Directive 2012/19/EU of the European Parliament and of the Council to remove batteries as components from separately collected WEEE; and
- Manual dismantling offers a flexible solution, without high capital investment in plant and equipment; it can efficiently manage irregular volumes of feedstock and avoid situations where plant is underutilised.

Disadvantage of a manual process for extracting PCBs from WEEE
- Requires a high degree of manual labour, which is expensive and time consuming compared to other automated techniques; and
- Not suitable or cost effective for WEEE containing small quantities of PCBs or low grade PCBs such as small mixed WEEE.

2.2.2 Fully manual segregation, including re-use

Advantages of a manual process for extracting PCBs from WEEE with a re-use focus
- Although only a small proportion of PCBs are suited for re-use, the value from this market is significantly higher than that achieved by recycling. Selling the PCB or processor chips into re-use or appliance repair markets can achieve a value of up to £100,000 per tonne, making it the highest value which can be recovered from PCBs; and
- Using PCBs and processor chips for repairing appliances extends product life times and provides a lower cost repair solution, supporting the concept of a circular economy.

Disadvantage of a manual process for extracting PCBs from WEEE with a re-use focus
- Requires a high degree of manual labour; and
- Operators need to have specialist knowledge of the sector in order to obtain best value from the components, i.e. they know what is suitable for repair.
Figure 7 shows examples of individual PCBs/processors stored for sale in the re-use market.

**Figure 7 PCBs/Processors Stored for Individual Sale**

2.2.3 Semi-automated with commercial shredding

**Advantages of a semi-automated process with shredding for extracting PCBs from WEEE**
- Processes high volumes of input material;
- Can be used on a small, medium or large scale and in conjunction with other techniques such as manual segregation, if high value PCBs are present in the in-feed material; and
- The value that can be obtained from even the lower grade PCBs can make it worthwhile.

**Disadvantage of a semi-automated process with shredding for extracting PCBs from WEEE**
- The level of recovery of PCBs is typically lower than that of manual recovery or semi-automated using smashing;
- Component loss is inevitable using a shredding process - there will be no potential for re-use; and
- Precious metals may also be lost in other material streams such process residues.

Figure 8 illustrates the lower quality output achieved through a mass shredder. Primarily the PCBs are broken during the initial shredding phase, with very little further damage during the extraction process.
2.2.4 **Semi-automated with commercial smashing**

**Advantages of a semi-automated process with smashing for extracting PCBs from WEEE**
- Allows for high volumes of input material to be processed and can incorporate a manual process;
- Allows for flexibility in the choice of process based on the category of WEEE to be treated and the value of the PCBs they contain; and
- Working closely with their end markets, treatment facilities can identify how best to process each WEEE category to maximise the value of the output material streams.

**Disadvantages of a semi-automated process with smashing for extracting PCBs from WEEE**
- Expensive to purchase the necessary equipment, and so is only viable in treatment facilities which have a large and consistent feedstock supply or the ability to use it to separately recover other revenue generating fractions; and
- PCBs can also be lost into other material streams e.g. plastics or aluminium.

As stated above, using the semi-automated/commercial smashing technique can result in PCBs being lost into other material streams, however one of the companies interviewed utilised additional technologies to further refine the quality of their recovered materials streams.

2.3 **Summary, Future Planning and Support**

The choice of technique is dependent on the quality of the input material, its PCB content and its prevailing market value.

The processing of streams which can contain high value PCBs such as IT and communications equipment should be done manually to ensure the maximum quantity of PCBs are recovered.
**Future Plans**

Recyclers indicated that they have sufficient capacity to recover higher quantities of PCBs. They indicated that there is sufficient end market capacity to recover precious metals from PCBs, both in the UK and EU.

The majority of WEEE recyclers indicated they had no intentions to invest in the recovery of precious metals from PCBs; only one respondent indicated they may consider this in the future.

**Support**

The recyclers interviewed indicated that the best way to increase the recovery of PCBs in the UK would be to increase in the quantity of WEEE collected. They suggested this could be aided by:

- Increasing public awareness of WEEE recycling through large sustained public awareness initiatives;
- Introducing more take-back schemes;
- Enforcement through legislation: better policing of the system to reduce or eliminate non-compliant WEEE recycling (illegal exports, leakage from HWRC sites and illegal doorstep collections by unlicensed operators); and
- Introducing bans on WEEE disposal through landfill and EfW.
3.0 Grades of PCBs Recovered in UK

PCBs

Respondents stated that there is no common international standard for grading PCBs, rather grades are agreed in advance with the end markets and are based on:

- Physical composition of the PCBs (presence of visible gold, aluminium parts etc.); and
- The prevailing market value of the metals contained.

Standard types of PCBs are often used in the manufacture of electrical items so the grades of PCBs recovered can frequently be determined based on the WEEE category from which they are recovered.

Treatment facilities stated that it is often easy to distinguish between the different grades of PCB and that staff can learn the differences between each of the grades quickly.

Terminology

The terminology used for grades varies between treatment facilities; some companies do not refer to grades at all, especially if they handle only one category of WEEE. Others refer to grades:

- A, B and C;
- Very High, High, Medium and Low; and
- 1, 2 and 3.

The following is an overview of three primary grades of PCBs segregated by treatment facilities:

Figure 9 Grades of PCBs

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
<th>EEE Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 1/A/High</td>
<td>Generally these will contain processors, semiconductors, gold pins</td>
<td>IT base units, hard drives &amp; laptops, Display screen equipment, including</td>
</tr>
<tr>
<td></td>
<td>and connectors containing precious metals which can be recovered</td>
<td>flexible PCBs</td>
</tr>
<tr>
<td>Grade 2/B/Medium</td>
<td>Whilst not as valuable as Grade 1 type boards, these will still contain</td>
<td>IT equipment, set top boxes, Display screen equipment, Small mixed WEEE</td>
</tr>
<tr>
<td></td>
<td>some semiconductors, gold pins and connectors containing precious metals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>which can be recovered</td>
<td></td>
</tr>
<tr>
<td>Grade 3/C/Low</td>
<td>These will generally only contain little, if any precious metals and are</td>
<td>Small mixed WEEE, CRT TVs, Large domestic appliances</td>
</tr>
<tr>
<td></td>
<td>mostly valuable for their copper content</td>
<td></td>
</tr>
</tbody>
</table>
For the purpose of the financial assessment, and to normalise each company’s description of grades, the project team created four key grades as shown in Figure 10, based on the value output. This has been done for the purpose of conducting the financial assessment only, and therefore does not exactly match the descriptions above, but will likely be variations of the above. Grades 1 and 2 in Figure 10 would be categorised as variations of Grade 1 above, Grade 3 in Figure 10 as Grade 2 above, and Grade 4 in Figure 10 as Grade 3 above.

**Figure 10** PCB Grades used within this project

<table>
<thead>
<tr>
<th>PCB Grading</th>
<th>Grade</th>
<th>Sales Value (per tonne of PCB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 1</td>
<td>Very High</td>
<td>£10,000+</td>
</tr>
<tr>
<td>Grade 2</td>
<td>High</td>
<td>£4,500 - £10,000</td>
</tr>
<tr>
<td>Grade 3</td>
<td>Medium</td>
<td>£2,500 - £4,500</td>
</tr>
<tr>
<td>Grade 4</td>
<td>Low</td>
<td>&lt;£2,500</td>
</tr>
</tbody>
</table>

**Figure 11** PCB Grades 2 (Left) and 4 (Right)

It should be noted that PCBs manufactured prior to 2006 typically contain more precious metals such as gold than those after this date. Since 2006, gold application technologies have improved in PCBs, which has reduced the quantity of these metals. Gold is used in connectors as it is an efficient conductor of electricity, which does not oxidise.

Also, PCBs containing a large number of semiconductor chips have a high value as these components contain a higher proportion of precious metals.

It should be noted that when PCBs are shredded there is a loss of material and as such precious metals will be lost to other material streams, such as plastics, process residues and other saleable metallic products. Respondents indicated this reduces the value of the PCBs by approximately 20%.

Downstream refiners will usually accept both graded PCBs or mixed loads. When a load is graded and a good relationship exists between the supplier and the refiner, the latter may pay for the material up-front. However as the refiner will not know the exact composition of the material they may offer a lower up-front value to the supplier.
Where the load is mixed the refiner will analyse a sample to determine its composition. They will then pay the supplier based on the ‘out-turn’, which is the quantity of each precious metal contained within the sampled load. This may be a higher value than receiving an up-front payment as the value is based on the metal content. When the load is tested longer payment terms will usually be offered, typically 90 or 120 days.
4.0 Precious Metal Recovery (UK)

4.1 Introduction

One of the key findings of this work is that PCBs are a globally traded commodity and as such PCBs recovered in the UK are sold to refiners in international end markets including the EU and Far East, as well as in the UK. Some of these companies have been identified in this section, and secondary research has been conducted to gather high-level information pertaining to the organisations key activities in relation to PCB recovery or materials recovery from PCBs.

Refiners will typically use pyrometallurgy or hydrometallurgy treatment processes to recover precious metals from PCBs.

**Pyrometallurgy** consists of the thermal treatment of PCBs to start physical and chemical transformations in the materials which enables the recovery of valuable metals.

**Hydrometallurgy** is a technique involving the use of aqueous chemistry for the recovery of metals from PCBs.

This section provides an overview of the UK’s main end market refiners of PCBs:

- Johnson Matthey;
- GC Metals;
- BASF Metals Recycling; and
- AWA Refiners.

**Johnson Matthey**

Johnson Matthey is a global speciality chemicals company with operations in over 30 countries. Their products and services are sold across the world to a wide range of advanced technology industries. The company receives electronic scrap from car manufacturers, WEEE companies and smaller recyclers. Their services are described as advanced precious metal refining.

The company has two sites in the UK which can be used for refining PCBs. One is in Brimsdown, which is an evaluation and smelting facility and the other in Royston, which is a Platinum Group Metals (PGM)\(^\text{11}\) refining facility.

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\(^{11}\) Ruthenium, Rhodium, Palladium, Osmium, Iridium, and Platinum
4.2 **G. C. Metals**

G. C. Metals are refiners of precious metals, based in Leicester. They recover gold, silver, platinum, palladium, and rhodium from PCBs as well as other metal containing items. They are a bullion trading company and trade other precious metals. However they also provide the option to the supplier of the feedstock material to buy the precious metals recovered from the feedstock.

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13 Source: http://www.refiningofpreciousmetals.com/materials.htm
The process at G. C. Metals starts with a compositional analysis on incoming loads to identify the materials contained. A sample is shredded, burned and milled into a powder before being fluxed, melted and analysed. This provides information on the amounts of payable metals and impurities included in the batch. Independent verification is also provided.

G. C. Metals then use advanced chemical, electrical and smelting techniques to recover precious metals. Once these are recovered international markets are used to secure the best value from the recovered metals.

4.3 BASF Metals Recycling Ltd (formerly Engelhard Sales Ltd)

At their Cinderford site, BASF specialise in precious metals refining and recycling from WEEE and catalytic converters. They recover and trade in platinum, palladium, rhodium, iridium, ruthenium, gold, silver and rhenium.

They use pyrometallurgy techniques to thermally treat PCBs and recover precious metals, which are then traded on the global market.

4.4 AWA Refiners

AWA Refiners purchase scrap computer boards, precious metals and high-value metals, performing chemical refining and melting processes at their facility in Harlow, Essex.

Their refining and melting processes are undertaken in-house where boards are stripped of any components that have metallic properties present. Examples of computer board scrap, and their materials, include:

- Integrated circuits that contain gold;
- Gold-plated plugs or connectors that may be refined;
- Other substrates that contain precious metals that can be treated as a payable material; and
- Edge connectors that can be chemically refined.

The organisations above are based in the UK; however as PCBs are global commodities they can also be sold to refiners outside the UK in markets offering the highest price.
5.0 Precious Metal Recovery (Global)

5.1 Introduction

During the project two overseas PCB refiners were interviewed in order to gather information on the processing of PCBs outside the UK. A full copy of the questionnaire can be found in Appendix II of this report. Information collected included:

- PCB grades;
- Precious metals recovered; and
- Feedstock sources;
- Value of PCBs.

The companies interviewed were Boliden in Sweden and Umicore in Brussels. Umicore is a global materials technology group based across Europe and Boliden is a mining and smelting company.

5.2 Umicore Precious Metals Refining (UPMR)

Umicore Precious Metals Refining operates one of the world’s largest precious metals recycling facilities. This business unit of Umicore is a market leader in recycling complex waste streams containing precious and other non-ferrous metals. They offer recycling and refining services for precious metal-bearing materials such as by-products from other non-ferrous industries (e.g. drosses, mattes, speiss, anode slimes), consumer and industrial recyclable products (e.g. electronic scrap, spent auto catalysts, spent industrial catalysts, sweeps and bullions).

Material Recovery and Capacities

UPMR samples and analyses approximately 8,000 incoming shipments per year, accounting for a total of 350kt of materials containing precious metals. Of this, the company treats between 35kt and 40kt of globally sourced precious metals bearing e-scrap per year. The quantity of material sourced from the UK is considered confidential and was not disclosed. The remainder of their capacity is used to treat other precious metals-bearing materials.

They have flexibility in their treatment process enabling UPMR to adapt to changing market conditions. This could allow them to receive more e-scrap from the UK.

The company recovers 17 different metals from its input feeds. The following critical raw materials and precious metals being key examples:

- Antimony;
- Silver; and
- Palladium;
- Gold.
- Indium;

Other metals recovered are lead, tin, bismuth, selenium and tellurium, however the latter three elements are often not present or if so, are in small quantities. The plastics from the boards are used both as a reducing agent and fuel replacement in the smelter.

They are used as replacement of fossil fuel and reducing agents, their calorific value is recovered via direct use in the smelting process and the waste heat recovery system, and the antimony (in flame retardants) in the plastics is recovered in their process.
PCB Grading

Umicore does not grade individual boards itself, but relies on its suppliers to do this based on:

- Physical composition of the boards; and
- Value of precious metals.

When PCBs are received, they use a sampling and assaying procedure for the identification of the exact content of precious, base, minor metals and plastics contained in the shipment. This serves as a basis for the financial settlement between UPMR and the supplier.

The company also uses its website to provide guidance to suppliers as well as issuing an information leaflet with guidance on how to optimise shipments. This includes tips on blending and quantities.

Umicore requires a minimum volume for shipping material, which depends on the type of material shipped.

Values

The average net value of a typical mix of circuit boards varies between 3,000 and 7,000 Euros per tonne of PCB. The company pays the net value of silver, gold, palladium and copper. The net value is the gross assayed value, minus the treatment costs. Treatment costs cover the smelting, refining, sampling and assaying.

The quality of the boards (i.e. its content of precious metals) is typically higher for those that have been manually removed, compared to similar ones that have been mechanically removed. When WEEE is mechanically pre-processed, in particular when high-intensity shredding is used, there is a loss of precious metals to the other material fractions.

5.3 Boliden

Boliden is a metals company with their core business within the fields of exploration, mining, smelting and metals recycling.

It operates five smelters to refine metal concentrates and other raw materials, such as electronic scrap, metal scrap, metal ashes and scrap car batteries, to produce both pure metals and customised alloys. The metals and by-products are sold and transported to customers such as steel companies and other manufacturers.

Material Recovery, Capacities and Process

The recycling operation treats complex waste streams containing precious and other non-ferrous metals. The operations can recover up to 20 types of metal from a wide range of feedstocks ranging from industrial residues to end-of-life materials. The largest proportion of input material is obtained from global secondary sources (recycled product).

In 2014 the company anticipates processing a total of 120kt of PCBs and upgraded material from WEEE fractions (sourced globally), and has the capacity to treat more. From PCBs the company recovers:
Copper; Gold; Silver; Platinum; Palladium; Zinc; Lead; and Additional elements that end up in slags and residues (silicon dioxide (SiO$_2$), aluminium oxide (Al$_2$O$_3$), iron, calcium and magnesium).

Waste plastic is used for generating electricity and high pressure steam. These are used respectively to power the smelter and for household heating in the surrounding district.

The upstream recovery technique used does not affect the quantity or quality of material extracted, however the company does have minimum requirements for copper (>10%), gold (> 20g/tonne, therefore ruling out low grade PCBs from CRT TVs), and silver (>400g/tonne in WEEE fractions and PCBs).

**Grading**

All circuit boards are sampled on arrival at the smelter in order to establish a value for the payable elements and to check for impurities. Therefore the company does not grade PCBs.

**Values**

The value of the PCBs treated by Boliden are calculated based on treatment, refining and sampling costs.

**5.4 Summary**

Overseas PCB refiners believe that to reclaim the highest possible quantities of metals, a combination of manual dismantling of the boards followed by treatment at a dedicated, highly efficient end-refiner is the best option.

In Europe, many WEEE recyclers choose the semi-automated option to avoid high labour costs. This involves a coarse, low intensity shredding followed by hand picking or manual dismantling to remove PCBs, followed by shredding and sorting for the rest of the materials.

There are also believed to be new mechanical processes for treating WEEE such as a low-impact crushing, yielding intact boards. This kind of technique appears to be a good compromise between manual dismantling and mechanical PCB recovery. Companies agreed that it is difficult to pin-point the most cost-effective method of recovering PCBs, as one method could be cost effective for a certain quality of PCB but not others.

The following points were considered to be valid for any country when asked what they believe could be done to improve the quality or quantity of PCBs recycled/reclaimed from the UK:

- Recover PCBs whole prior to high intensity shredding to avoid the loss of precious metals;
- Increase collections of WEEE; and
- Prevent illegal exports of WEEE to developing countries.

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14 Note: This is the opinion of the individual smelter when asked what they believe to be the best way for WEEE treatment facilities to recycle/reclaim PCBs from WEEE and why and whether they believe this is the most cost-effective method.
6.0 Financial Assessment

6.1 Introduction

The following section details a financial analysis of each of the four recovery techniques broken down by each of the WEEE streams processed.

**Figure 13 WEEE Streams**

<table>
<thead>
<tr>
<th>Stream</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream A</td>
<td>Large Domestic (Household) Appliances (other than cooling appliances) (LDAs)</td>
</tr>
<tr>
<td>Stream B</td>
<td>Cooling Appliances Containing Refrigerants</td>
</tr>
<tr>
<td>Stream C</td>
<td>Display Equipment including Cathode Ray Tubes</td>
</tr>
<tr>
<td>Stream D</td>
<td>Gas Discharge Lamps</td>
</tr>
<tr>
<td>Stream E</td>
<td>Small Mixed WEEE (all other WEEE)</td>
</tr>
</tbody>
</table>

The analysis is broken down into the financial inputs and outputs and is based on the data provided by WEEE recyclers interviewed. The data was aggregated and then analysed in a dynamic Microsoft Excel model to provide the platform to analyse the differences between the techniques. Figure 14 illustrates the model used to input data. One table was created per technique (four in total), and each white cell populated with data.

**Figure 14 Data Model**

The data inputted into the table illustrated in Figure 14 was then interpreted through formulas to produce results which were illustrated in a model such as that illustrated in Figure 15 (again one for each technique).
Figure 15 Data Model Calculations/Outputs

<table>
<thead>
<tr>
<th>Outputs</th>
<th>Costs</th>
<th>Net Present Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input %</td>
<td>Processing Costs €</td>
<td>Total Benefit €</td>
</tr>
<tr>
<td>Grade 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-Use Grade</td>
<td>Capital Costs €</td>
<td>Marginal Benefit (per tonne) €</td>
</tr>
<tr>
<td>Total % Recovered</td>
<td>Material Value €</td>
<td></td>
</tr>
<tr>
<td>Per Tonne</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grade 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-Use Grade</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It should be noted that this analysis is completed at a high level due to the assumptions made\(^{15}\) and the robustness of the data gathered at the primary research phase. It should also be noted that the data has been aggregated to protect commercially sensitive information.

For comparison, the streams have been assessed assuming the same input tonnage (one tonne of PCBs) across all techniques. Additionally, sensitivity analysis has been performed to identify the tipping points for when one technique is more advantageous than another.

\(^{15}\) Where assumptions have been made, details are provided
### Figure 16 Financial Assessment Summary

<table>
<thead>
<tr>
<th>Technique</th>
<th>Stream</th>
<th>Grades</th>
<th>Operational Costs (per tonne of PCB recovered)</th>
<th>Capital Costs</th>
<th>Recovery Levels&lt;sup&gt;16&lt;/sup&gt;</th>
<th>Sales Value</th>
<th>Total benefit / tonne</th>
<th>Net Benefit&lt;sup&gt;17&lt;/sup&gt; / tonne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Segregation</td>
<td>C</td>
<td>Predominantly Low Grade</td>
<td>£160</td>
<td>NA</td>
<td>100%</td>
<td>Up to £10k+ (weighted towards grade 4)</td>
<td>£1,260</td>
<td>£1,100</td>
</tr>
<tr>
<td>Manual Segregation</td>
<td>E</td>
<td>All grades</td>
<td>£190</td>
<td>NA</td>
<td>100%</td>
<td>Up to £10k+ (weighted towards grade 2)</td>
<td>£7,670</td>
<td>£7,480</td>
</tr>
<tr>
<td>Manual with re-use</td>
<td>C</td>
<td>Grades 2, 4 and re-use grade</td>
<td>£250</td>
<td>NA</td>
<td>100%</td>
<td>Up to £100k (weighted towards grade 2)</td>
<td>£8,533</td>
<td>£8,283</td>
</tr>
<tr>
<td>Manual with re-use</td>
<td>E</td>
<td>Grades 2, 4 and re-use grade</td>
<td>£250</td>
<td>NA</td>
<td>100%</td>
<td>Up to £100k (weighted towards grade 2)</td>
<td>£11,675</td>
<td>£11,425</td>
</tr>
<tr>
<td>Semi-automated with smashing</td>
<td>A</td>
<td>Grades 3 and 4</td>
<td>£0.43</td>
<td>NA</td>
<td>67%</td>
<td>Up to £4,500 (weighted towards grade 4)</td>
<td>£1,139</td>
<td>£1,139</td>
</tr>
<tr>
<td>Semi-automated with smashing</td>
<td>E</td>
<td>Grades 3 and 4</td>
<td>£0.43</td>
<td>NA</td>
<td>80%</td>
<td>Up to £4,500 (weighted towards grade 4)</td>
<td>£2,464</td>
<td>£2,463</td>
</tr>
<tr>
<td>Semi-automated with shredding</td>
<td>A</td>
<td>Grades 3 and 4</td>
<td>£12</td>
<td>NA</td>
<td>30%</td>
<td>Up to £4,500 (weighted towards grade 4)</td>
<td>£510</td>
<td>£498</td>
</tr>
<tr>
<td>Semi-automated with shredding</td>
<td>E</td>
<td>Grades 3</td>
<td>£12</td>
<td>NA</td>
<td>30%</td>
<td>£2,500 - £4,500</td>
<td>£1,050</td>
<td>£1,038</td>
</tr>
</tbody>
</table>

<sup>16</sup> This refers to the proportion recovered of PCB component during the recovery process. Recovery levels are not linked to grades as grades have been based on value received for PCBs (based on information provided by the companies)

<sup>17</sup> Net benefit is the total benefit minus the costs
6.2 Manual Segregation

**Inputs - Stream C: Display Equipment including Cathode Ray Tubes**

There are no capital costs attributed to manual segregation since no machinery will have been specifically purchased for the process. The process is however more labour intensive than automated processes.

Stream C produces low, medium and high grade PCBs. The operational costs, including labour costs, are approximately £160 per tonne. The recovery levels are assumed as 100%. The value of material is predominantly high as bruising is limited and components remain intact, although some low grade PCBs from CRT TVs will also be included. These data are summarised below.

**Outputs - Stream C: Display Equipment including Cathode Ray Tubes**

The total costs are assumed to be £160 per tonne, while the total benefits accrued are £1,260 per tonne, equating to a net benefit of £1,100 per tonne.

**Inputs - Stream E: Small Mixed WEEE**

As with Stream C (displays), there are no capital costs attributed with manual extraction of PCBs from mixed WEEE. However unlike Stream C (displays) all four grades of PCB (as previously defined in Section 3) are extracted. These account for the PCs and telecommunications equipment, which contain high grade PCBs.

The operational costs (including labour costs) amount to £190 per tonne based on staff costs and time to recover one tonne of PCBs.

The value of material is generally high as bruising is limited and components remain intact, although slightly distorted by the lower grades.

**Outputs - Stream E: Small Mixed WEEE (all other WEEE)**

Based on the PCB input detailed above, it is assumed that the PCBs are fully recovered. The total costs are assumed to be £190 per tonne, while the total benefits accrued are £7,670 per tonne, equating to a net benefit of £7,480 per tonne.

6.3 Manual Segregation with Re-use

**Inputs - Stream C Display Equipment including Cathode Ray Tubes**

There are no capital costs attributed to this technique. For Stream C (displays) the high grade, low grade and a proportion of PCBs which are suitable for re-use are present (split 72%, 25% and 3% respectively). The operating costs were estimated to be £250 per tonne. The recovery levels are assumed to be 100%.

**Outputs - Stream C: Display Equipment including Cathode Ray Tubes**

Based on the assumed input all PCBs are successfully recovered. The cost associated with this technique is £250 per tonne. The total benefits accrued are £8,533 per tonne equating to a net benefit of £8,283 per tonne. The benefits are so high due to the high value of the successfully re-used PCBs.
Inputs - Stream E: Small Mixed WEEE

There are no capital costs attributed to this technique. As with Stream C (displays), Stream E (small mixed WEEE) contains high grade, low grade and a proportion of PCBs which are suitable for re-use (split 75%, 19% and 6% respectively). The operational costs were also estimated to be £250 per tonne. As with Stream C (displays) the recovery levels are 100% due to the manual element of the work.

Outputs - Stream E: Small Mixed WEEE (all other WEEE)

Based on the assumed PCB input all are successfully recovered. The costs associated with this technique are £250 per tonne and the total benefits accrued are £11,675 per tonne equating to a net benefit of £11,425 per tonne. The benefits are so high due to the high value of the successfully re-used PCBs.

6.4 Semi-automated with Smashing

Inputs - Stream A: Large Domestic (Household) Appliances (other than cooling appliances) (LDAs)

There are capital costs attributed to this technique. However these only equate to £0.43 per tonne, which is based on the total cost of the equipment divided by the total tonnes it will process over its lifetime, for all target material. For Stream A (LDAs) only medium and low grade PCBs are present, split 20% and 80% respectively. Although the operation costs were minimal the recovery levels were around two thirds.

Outputs - Stream A: Large Domestic (Household) Appliances (other than cooling appliances) (LDAs)

Based on the assumed PCB input, 67% of PCBs are estimated to be successfully recovered. The costs are minimal while the total benefits accrued are £1,139 per tonne equating to a net benefit of £1,139 per tonne.

Inputs - Stream E: Small Mixed WEEE (all other WEEE)

As with Stream A (LDAs) the same capital costs attributed to the semi-auto smashing technique are £0.43 per tonne (which is based on the total cost of the equipment divided by the total tonnes it will process over its lifetime, for all target material) and both the medium and low grade PCBs are present (split 78% and 22% respectively). The operation costs were again minimal. The recovery levels were around two thirds for the low grade but higher for the medium grade.

Outputs - Stream E: Small Mixed WEEE (all other WEEE)

Based on the assumed PCB input 80% are estimated to be successfully recovered. The costs associated with this are minimal while the total benefits accrued are £2,464 equating to a net benefit of £2,463 per tonne.
6.5 Semi-Automated with Shredding

**Inputs - Stream A: Large Domestic (Household) Appliances (other than cooling appliances) (LDAs)**

Contrary to the semi-automated technique with smashing, no capital costs have been attributed to the semi-automated shredding technique. This is because the operators stated that all machinery was purchased and installed with no focus on extracting PCBs. These are a valuable by-product only, extracted for legal reasons but also as they have a commercial value. Their extraction is part of a larger process aimed at other key materials.

Medium grade (20%) and low grade (80%) PCBs are contained within Stream A (LDAs) equipment. The recovery levels are only 30% and the operational costs were set at £12 per tonne.

**Outputs - Stream A: Large Domestic (Household) Appliances (other than cooling appliances) (LDAs)**

Of the PCB input only 30% is successfully recovered. The costs are assumed to be £12 while the benefits are only £510 equating to a net benefit of £84 per tonne.

**Inputs - Stream E: Small Mixed WEEE (all other WEEE)**

Stream E (small mixed WEEE) equipment contains all medium grade PCBs. The operational costs were calculated at £12 per tonne. Recovery levels were 30%.

**Outputs - Stream E: Small Mixed WEEE (all other WEEE)**

Of the PCB input only 30% is successfully recovered. The total costs are assumed to be £12 while the total benefits accrued are £1050 equating to a net benefit of £1038 per tonne.

6.6 Results

The results of the financial assessment is summarised in Figure 17, detailing the net benefit per tonne of each technique broken down by each stream.

**Figure 17 Net Benefits of Each Recovery Technique (Per Tonne of PCB)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stream A (LDA)</td>
<td>N/A</td>
<td>N/A</td>
<td>£1,139</td>
<td>£498</td>
</tr>
<tr>
<td>Stream C (Display)</td>
<td>£1,100</td>
<td>£8,283</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Stream E (SMW)</td>
<td>£7,480</td>
<td>£11,425</td>
<td>£2,463</td>
<td>£1,038</td>
</tr>
</tbody>
</table>

PCBs are therefore recovered from Stream A (LDAs) through one of two semi-automated techniques, with the financial assessment showing the preferred method to be semi-automated with smashing.

Manual with re-use appears to be the most economic technique for extracting PCBs from equipment within Stream C (displays) and E (small mixed WEEE), taking into account greater processing time as it is primarily used to recover the maximum quantity of very high value PCBs. The semi-automated technique with shredding appears to be less worthwhile for
stream A however the value of the other material streams extracted during the process makes it cost effective. The sensitivity analysis also shows that once a certain tonnage is reached it becomes more worthwhile.

It is worth noting that the lower benefit per tonnes seen using the shredding process for extracting PCBs from products from WEEE stream A is likely due to the type of equipment handled.

PCBs will not necessarily be target material for semi-automated techniques; therefore the process will not have been set up with focus on extracting PCBs. Other value streams will be recovered using the technique, which will bring additional value to the organisations, and makes the process worthwhile for extracting PCBs as a by-product. Higher tonnages and value will be seen from LDAs mainly within the metals stream, which would bring up the value of £498 to show greater revenue for the organisation. In comparison, displays, having higher value PCBs, are worth the investment time of a manual extraction process.

6.7 Sensitivity Analysis

STREAM A

For Stream A the only methods used were semi-automated with smashing and semi-automated with shredding. The analysis highlighted that the grades within Stream A were medium and low grade (80% / 20% split respectively for each technique). The data suggested that semi-automated with smashing was preferable to semi-automated with shredding. This was due to lower operational costs and higher recovery rates. Assuming that Stream A could only contain either medium or low grade PCBs an analysis was performed on amending the input proportions. The analysis highlights that even if the input material were 100% medium grade the benefit per tonne using semi-automated with shredding would be £1,038, which remains less than semi-automated with smashing.

STREAM C

The data showed that for Stream C only manual and manual with re-use were used and the results showed that manual with re-use was the preferred method due to the high value of re-used PCBs.

The manual process included all grades, proportioned as follows:

- High 0.15%;
- Medium 0.04%; and
- Low 99.81%.

In comparison the grades for manual with re-use were proportioned as follows:

- High 72%;
- Low 25%; and
- Re-use 3%.

Assuming the proportion of high and low grades for manual with re-use is held constant while reducing the level of the re-use grade to 0%, manual with re-use is still more economically viable in comparison to manual.
STREAM E

For Stream E all the methods were used. When comparing semi-auto smashing and semi-automated with shredding, the results showed, as with Stream A, that semi-automated with smashing was the preferred method. This was due to lower operational costs and higher recovery rates. Unlike Stream A, however the split between medium and low grade was different, 78% / 22% for semi-automated with smuggling and all medium grade for semi-automated with shredding.

When comparing manual and manual with re-use the results showed that manual with re-use was the preferred method due to the high value of re-used PCBs. The manual process included all grades, proportioned as follows:

- Very High 9%;
- High 80%;
- Medium 7%; and
- Low 4%.

In comparison the grades for manual with re-use were proportioned as follows:

- High 75%;
- Low 19%; and
- Re-use 6%.

Assuming the proportion of high and low grades for manual with re-use are held constant while reducing the level of the re-use grade, manual with re-use is only more economical than manual when the level of re-use is $1.8\%$\textsuperscript{18}. So if the re-use level is below this then manual separation is preferable.

\textsuperscript{18} With 78.35% high grade and 19.85% low grade
7.0 Conclusions

This section presents the conclusions and summarises the key findings of the project.

Four Techniques used for Recovery of PCBs

WEEE recyclers in the UK use four techniques for the recovery of PCBs:

- Fully manual;
- Fully manual with re-use;
- Semi-automated with commercial shredding and
- Semi-automated with commercial smashing.

Often treatment facilities will use a combination of these techniques.

Recovery Technique used Varies Depending on the Value of PCB

Manual recovery techniques are typically used for extracting high grade PCBs, mainly from IT and communications equipment as well as FPDs. CRTs are also treated manually due to their hazardous nature, even though the PCBs recovered are typically low grade.

Automated recovery techniques will typically be used for large domestic appliances and small mixed WEEE, where the size, grade and value of circuit board extracted is often low. In these cases it is not cost effective to use manual recovery techniques.

Grade of PCB Often Dependent on the Category of WEEE and its Age

Sophisticated IT equipment such as computers, telecommunications equipment, and displays will often contain high grade PCBs, however PCBs from CRTs, other small mixed WEEE and white goods will be low grade, and not cost effective to recover manually.

Printed circuit boards from items which were manufactured pre-2006 will often have a high gold content, making them high grade. However PCBs from post-2006 items will often contain less gold than their earlier counterparts due to improvements in the application of gold, making them less valuable.

Materials Recovered from PCBs

The following precious metals and CRMs are typically recovered from PCBs:

- Silver;
- Gold;
- Copper;
- Platinum;
- Antimony;
- Palladium; and
- Indium.

Value of PCBs Influenced by Global Precious Metal Prices

PCBs are considered a global commodity and the value that UK operators receive is dependent on the prevailing market price of the materials they contain.

The value of PCBs contained in a WEEE stream can influence the technique used for recovery. For example, when material prices are high, PCBs may be manually recovered.
However with lower prices, they may be recovered using less time-consuming, automated techniques.

**Manual Recovery with Re-use Captures Most Value from PCBs**

The main advantage of using a manual technique is that it can help recover the PCBs whole, minimising the potential loss of precious metals. The net benefit of using manual recovery is approximately £7,480 per tonne for Stream E and £1,100 per tonne for Stream C.

It also means that other items which have a value or which are legally required to be separated can be recovered in a controlled way, minimising process losses and risk.

Another key benefit of recovering PCBs/processor chips whole is that they can be tested, and if in good working condition, sold individually for re-use in the repair sector. It is estimated that an individual PCB/processor chip is worth an average twenty times more in the re-use market than the value achieved from recycling. This work identified the net benefit of using manual recovery with re-use as approximately £11,425 per tonne for Stream E and £8,283 per tonne for Stream C.

Component re-use also helps extend the working life of products. When used in the repair of electrical items it extends their working life prior to recycling, supporting the concept of a circular economy.

**The UK has Significant Capacity for the Recovery of PCBs**

All treatment facilities engaged during this project indicated they had significant capacity to recover more PCBs from WEEE.

**To Increase PCB Recovery UK must Collect more WEEE**

Treatment facilities also indicated that they believed that PCBs were already being efficiently recovered from WEEE. They stated that the main way to significantly increase the capture of PCBs would be to increase the quantity of WEEE being recovered for recycling.

They indicated that this could be done by:

- Increasing public awareness of WEEE recycling through large-scale sustained public awareness initiatives;
- Introducing more take-back schemes;
- Better policing of the system to reduce leakage from:
  - Illegal exports
  - WEEE not being treated at ATFs/AATFs;
- Introducing bans on whole WEEE disposal through landfill and EfW.

**Strong Demand for UK Sourced PCBs**

There is strong end market demand for UK sourced PCBs from refiners based in the UK, Europe and the Far East. During the project one organisation interviewed stated it exported PCBs to the Far Eastern market in order to supply feedstock to another part of its organisation. The end destinations are highly dependent on the prices being offered and the associated transportation costs.
End market refiners typically use pyrometallurgy or hydromeallurgy treatment processes to recover precious metals from PCBs.

**Further work**

During the project there were several areas of future work identified, which could benefit the PCB recovery sector. These include:

- Developing a 'live' online tool, which UK recyclers could use to help them identify which technique to use for recovering PCBs and the potential benefits. This could include information such as:
  - Type of WEEE treated;
  - Treatment cost (estimated);
  - Type of PCB;
  - Composition of PCBs; and
  - Prevailing value of PCBs.

- Undertaking a market assessment of UK PCB refiners to identify:
  - Total UK Capacity;
  - Key issues; and
  - Opportunities for keeping the recovery of precious metals from PCBs in the UK.
Appendix 1 UK Questionnaire

Context
WRAP have commissioned Valpak’s Consulting department to conduct research into the financial benefit of various recycling and reclamation techniques for Printed Circuit Boards (PCBs) from WEEE.

The project aims to identify whether one technique is more beneficial than another in terms of the value material recycled/reclaimed against the cost of recycling and reclamation. The balance of quality over quantity will be addressed, to understand whether one mechanism or a mix of technique could be considered best practice. Tipping points in each technique, as to when a process becomes non-cost beneficial or cost beneficial will be analysed by conducting a sensitivity analysis.

WRAP aims to use this information to help businesses maximise material recycling and reclamation in the most cost efficient way.

The following questions aim to help WRAP understand the mechanism you use for recycling/reclaiming PCBs, the costs associated with separation, and the level of recycling/reclamation achieved, in order to carry out a financial assessment on the method.

All information/data provided as part of this survey will be treated as confidential and anonymised and will not be shared in such a way that will identify the company to anyone outside the Valpak and WRAP project team.

Background Information

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<tr>
<th>Company Name</th>
<th>Location (Why this location?)</th>
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Overview

1) What WEEE categories do you recycle/reclaim PCBs from?

2) What grades of PCBs do you recycle/reclaim (by WEEE category)? How do you identify the different grades? Is there a universal standard on PCB grade?

3) Please describe your current recycling/reclamation process regarding PCBs? (I.e. commercial shredding, smashing, manual segregation etc. By stream) – Please talk us through each process and the key stages of each process. Also, why do you use this method?
4) Are the PCBs positively or negatively sorted from WEEE (by category) i.e. do you target PCBs or are they residual from a process targeting other materials? Do you think this has an impact on the quality of PCBs recycled/reclaimed?

5) What are the advantages and disadvantages of this process (by WEEE category)?

6) What is your maximum annual capacity for recycling/reclaiming PCBs? (i.e. not current throughput, but capacity) (how many tonnes/units can your process recycle/reclaim per month/year) (by stream)

**Inputs**

1) What is your current annual tonnage throughput for PCBs/WEEE category (How do you monitor this e.g. number/tonnes of WEEE products per category or do you know how many PCBs do you recycle/reclaim currently per month/year) – please provide answer by grade/category if possible: (1/2/3 or low/medium/high or other) For example,

- **Grade 1** - Generally these will contain processors, Gold pins and connectors containing precious metals which can be recycled/reclaimed

- **Grade 2** - Whilst not as valuable as Grade 1 type boards, they will still contain some processors, Gold pins and connectors containing precious metals which can be recycled/reclaimed

- **Grade 3** - These will generally only contain sparse, if any precious metals and are mostly valuable for their Copper content

2) What is the associated capital cost with your current recycling/reclamation process for PCBs (i.e. the cost of any equipment including sort lines, shredders, equipment etc.)? (note this needs to be apportioned to PCBs so ask if cost of specific for pulling out PCBs or other material too, and what proportion they think is for PCB (by tonnes / time spent/other))

**Process**

1) What do you do with the PCBs when reclaimed?

2) Do you recycle/reclaim any material from the PCBs? What materials? (With associated weights) What can you typically expect to recycle/reclaim from one tonne of PCBs? Can you please provide information on the technique used to recycle/reclaim each material and the associated costs? (by WEEE category)

3) Does this vary by Grade of PCB or WEEE product/category, if so how?

4) What other materials/components will be captured during the PCB recycling/reclamation process? What is the value of these and where do you send them?

5) When you recycle/reclaim PCBs, are you aware of any process losses/material losses that you can quantify for us (by WEEE category)? i.e. what is the % of PCB (by WEEE category) you recycle/reclaim and what is the % you estimate is lost in other
Techniques for Recovering Printed Circuit Boards (PCBs)

Materials / waste recycled/reclaimed? N.B. should add up to 100%! (by WEEE category)

a. Is there any other material lost from the WEEE during the extraction process of CBS?

6) Can you please give us an indication of your operational costs (by tonne of PCB/tonne of WEEE/other) for your process, which may include (but please complete the list for us) (specify by WEEE category): (For each please estimate if annual/monthly/other and if this is an estimate or is actual)

a. Staff (labour) costs (specify what this includes and normalise e.g. per tonne throughput)

b. Power costs (specify what this includes and normalise e.g. per tonne throughput)

c. Maintenance costs (specify what this includes normalise e.g. per tonnes throughput)

d. Other (please specify what this includes normalise e.g. per tonnes throughput)

7) How many staff members are employed and dedicated to the process of extracting PCBs?

Outputs

1) Where do you send your extracted PCBs?

   i. What is the name of your downstream partners? What they do with the PCBs (what material do they recover etc.)?

   a. UK brokers:

   b. UK recyclers:

   c. Direct to overseas reprocessor:

      a. If ‘c’, why do you not work with end markets in the UK?

2) What value can you typically expect to receive from these materials? Is this a fixed price? (by grade and a price range would be fine)

3) Are you subject to minimum trading quantities? (specify)

4) Do you have to subscribe to a certain specification or a trading group? How do you track quality?

5) Are there any associated costs of disposal of any by-product, please provide information about each by-product and cost per tonne disposed?

   a. What is the material? (E.g. cable ends / button cells etc.)

   b. Where does it go? (e.g. landfill)
Future Planning & Support

1) What do you believe is the best technique you are aware of for recycling/reclaiming PCBs and why?

2) What do you believe is the most cost effective technique you are aware of for recycling/reclaiming PCBs and why?

3) Do you intend to invest in the short to medium term future in new techniques for recycling/reclaiming PCBs? Please provide details and reason?

4) What are the main barriers to improving the recycling/reclamation of PCBs in the UK to increase the quantity and or value of PCBs recycled/reclaimed?

5) What do you think could be done to improve the recycling/reclamation of PCBs in the UK to increase the quantity and or value of PCBs reclaimed? Could any of the following help, please specify:
   a. Education and training
   b. Development of end markets
   c. Financial
   d. Legislation
   e. Technology Investment
   f. Other (please specify)

Increased Recovery of PCB Materials / Components

1) What do you believe could be done to improve the recycling/reclamation of valuable materials / components from PCBs in the UK?

2) Do you have plans to further refine your process at all to increase the recycling/reclamation of valuable materials / components from PCBs?
Appendix 2 Overseas Questionnaire

Context

WRAP, have commissioned Valpak’s Consulting department to conduct research into the financial benefit of various recycling and reclamation techniques for Printed Circuit Boards (PCBs) from WEEE.

The project aims to identify whether one technique is more beneficial than another in terms of value, material recycled/reclaimed against the cost of recycling and reclamation. The balance of quality over quantity will be addressed, to understand whether one technique or a mix of mechanisms could be considered best practice. Tipping points in each mechanism, as to when a process becomes non-cost beneficial or cost beneficial will be analysed by conducting a sensitivity analysis.

WRAP aims to use this information to help UK businesses maximise material recycling and reclamation in the most cost efficient way.

The following questions aim to help WRAP understand the technique you use for recycling/reclaiming PCBs, the costs associated with separation, and the level of recycling/reclamation achieved, in order to carry out a financial assessment on the method. They are also keen to understand the type of material and minimum volume traded that you accept from the UK and why.

All information/data provided as part of this survey will be treated as confidential and anonymised and will not be shared in such a way that will identify the company to anyone outside the Valpak and WRAP project team.

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1) How do you grade PCBs? (high / medium / low / other). How do you identify these? E.g. product/category specific? Perhaps you provide guidance on quality/size/type?

2) What grades of PCBs do you treat?

3) What proportion of this material is sourced from the UK on a 12-month basis?

4) Where else do you source them? How does the quality compare?

5) What materials do you recycle/reclaim from PCBs? (By type, associated weights, etc.).
   a. CRMs (By type, if possible)
   b. Metals (By type, if possible)
c. Plastics (By type, if possible)

6) What can you typically expect to recycle/reclaim from one tonne of PCBs? (This answer should include specific types of metal, elements, etc.)

7) Are they all target materials? What do you target? What do you do with non-target material?

8) Please describe the process you use for extracting each target material.

9) Does this vary by Grade of PCB, if so how? Does it make a difference to the recycling/reclamation levels how the PCB was extracted from the WEEE prior to it reaching you?

10) What is your plant’s capacity specifically for PCBs, are you currently operating under capacity / over capacity? Could you receive more material from the UK? Do you process anything else at the plant?

11) Can you please give us an indication of your operational and capital costs (by tonne of PCB) for your process?

12) What do you pay per tonne grade of PBC?

13) Can you give us details of how the amount paid for PCBs are calculated? (e.g. per grade/depending on extraction method/other)

14) What do you believe is the best way for WEEE treatment facilities to recycle/reclaim PCBs from WEEE and why? Do you believe this is the most cost-effective method?

15) What do you believe could be done to improve the quality or quantity of PCBs recycled/reclaimed from the UK, please specify?

16) Would you consider investing in processing for recycling/recovering valuable metals / materials from PCBs in the UK? Please explain why / why-not?
www.wrap.org.uk/WEEE