An Integrated Approach to Electronic Waste (WEEE) Recycling

Project funded by DEFRA Waste and Resources Research Programme

Reference WRT208

Final Project Report
Deliverable M12
SID5 Form – Section 8

January 2007

C-Tech Innovation Ltd
Capenhurst Technology Park
Capenhurst
Chester
CH1 6EH

Tel: +44 (0) 151 347 2900
Fax: +44 (0) 151 347 2901

e-mail: info@ctechinnovation.com
website: www.ctechinnovation.com
Contents

1. Scientific objectives 1
2. Extent to which objectives have been met 1
3. Methods used and results obtained 2
4. Discussion of results and reliability 15
5. Main implications of findings 18
6. Possible future work 19
7. Actions resulting from the research 20
1. Scientific objectives

The scientific objectives are centred on the development of a hierarchical approach to WEEE recycling needs and aims. The main emphasis is the assessment of the potential for new technologies, either under development or at the research stage, to enhance the possibilities for increased recovery, recycling and reuse in the future, as defined in the WEEE directive.

(a) Sectoral WEEE waste composition, trends and logistics

Complete a comprehensive analysis of sectoral WEEE composition, including a projection of expected future trends, and a sector-based analysis of resource recovery logistical issues

(b) Intelligence on resource recovery technologies

Provide information on current industrial technologies, their limitations and future aims for technological developments, structured on a sectoral basis and technological intelligence containing comprehensive details of emerging technologies and research

(c) Develop an integrated hierarchical approach to sectoral recycling needs and aims

Match the treatment objectives with the technological methods available for each sector, now and in the future, and to formulate a best practice strategy and approach in each case. Develop generic economic modelling spreadsheets per sector and to deliver these to DEFRA along with reports on an integrated, hierarchical approach to recycling electronic waste and an outline strategy for future research and technological development

(d) Life cycle analysis

In order to assess the sustainability of each generic sectoral treatment methodology for electronic waste, develop a Life Cycle Analysis methodology to enable the sustainable assessment of the complete life cycle of new technologies and products.

(e) Manufacturing guidelines for improved sustainability in resource consumption

Prepare a set of sector-based eco-design manufacturing guidelines, which aim to improve product design with “recyclability” as key factor to reduce waste production and enhance resource recovery

(f) Socio-economic analysis

Prepare an analysis of societal influences on generic sectoral processing methodologies defined during Objective (c) and to assess the potential impact of new technologies emerging from research activities

2. Extent to which objectives have been met

All deliverables were completed according to the scientific objectives set out within the scope of the contract.

The nature of all the tasks in this project is such that further work could of course be undertaken. The specific activities in which extensions of the current objectives are particularly recommended for further work are:

- Life Cycle Analysis methodology
- Economic modelling spreadsheets

See section 6 for further details.
3. Methods used and results obtained

3.1 Methods

A wide range of public and private sources of information were used. These were obtained from the literature and by conducting interviews with leading representatives in the electronics and recycling sectors. This assessment was supported by the collation of business and market trends for various product groups.

Dialogue with key personnel involved in the overall process of WEEE collection and processing provided a greater understanding of the logistical issues related to collection and distribution of sectoral WEEE. A range of organisations and companies were consulted, including the ten in-kind contributors, about their experiences with WEEE collection, transportation and recycling. Many site visits were conducted. The companies chosen reflected a broad range of organisations and categories active in the handling and processing of end-of-life electronics as part of the requirements of the WEEE Directive.

The resources within the project consortium have been utilised to set the context for the investigation, and to provide valuable information and experience. The project partners were:

- C-Tech Innovation Ltd (Contractor and project manager)
- Rohm and Haas Electronic Materials Ltd (Sub-contractor)
- PRK Environment (Sub-contractor)
- Intellect (Sub-contractor)

Project management activities (C-Tech Innovation Ltd):
- Act as the interface between the project and DEFRA
- Monitor progress and direct the technical and financial aspects
- Submit deliverable reports and invoices to DEFRA
- Defining any changes to the work programme
- Arranging full project meetings every 3 months, preparing agendas, chairing meetings and preparing minutes
- Monitoring follow up actions
- Arranging additional meetings as required by the work programme
- Setting up and maintaining communications channels and information flow

3.2 Discussion of Results

Waste Electrical and Electronic Equipment (WEEE) is one of the fastest growing sources of waste in the European Union and the WEEE Directive has focussed attention on the need to recycle, recover and reuse materials that would previously have been consigned to landfill. This project has addressed the complex challenges of recycling WEEE in a structured and integrated manner through a detailed analysis of the principal issues having an impact on the recycling of such goods. The WEEE Directive defines ten specific categories of waste, each of which has its own distinct and evolving compositions and it is essential that the appropriate recycling technologies are chosen for each category if the recycling targets defined by the Directive are to be achieved in a manner which is economically viable and which is also capable of producing material streams that are suitable for reuse in new applications.

Task (a) Sectoral WEEE waste composition, trends and logistics

The report for Deliverable M4 provides an overview and understanding of the current situation regarding the composition of WEEE in terms of the 10 categories defined by the WEEE Directive. Currently, the process of WEEE recycling is not well defined and not fully understood by those that will be most impacted by the legislation. Whilst it will be possible to
identify appropriate recycling technologies specific to a defined waste stream, the current logistics of WEEE recycling mean that it is not yet possible to define the material compositions likely to occur in real recycling operations.

Delays in finalising the exact details of WEEE implementation in the UK and the current absence of any clearly defined WEEE allocation and collection systems in the UK has seriously hampered an evaluation of the logistics for handling WEEE. However, a synopsis of WEEE recycling schemes that have been implemented across the various Member States was produced along with information on the WEEE collection scheme employed in Japan, which focuses on a much narrower range of products as required by the Home Appliance Recycling Law.

While the WEEE Directive segregates end-of-life electronics into ten specific groupings, each may well contain a wide range of individual product types with its own specific material composition requiring an optimal recycling technology. At the very top level, it is therefore important to define exactly which products are likely to be encountered and what product mix is actually appearing at CA sites. It has been deemed impracticable to have ten separate skips/containers for collecting the ten different categories of WEEE and a proposal has been adopted that five groupings be used in order to enable the practical and efficient collection of household WEEE from CA sites: refrigeration equipment; other large household appliances; equipment containing CRTs; linear and compact fluorescent tubes; all other WEEE.

Thus, it must be concluded that any of the recycling and recovery technologies identified in other work packages of this project will be required to address the items that would typically be found in each, or some, of the above five groupings. It seems likely that one of the biggest challenges will be in the development of technology and equipment for treating the wide range of products likely to be encountered in the ‘All other WEEE’ category.

**Task (b) Intelligence on resource recovery technologies**

**Current WEEE recycling technologies**

Whilst the methodologies outlined are all either being used commercially or are being actively investigated for commercial use, the actual sequence of deployment and operational approach varies between different recyclers.

There are a number of methods used for sorting and disassembly. It is clear that a major cost element within any recycling methodology is that devoted to manual disassembly and sorting, whether this is the manual removal of hazardous components such as batteries and other items prescribed by the WEEE Directive or the manual sorting into classifications such as high and low grade material. Disassembly is a systematic approach that allows the removal of a component, part, group of parts or a sub-assembly from a product (partial disassembly) or the separation of a product into all of its component parts (complete disassembly) for a defined purpose. Existing practice in the recycling of WEEE places selective disassembly as a vital and integral element of the process in that priority is afforded to the reuse of components, the dismantling of hazardous components and the recovery of valuable materials from such as printed circuit boards, cables and engineering plastics. However, most recycling plants utilise expensive manual dismantling.

The overall process of disassembly may be broadened in definition to include mechanical processes such as physical impacting and primary forms of shredding and fragmenting and in certain instances granulation may be interpreted as being within the scope of disassembly. Physical impaction comprises methods which break down products to enable the salvaging of reusable and recyclable parts, components and materials, whereas shredding in its primary form is the breakdown of the product into pieces via fragmentation, ripping or tearing which
may then be sorted into differing material streams with dissimilar subsequent processing demands.

Shredding/Fragmenting is a process in which products are fed into a shredder which fragments, grinds, rips or tears the product into pieces which are then sorted into different materials streams and recyclable or valuable materials extracted.

Granulating is the mechanical processing of production scrap, post-consumer plastic packaging, industrial parts, or other materials into fine particles. The process is defined as: “Granulators consist of a feed hopper, cutting chamber, classifying screen, and rotating knives that work in concert with stationary-bed knives to reduce the plastic scrap until it is small enough to pass through the classifying screen. The resulting particles, called regrind, can vary in size from 3 mm to 20 mm.

Mechanical recycling of plastics involves melting, shredding and granulation of waste plastics which must be sorted prior to mechanical recycling into polymer types and/or colour. The plastic is then melted down directly and moulded into a new shape or melted down after being shredded into flakes and then processed into granules called regranulate. Granulating is ideal for products with a high plastic content such as small household or gardening appliances and power tools. It is important that there are no contaminants i.e. hazardous materials / components present, therefore these may require manual removal prior to granulating. A specialist granulator is used to process WEEE so that different material streams can be easily separated.

Automated disassembly comprises a fully automated production line based disassembly system. Automated disassembly will provide a cost-effective means of recovering and recycling components and materials on a large scale in the future and replace much of the current manual disassembly. The main advantages of establishing automated disassembly are based on the fact that it is ideally suited for high metal content waste and it is lower cost than the high labour content of manual disassembly. However there are many difficulties in effecting total disassembly of most electronic goods with automation due to the problems associated with fasteners and access to parts situated in close proximity. The approach is also most effective when applied to large quantities of feedstock with a very consistent quality.

One of the most common pieces of equipment used for initial crushing and shredding is a hammer mill. Hammer mills accomplish size reduction by impacting a slow moving target with a rapidly moving hammer. The target has little or no momentum (low kinetic energy), whereas the hammer tip is travelling at rates of typically up to 7000 m/min and higher (high kinetic energy). It is the transfer of energy resulting from this collision that fractures the feedstock. Material disintegration may also be effected by the use of metal crushers which have low specific energy consumption and offer high operational immunity to the presence of solid pieces and may be also used a pre-stage prior to shredding.

Separation processes are used for classification of powders or other bulk materials by particle size as well as separation of particles by density, magnetic properties or electrical characteristics. Round and rectangular screeners, magnetic separators, electrostatic separators, rotary sifters, wet or concentrating tables, rake classifiers, classifying hydrocyclones, floatation systems and trommels are included in the category.

Screeners are sifting units that are rotated as powder is fed into their interior and are available in three main types: drum sifter, rectangular deck, and round deck.

Air classifiers, cones or cyclones use the spiral air flow action or acceleration within a chamber to separate or classify solid particles.

Concentrating tables or density separators screen bulk materials or minerals based on the
density (specific gravity), size and shape of the particles.

Electrostatic separators use preferential ionisation or charging of particles to separate conductors from dielectrics (non-conductors).

Floatation systems separate hydrophobic particulates from hydrophilic particulates by passing fine air bubbles up through a solid-liquid mixture.

Magnetic separators use powerful magnetic fields to separate iron, steel, ferrosilicon or other ferromagnetic materials from non-magnetic bulk materials.

Rake, spiral and bowl classifiers use mechanical action to dewater, deslime or separate coarse bulk materials from finer materials or liquids.

Trommels are large rotary drum shaped with a grate-like surface with large openings and are used to separate very coarse materials from bulk materials such as coarse plastics from finer aluminum recycled material.

Water classifiers such as elutriators and classifying hydrocyclones use settling or flow in water or a liquid to separate or classify powdered materials based on particle size or shape.

Emerging and future WEEE recycling technologies

The areas of technology that are relevant to future WEEE recycling requirements can be categorised according to their potential role in the process. Different levels of innovation were found in each area:

− Disassembly
− Comminution (size reduction)
− Separation
− Thermal treatment
− Hydrometallurgical Extraction
− Dry Capture Techniques
− Biotechnological Capture Techniques
− Sensing Technologies
− Design for recycling, and reverse supply chain technology

Automated Disassembly

Disassembly is seen by many as an essential element, even for relatively well-defined input streams, if value is to be extracted. The high labour burden of this stage is driving research into automated techniques. Switzerland, however, has instead reduced reliance on disassembly by concentrating on collection logistics. In automating the process the main issues are: imaging, recognition and robotics. Demands on these are reduced by attention to upstream issues.

Disassembly can be simplified through design features that employ mechanical, chemical, thermal, electromagnetic and biological means. Biodegradable components are an interesting new development, while an important new class of materials is shape memory polymers (see “Design For Recycling”). Logistics and process planning of disassembly are very active research areas. Simulation tools are being developed that allow critical assessment of disassembly system designs, and some are commonly available. Radio Frequency tagging (RFID) is an established technology whose potential for automated disassembly is now recognised, particularly in Japan, where emphasis is placed on logistics and voucher systems, and RFID tag information is integrated with comprehensive databases via the internet.
Relevant demonstrations of robotics are restricted to a few items, such as PCBs, which have predictable shapes and components. Some researchers are now extending this to more than one product through incorporation of computers and databases in a “hierarchical” approach that groups items into families. Matsushita have a vision-based system, using a single camera, which measures misalignment. This demonstrates a quality control capability that could also be applied to disassembly. They have also introduced an automated method for removing the glass from CRTs. Some groups are incorporating electromagnetic sensors for location of pieces and identification of materials within robotic control systems. Some companies, such as Adherent Technologies, however, claim to by-pass the need for disassembly by using a “conversion process” (see “Separation”).

Comminution

Shredding, crushing, pulverising, grinding, and ball milling, are all relatively conventional methods for reducing particle size. These are mainly mature technologies, and there is less long-term research in this area than in the others, although use of cryogenics is being studied. Advancements in automated recycling are not likely to depend crucially on developments in this area. The main issues are: the optimum size of product from these processes for the sorting technologies that are to follow; and the economics of these processes. It is attractive to recyclers to limit the degree of size reduction since the cost escalates rapidly as particle size diminishes. Increasingly, the influence of the particle size on the subsequent efficiency of sorting is receiving attention. Better matching of fragment size to sorting process can greatly increase efficiency of recovery.

Separation

Efficient separation, is a prime requirement for effective WEEE recycling, and can reduce reliance on dismantling. Sorting systems exist for separating materials in general scrap, after comminution, according to properties such as weight, size, shape, density, and electrical and magnetic characteristics. These include: grids, sieves, and vibrators for particle size separation; floatation, agitation, ballistic devices and trommels for density separation; magnetic fields for separating ferrous metals; eddy currents (AC fields) for non-ferrous metals; and electrostatic devices for removing plastics. Some groups are carrying out characterisation studies in order to determine costs, and to optimise the level of particle size from the comminution process. Particle size as low as 5mm to 10mm is preferred on technical grounds, but is more costly to generate. Although new techniques are being developed, much of the novelty in WEEE separation comes from adapting existing techniques, and from novel combinations. Initially this is usually for specific input streams, but more sophisticated routes are being developed to handle a wider variety of input items.

Current technologies can separate plastics from other materials, but segregation of the different types is a key aim, in which sensors have a vital role (see “Recycling of Plastics”). Mechanical devices for plastics classification include a novel air force sorter, and a “weak flow watercourse separator”. Adherent technologies in the US reported a complete “conversion process” that gasifies the plastics in heated screw feeds, and then reforms them into secondary materials, while metals are recovered by leaching, electrowinning and electrolyrefining.

Some researchers are combining separation techniques, for example, screw threads within floatation tanks, and jiggers or conveyor belts with water added, in some cases with superimposed magnetic fields. In other areas, existing techniques are being enhanced: for example, eddy current methods with rotating electrodes or with pulsed excitation, and corona separators with novel electrode designs. Electrostatic separators are good for extracting plastics, but are limited to relatively small particle size. Sand-based fluidised beds for gravity separation are also under investigation. Value may be extracted even from residual powder.
materials in processes under research in the automotive industry. Following pyrolysis and magnetic separation, sufficient carbon and iron dust is retrieved to render the process viable.

Separation of wire is a specific requirement. One patented method forms the wire, after crushing the other components, into coil shapes that allow gravity separation. Another approach uses spiked drums that both rotate and oscillate to facilitate separation and subsequent disengagement.

A major advance in separation is likely to come through sensing methods. Opto-electronic sorting is now being incorporated into research systems. The construction sector is developing electromagnetic field methods for both sensing and sorting. At low field levels, enhanced with pulsed excitation, signature combinations of conductivity and permeability of each material allow them to be discriminated. Higher fields eject the metal pieces from a conveyor belt while, signals are fed to a processor that activates appropriately positioned air nozzles to effect separation in the falling zone. Another system under research in the construction sector uses a similar intelligent ejection unit, but linked to a camera, and sorting on colour, shape and position. X-Ray systems are also under investigation, and could equally be linked to such an automatic ejection system.

**Thermal Treatments**

Thermal treatments have the advantages of greatly reducing bulk and avoiding liquid effluent for the primary recycler, although ultimately further refining is necessary to extract pure metals. They are not yet widely implemented in WEEE recycling, but are subject to much research, often adapting methods from the mining industry. Pyrometallurgical routes are potentially suitable for PCBs, which contain 29%wt of valuable metals, even though comprising only 3%wt of WEEE. Typically, after some initial sorting, the organic content is reduced to ash, which can be used as feedstock in the pyrometallurgical processing. The final products tend to be loosely refined metal ingots, such as ferrous, aluminium, mixed tin/lead, and, most importantly, a copper-rich precious metals mix. These are suitable for further refining. There are established operators (e.g. Engelhard), and much continuing research into these methods. For example, partial vacuum methods are being investigated.

Other thermal routes include encapsulation, using either glass or binder, to produce low grade block products for use in construction. Harmful contents are safely sealed in, but the opportunity to recycle valuable resources is lost. Research topics include use of vacuum, thermal plasmas, and lasers to enhance the thermal treatment. Other emerging variants include processes for copper-rich and iron-rich items. The latter is adapted from the car industry, but claimed to be suitable for WEEE.

**Hydrometallurgical Extraction**

Hydrometallurgy is well established for extracting and applying precious metals. The need to reduce reliance on the hazardous cyanide containing solutions that are routinely used drives current research. Processes have been developed for WEEE based on strong acids and hydrogen peroxide, with fluoroboric acid proving useful for extraction from mixed streams, including products from pyrolytic processes. The search for still less hazardous reagents continues, however. Thiourea and thiosulphate are candidates, as well as solvents such as polyhydric alcohol, ketones, polyether or cyclic lactone. Stability, process control, reagent recyclability, and economics are the outstanding issues for such methods. Research in the mining industry has generated a methodology based on oxygen, ozone and a complexing agent that facilitates passivation of the waste feed material and selective recovery of metals, without by-products. Catalytic processes are being developed for tin and lead.

Electrochemical methods are under investigation. A novel combined approach in which a non-selective leach process permits selective recovery in a subsequent electrochemical reactor
is under research at Imperial College. Further novelty in combined approaches is found in a project by the University of Birmingham, Alchema and C-Tech Innovation, where selective electrochemical recovery is augmented by microwave-enhanced biodigestion for the precious metals.

**Dry Capture Technologies**

Emerging dry capture technologies relate mainly to extraction systems and filtration, enhanced by the advent of nanotechnology, such as ultrafiltration. Little application to WEEE is found, but the generation of fine powder, which comprises 4% of WEEE arisings and contains valuable metals, may promote interest in this area in the future.

**Biotechnological Capture**

Microbial cells provide another means of recovering metals from fine powder WEEE residues. Many have developed an ability to capture metals as a way of dealing with their presence in the environment. Suitable cultures can be used to selectively extract metals from leachates from fine powder, or from other WEEE sources, and this method is under research by several groups, including Zurich Institute of Environmental Science and C-Tech Innovation. Chitosan, which is readily available as the structural element in crustaceans’ exoskeletons, also has an affinity for cations, and can therefore be used to extract metals, as well as being a good filter material for removal of contaminants such as oils.

**Sensing Technologies**

Sensing methods can greatly improve the effectiveness of WEEE recycling. They are crucial to implementation of automated disassembly and can facilitate great improvements in separation. Opto-electronic sorters, which use conventional imaging devices to discriminate on shape and colour, have been developed for various industries. Augmentation by electromagnetic sensing permits identification of metals, as well as of rubbers and plastics, allowing selective ejection of the identified items in automated separation processes. Laser Induced Breakdown Spectroscopy (LIBS) is a laboratory technique that is being adapted for on-line operation in separation processes, and to which enhancements such as pulsing are being applied. It is useful for heavy metals, and is of particular interest because it can detect brominated flame retardants. High accuracy and operational speed have been demonstrated. Precise identification of plastics is key to economic viability of WEEE recycling. Current recycling methods generate low grade mixed plastics, suitable only for de-rated applications. Laboratory analytical techniques are under research for adapting to this application, including laser-induced breakdown spectrometry, fluorescence from Ultra-Violet laser irradiation and X-ray methods. Adaptations of electromagnetic sensing for conducting materials are also being developed.

**Design for Recycling, Inverse Manufacturing**

Disassembly is a major cost in WEEE recycling that can be greatly reduced in the future through equipment design. Efficient use of resources can also be assured. Fundamental design principles for realising this have been set out by Envirowise. Other centres promoting this approach include the Sustainable Design Network led by Loughborough University, and SUMEEPnet at the University of Surrey. “Inverse Manufacturing” is a complementary activity that aims to support a reverse supply chain infrastructure for the re-use of components and sub-assemblies. A dedicated forum for this was established in Japan as long ago as 1996. Shape memory metals and polymers, which are materials that return to a pre-determined shape on heating to a transition temperature, are a major new development that will assist disassembly. Components made from these materials can be designed to release when heated. This has been demonstrated on LCD screens, and has been incorporated into some Nokia mobile ‘phones. Microwave heating can greatly increase the speed of the process. The
Japanese company Diaplex produces a range of shape memory fasteners, while the Fraunhofer Institute is developing detachable joints using shape memory snaps, screws and foam supports.

**Task (c) Develop an integrated hierarchical approach to sectoral recycling needs and aims**

The aim of task (c) was to identify the various options for Electronic Waste Recycling using a hierarchical approach for end of life management options: Repair and reuse, Refurbishing, Remanufacturing, Component recovery, Recycling, Energy from Waste, Waste disposal.

Section 1 provides an overview of the waste hierarchy approach and how it has been integrated into a generalised economic spreadsheet, which must be broad enough in its scope to cover all items of WEEE. It represents a useful tool to perform quick cost comparisons between the various technological options available for WEEE.

The primary hierarchy for handling waste materials including WEEE is given in previous work, but to identify process routes to take when handling the different WEEE materials streams, more questions need to be asked to establish residual value in the materials and the cost for recovering that value. A generic material flow analysis is represented in Figure 1.

Figure 1: Generic mass flow sheet tracking recovery of equipment, components and materials

The detailed flow of materials can be represented in the form of a more traditional mass flow sheet, with each block representing a specific process step and having both the transfer of materials through the block and also the associated economics of material arriving at the process and being processed through it (see Figure 2). In all cases, if specific information is available then this can be incorporated into the economic evaluation. Otherwise generic information from government and literature sources can be used as a first estimation of the local economics of the overall process from identification of WEEE to final transfer back into the market or as disposal as waste.

A spreadsheet was devised and constructed in order to enable user-friendly economic assessment of the various end of life options for electrical and electronic equipment utilising the hierarchical approach defined in this project. A description of the spreadsheet and outline instructions for its use is given in Section 2 of the report, along with the basis upon which the
spreadsheet has been constructed. It also describes the data required to be entered by the user, a basic guide as to its operation and examples of output data (See Figure 3).

Figure 2: Mass Flow Sheet for Detailed Flow of Materials

Figure 3: Examples of Output Data

The end of life of an item of WEEE was broken down into four options:

- **Refurbishing / Repair**: The least invasive of all options, is to return the item back to its original use, but the end product may not be of the same quality as the new product. In repair, the product will have components removed and replaced and will be returned, nominally, for the same use as the new product, although the end specification may be reduced, or indeed enhanced if components of higher specification are installed.
- **Cannibalisation**: the product will be disassembled and useful components recovered and re-used (probably in the steps given above).

- **Recycling**: the product is broken down and the materials recovered to be used in manufacture of new products. The recovered value will be very dependent upon the quality of materials.

- **Waste**: no useful components can be obtained, although energy recovery is an option, otherwise the Item must be disposed of e.g. to landfill or incineration.

Detailed process flow sheets form the basis for the spreadsheet construction. The flow sheets highlight the key stages in the process and describe how fractions of the waste stream could be used at each stage with the remainder passing onto the next stage. All calculations are based on the percentage of items or item components being utilised at each stage, the remainder passing on for consideration in the next stage. The choice of which items or item components are used at each stage is determined by the user of the spreadsheet. The direction each piece of waste can take is entirely customisable. Therefore the user may search for the optimum route or consider what is possible with currently available facilities and equipment.

In Task (c) section 3, an overview of the objectives for future research and development activities, which are of greatest relevance to WEEE recycling, has been provided, with the technology categories identified and discussed during Task (b) “emerging and future WEEE recycling technologies” as the basis. Three important target application areas for new technologies were identified and discussed:

- **Recycling of Plastics**: Recycling of mixed plastic waste is a problem because the recovered material is a low value product with a limited scope of market applications in the UK. Contamination of the recovered plastics by other polymers or non-polymeric materials prevents its use in high added-value applications and lowers recovered value. A key issue in achieving WEEE recycling targets and obtaining maximum value from recovered materials will be the ability to separate different types of plastic to provide relatively pure recycled feedstock for manufacturing uses. Current technologies can separate plastics from other materials, but segregation of the different polymer types is a key aim. The development of new sensors will play a vital role. Advances are being made, notably in the UK by Axion Recycling Ltd. Adequate collection arrangements and design for recycling will help reduce contamination.

- **Liquid Crystal Display Screens**: The WEEE directive requires the removal and separate treatment of liquid crystal displays (LCD) over 100 cm² and/or containing Hg backlights. WEEE containing LCDs is the fastest growing waste source in the EU, and LCD televisions have overtaken CRT sales in the UK. LCD usage is increasing rapidly in both number and size of devices with no sign of slowing down and is estimated to be greater than 3 billion worldwide in 2006. These items will provide a driving force for research into “Active Disassembly”, and into the use of shape memory materials. Active disassembly using innovative design and smart materials could significantly reduce future disassembly costs. Other research should explore the recycling of the high value liquid crystal polymers and the incorporation of the screen itself as a filler in ceramic and glass products. C-Tech is leading a new collaborative research project on this topic (started August 2006) funded by the UK Government Department of Trade & Industry.

- **Mobile Telephones**: The recycling of mobile telephones offers many opportunities for specialised recycling schemes beyond the recovery of the polymer and metallic materials. High recovery and re-use rates could be achieved if manufacturers considered recyclability and reduced toxicity during product design. This approach was highlighted back in 2002 by Nokia in a study report, in which they stated that their on-going Design for Environment
(DfE) programme was aiming to maximise recovery and recycling of their products, as well as minimise material and energy use. The basic process for used mobile phones involves shredding, after battery removal, followed by ferrous metals, aluminum and plastics separation. The metals and plastics can be recovered after further processing, but the material recovery achieved is limited. However, more effective separation and dismantling before shredding could increase the amount of cleaner fractions for recycling, and could offer possibilities for cannibalisation of components for use in new products.

WEEE recycling technologies will be required to respond to future developments in electronics manufacturing. In this rapidly developing sector, major advances in electronic technologies will be introduced in the future, requiring significant changes to recycling techniques. Even small changes to the composition of electronics are important to the economics of recycling processes, for example when high value metals such as gold and palladium are involved. In planning future research strategies therefore, it is important to take into account market drivers for electronic products.

Compliance with the WEEE Directive will require the future development of new technologies. The Best Available Treatment, Recovery and Recycling Techniques (BATRRT) concept refers to the extension of the principles of BAT to systems which provide for the recovery, recycling and treatment (RRT) of WEEE. However, the WEEE Directive also states that, where appropriate, priority should be given to the reuse of WEEE and its components, subassemblies and consumables. According to the WEEE Directive, specified substances, preparations and components are required to be removed from any separately collected WEEE. In addition, taking into account environmental considerations and the desirability of reuse and recycling, the selective treatment of WEEE must be carried out in such a way that environmentally sound reuse and recycling of components or whole appliances is not hindered.

The final section 4 of this project task highlights the importance of environmental legislation as a driver influencing the direction of future technological developments. Legislation impacting both the design and recycling of electronic products is being enacted throughout the world (including China). Environmental legislation is a major driver introducing changes to the electronics industry. Printed Circuit Board fabrication as well as assembly processes will be impacted heavily, with important consequences for end-of-life WEEE recycling.

Environmental legislation in various product segments is influencing the electronics industry:
- Detailed material content data of products and components must be shared
- Regional legislative requirements must be met
- Manufacturers must remove environmental “materials of concern”, such as lead
- End-of-life or producer responsibility legislation must be taken into account

To remain compliant with environmental legislation such as WEEE and RoHS, while maintaining competitiveness, the electronics industry must continue to keep pace with emerging issues in:
- Design: qualification of replacements for hazardous substances; product and WEEE compliance verification processes; LCA/SLCA tools
- Materials: Lead-free for high reliability requirement applications; cadmium and lead-free PVC cables; REACH risk assessment for chemical emissions
- Energy: Cost effective methods to improve power supply efficiency; enabled power management of IT equipment
- Recycling: compliance to diverse regional recycling requirements
- Sustainability: Standard sustainability indicators and reporting protocol for EEE
Task (d) Life cycle analysis

This study investigated the suitability and value of life cycle analysis (LCA) approaches for assessing the potential of new recycling methodologies for electronic waste i.e. the generic sectoral technologies defined in this project.

A full life cycle assessment of the various recycling technologies on any given product would require, even in the most simplified approaches, a calculation of all the environmental impacts of recycling specific tonnages of each type of electronic product from collection, sorting, dismantling, recycling and disposal and the transformation of the various waste streams into secondary material. In order to focus on the specific goals of the project, an assessment was made within the overall framework of environmental life cycle assessment taking into account the specific challenges posed in the selection of WEEE treatment technologies that can potentially deliver improved environmental performance.

In order for such an approach to be subsequently further developed, it has been necessary to apply suitable constraints in the scope of the study and to focus on environmental performance indicators and the key environmental impacts that can arise when reprocessing end of life electronic products. There is currently no published, standardised life cycle methodology that focuses on WEEE treatment technologies or that also supports the integration of new technologies or developments.

This report has a specific focus on the environmental implications of WEEE treatment technologies and not WEEE collection and separation, which were viewed to be outside the scope of this study. The study has addressed the usefulness of life cycle analysis and related approaches in the specific context of end of life electronic product recycling and the different new and emerging technologies that may be introduced in the near future. Case studies were completed with the same materials streams that were covered in task (c), i.e. washing machines, televisions, mobile telephones.

It is clear that the overall environmental impact of many types of WEEE actually arises during the use phase and this is where improvements can bring the biggest benefits. Various LCA studies have been undertaken and these have often turned out to be extremely complex in terms of the levels of information required. In the case of mobile phones, for example, Nokia found that standard LCA approaches were not really suitable for making the kind of assessments they required. A key challenge, therefore, is to develop more practical techniques that offer the benefits of life cycle analysis while substantially simplifying the time and data requirements (SLCA: streamlined life cycle analysis). In many cases more simplified life cycle approaches may be sufficient enough to allow the key target areas to be identified and prioritised and addressed.

Task (e) Manufacturing guidelines for improved sustainability in resource consumption

Disassembly is sometimes referred to as de-manufacturing or inverse manufacturing, and invariably involves a large degree of manual labour with its associated high costs. Active disassembly techniques in which products are designed to disassemble under an external stimulus will no doubt form an ever increasing element in disassembly methodology. The study covered a number of active disassembly techniques that are currently being researched and developed.

The choice of fasteners and associated elements is a key design element for disassembly whilst the choice of materials may be considered to be at the core of design for recycling. There are many available choices of fasteners, which can enhance disassembly, and in many instances manufacturing efficiency. An example of a unique and functional product feature is the clever “push button” fastener on a Dell personal computer cover. Simply by pressing in on
two buttons, one on each side of the cover, then lifting it up, the entire cover can be removed without the use of any tools.

A key element of future WEEE recycling is the identification and referencing of product data to enable material and producer information to be accessed. Radio frequency identification (RFID) will become increasingly important in future. The technique provides a non line-of-sight reading capability with unique identification information and can be linked with other communication systems. In use RFID tags will be used for storing product information as mandated by the WEEE Directive which will allow for more automated and efficient management of information associated with product recycling. It is also anticipated that product marking and RFID technology will provide producers and waste treatment facilities with new service, applications, and business opportunities. RFID technology will thus affect the management of product information during the entire life cycle of a product.

Active Disassembly involves the disassembly of components using an all-encompassing stimulus, rather than a fastener-specific tool or machine. Designing for active disassembly involves the use of smart materials which undergo self-disassembly when exposed to specific temperatures. Shape Memory Polymers (SMPs) and Shape Memory Alloys (SMAs) form the majority of the smart materials used. Often in the form of screws, bolts and rivets, active disassembly fasteners change their form to a pre-set shape when exposed to a specific trigger temperature, which can range from approximately 65°C to 120°C. Taking the example of the screw, the thread disappears when exposed to the trigger temperature, allowing it to fall naturally out of the cavity without any extra stimuli.

**Task (f) Socio-economic analysis**

Socio-economic factors have a significant influence on the viability of both the overall approaches to materials recovery and the specific techniques that are likely to be successfully implemented in the future. At present, there appears to be a disconnect between the desire for society to behave in a more sustainable manner and the introduction of new and more efficient processes that can provide high value recyclates having real application. For example, there is virtually no serious use of recycled polymers from end of life electronics. Technology exists for producing higher quality polymers but it is compromised by collection mechanisms that often lead to the basic granulated material being contaminated. Part of this is due to the way business operates in Europe, with there being little connection between the manufacturers and the recyclers. This is due to a combination of historical and cultural factors, since for example in Japan, the major electronics manufacturers also own the recycling facilities and they are keen to source high quality recylcate for reuse in their own products.

In order for industry to adopt the new recycling technologies identified by this project, there will need to be significant changes in the economics of recycling. The electronics industry is a truly global business and this extends to end of life recycling. This is evidenced by the exports of WEEE from Europe which have caused controversy and embarrassed some well known manufacturers of electronics. Other global factors also clearly have a major impact on what level of recycling activity takes place. For example, the value of many of the metals found in WEEE has increased significantly in recently years, largely in response to increasing demand from expanding countries such as China. The price of copper has tripled since the turn of the century and this offers an opportunity for newer technologies to be introduced. Whether these increases in the value of basic materials will be sustained will be one important factor influencing decisions about expansion and investment in metals recycling. Similar important considerations also apply to oil and energy prices since these have an impact on the manufacture of raw materials used in electronics as well as the cost of transport for moving WEEE to the recyclers and indeed the cost of operating recycling processes.
The socio-economic factors that influence the need and ability to introduce new technologies into electronics recycling are many and varied. Many of them are also inextricably linked and thus there is a complex set of interactions and variables that impact what happens to end of life electronics. The need to achieve enhanced levels of reuse, recycling and recovery from end of life electronics in the UK is clearly demonstrated by comparisons with what is achieved in countries such as Sweden, and Japan. The WEEE Directive is already requiring specific targets to be met for each category of WEEE and it is likely that these will become increasingly stringent in the future. This in itself will do much to encourage the adoption of enhanced and new recycling technologies. From a socio-economic perspective there is much that could be done in the UK to help facilitate the introduction of these technologies and thus the improved processing of materials from WEEE. Ultimately, the recycling of materials is essentially driven by economics since, without the overall financial equations balancing, recycling would not be viable.

4. Discussion of results and reliability

Waste Composition and Collection Logistics

One of the key findings from this study was the disparate nature of WEEE recycling logistics in the UK. There is as yet no single well defined or established process that will enable characterised waste streams to be delivered to recyclers. This in turn means that severe limitations will exist in terms of the ability of the recyclers to employ specific high efficiency recycling processes that are tailored to specific types of WEEE. This contrasts dramatically with the approach that has been adopted in Japan.

In broad terms, and considering the overall recycling process from final user, through collection and transportation to a suitable treatment facility, there is still no agreed or recommended pathway. Producers are uncertain as to which sites they will be allocated and smaller companies are unsure how best they can discharge their WEEE obligations through the numerous compliance schemes that have emerged. There is also a lack of definition around the specific details of the treatment requirements of WEEE, for example, there is uncertainty about exactly at what stage of the recycling process printed circuit boards and LCDs will need to be removed from the waste stream.

The unreliability and lack of specific and detailed information creates an uncertain environment for development of the WEEE recycling industry and is hampering investment in recycling facilities.

Current Technologies for WEEE Recycling

The traditional methods that define the recycling of electrical and electronic products are still essentially the same as those that are used in scrap metal recovery and WEEE recycling is often still focussed on the recovery of metals by processes that involve smelting operations. There are numerous other technologies that could be employed to give more efficient recovery processes if adopted but as yet there seems to be little incentive for their adoption. Again, the unreliability of the available data on logistics and feedstock quality is a barrier.

The generic approaches to the recycling of WEEE have become fairly rapidly established and tend to follow a route comprising sorting/ disassembly, size reduction, separation and material recycling. The demands of WEEE however are increasingly becoming dominated by a preference of following a standardised waste hierarchy approach in which emphasis is placed upon reuse which in turn is generating increasing importance on disassembly and related design inputs. The processes being currently deployed in respect particularly of size reduction and separation are subject to continuing levels of improvement and modification to integrate
newer and emerging technologies. The actual sequence and deployment of current techniques may be seen to vary between different recyclers, depending to a great extent on the particular WEEE feedstock being processed, the volume of feedstock and the local operational costs.

**Emerging Technologies and Research**

There is a wide range of emerging and future technologies that potentially present many options for WEEE recovery and recycling routes. However, it is not clear which, if any, of the processes under investigation will be economically attractive, because of the unreliability of available data, as discussed previously. Although viability will depend also on the implementation of the legislation, several organisations in the UK consider that the technologies are, or will be, available to make WEEE recycling an attractive commercial proposition.

WEEE recycling is a highly complex process because of the diversity and unpredictability of feed material. Many observers agree that initial sorting, which is highly labour intensive, is necessary if maximum value is to be retrieved. Research is required to reduce the cost of this very expensive stage. The recycling of plastics is very important to the viability of WEEE recycling: the ability to differentiate and separate the various types will lead to product streams of much greater value.

Impressive advances have taken place in many areas, including imaging, sensing, artificial intelligence, automated systems, hydrometallurgy, electrochemistry, biotechnology, and an array of novel separation processes. Technologies from other fields, such as mining, construction and automotive should be considered.

The nature of WEEE continuously evolves, and much research today is anticipating these trends. They include the burgeoning sales of LCD screens, the increasing presence of brominated flame retardant plastics, and the introduction of lead-free solders.

Reference to the many experts consulted, including those within the project consortium, suggests that the review is comprehensive and reliably covers all of the major possibilities.

**Hierarchical Methodology and Economic Spreadsheet**

The methodology proposed aligns with the mechanism associated with general resource efficiency priorities as given by the waste hierarchy: Reduction; Re-use; Recovery; Disposal. Although this methodology specifically addresses the issues surrounding the recovery stage, this will inevitably have an impact on the other three stages, and therefore cannot be considered in isolation. For example, reducing one constituent in production may cause recovery of other materials to be much more difficult – or vice versa. However, the primary assumption in developing the methodology for resource recovery is that the materials being presented for recovery are those presently used, and that the product has reached the end of its useful life in its current form. The methodology can identify recalcitrant materials, or components that should ideally be replaced or eliminated completely. A valuable output from the methodology will be to highlight strategy for future best practice or research.

The difficulty with the reliability of any proposed methodology is the huge number of variables that need to be taken into consideration. This is particularly true when there are a large number of components even within nominally simple products, and that for similar products there is significant variability. Therefore, it has to be recognised that a definitive solution cannot be provided, as the preferred economic optimum will alter with the variability in the composition of the waste stream, and also the demand for materials being recovered. The methodology developed has to be used in conjunction with the wider issues and must assist in identifying the appropriate time at which to take these into account.
The central aim of the spreadsheet tool that has been developed during the project is to assess the economics of potential routes for WEEE using a hierarchical approach and to optimise the reliability of the evaluation.

In operation of the spreadsheet, the user selects the required fractions of WEEE going to each of the available stages. The outputs are presented numerically and graphically. In its current form, the outputs give:
- A breakdown of the WEEE by percentage treated during each waste route/stage;
- An assessment of the economics of each of these stages
- An overall economic assessment of the selected route for processing the WEEE stream.

Using this, it is possible to show which stage/s are uneconomical and the user can modify the processes as necessary to remedy the problem. The data and analysis capabilities in this spreadsheet are extensive and can be broken down into many sub-categories which could be specified by the user depending upon their particular interest. C-Tech innovation could tailor the output to suit any future user requirements.

The spreadsheet will be a reliable tool for assessing the economic viability of potential new processes for increasing the extent and quality of WEEE recycling. Of course the reliability of the data input to the tool is a separate factor that must be addressed.

**LCA Methodology**

A key finding form this work is that LCA studies are often extremely complex and that standard approaches may not be suitable for making the kind of practical assessments required by recyclers. A major challenge, therefore, is to develop more user friendly techniques that can offer the benefits of full LCA, while substantially simplifying the time and data input requirements. Streamlined life cycle analysis, as proposed in this study, may be sufficiently reliable to allow the key target areas for recycling technologies to be identified, prioritised and addressed.

**Manufacturing Guidelines for Improved Resource Efficiency**

In order to cultivate a hierarchy of recycling and reuse it is apparent that design for disassembly is a key element in that disassembly has a clear impact on the overall financial viability and additionally can place limitations on the recycled material yields attainable. Disassembly can provide much more effective segregation of these kinds of materials and components than shredding with the following benefits:
- Recovery of materials and components which may be viable for reuse or remanufacture
- Removal of materials having negative environmental impacts on subsequent recycling, e.g. by those within the RoHS Directive
- Effective segregation of material streams to enhance yields from subsequent recycling process stages

**Socio-economic Aspects**

If society is to behave in a more sustainable manner, the recycling of end of life electronics will have to evolve significantly from the practices that are currently being used and a more holistic approach will be needed that encompasses the product life cycle from design to end of life. There will also be a need to consider the end of life value hierarchy and to change the way society perceives waste and the value of recycled materials. There are many changes that could be made to encourage the reuse and re-purposing of end of life electronics well before they are consigned to basic material and energy recovery practices. Even when there are no further options other than basic materials recovery, there is still much more that could be achieved.
Irrespective of the requirements of the WEEE Directive, mechanisms need to be put in place to enable better quality waste streams to be made available to recyclers. This would need to involve all aspects of the supply chain from end user to recycler and would require the co-operation of consumers, businesses, local authorities, civic amenity site management, transport and storage companies, as well as recyclers. There are various elements to how this might be achieved ranging from enhanced public education programmes, through specialised training, to the provision of financial incentives or the imposition of financial penalties.

There needs to be a more joined up approach to recycling that provides holistic thinking from design through to end of life. The problem in the UK is that there is no intrinsic link up between the various stages of a product’s life cycle. This is because there are few major electronics manufacturers in the UK and thus limited opportunity for vertical integration.

There needs to be a centre of excellence established which provides training on aspects of the recycling of WEEE, beginning with design and that is also able to be a showcase for demonstrating and providing training on new recycling technologies. This type of approach has been successfully implemented in Japan and it provides a good way of educating the public about the importance of WEEE recycling.

Preparations need to be made to enable the recycling industry to handle new types of electronic products and the materials they contain. There will be significant technological changes in some areas, for example, the move to large area LCD televisions, the digital switch over and the emergence of plastic and printed electronics. These new products will bring new materials recycling challenges and it will be important to have appropriate technologies in place that can recover and recycle them efficiently.

More attention needs to be paid to the health and safety implications of materials recycling. For example, there are concerns over the exposure of workers to materials such as brominated flame retardants during polymer recycling.

The main conclusions are that a broad range of new technology areas could be utilised to increase the level of recycling, and that a key element in achieving this goal is the need to introduce collection and segregation systems to provide specific, clearly defined streams compatible with these technologies.

5. Main implications of findings

- There is a wide range of emerging and future technologies that potentially present many options for WEEE recovery and recycling routes
- Impressive advances have taken place in many areas, including imaging, sensing, artificial intelligence, automated systems, hydrometallurgy, electrochemistry, biotechnology, and an array of novel separation processes. Technologies from other fields, such as mining, construction and automotive should be considered
- WEEE recycling is a highly complex process because of the diversity and unpredictability of feed material. Many observers agree that technological improvements to initial sorting are necessary if maximum value is to be retrieved. Future research is required to develop technologies to reduce the cost of this highly labour intensive and expensive stage
- The recycling of plastics is very important to the future economic viability of WEEE recycling and to enable the recycling targets in the directive to be achieved. The ability to differentiate and separate the various types will lead to product streams of much greater value. Techniques for the separation of polymers containing brominated fire retardants are urgently required
- The nature of WEEE continuously evolves, and much research today is anticipating these trends. They include the burgeoning sales of LCD screens, and the influence of
environmental legislation on the range of materials used in electronics manufacturing. Researchers should be aware of future trends in markets and technological capability (e.g. iNEMI roadmap for the electronics industry) to anticipate changes and devise solutions in advance

- Primary separation of WEEE at CA and other collection sites should be established to enable segregation into specific, clearly-defined streams compatible with technologies for recycling and reuse
- Collection systems should provide input WEEE equipment in good condition that is compatible with recycling needs
- Generation of highly mixed waste streams, e.g. “all other WEEE” category, does not encourage reuse of components and recycle of added value products. Primary segregation of smaller electronic products would enhance recycling opportunities
- There is an urgent need to address logistics issues in order to enable recyclers to define optimised processes for materials acquisition, processing and recovery
- Environmental legislation is likely to be further refined and tightened in the future. A key aspect of ‘design for the environment’ will be to enable disassembly using environmentally friendly processes to achieve these increasingly demanding environmental requirements, whilst also maintaining cost effectiveness. Future research should address design and materials requirements to enable automated disassembly leading to recovery and recycling of components and high added value materials
- Recyclers need to develop closer relationships with manufacturers, in order to gain a better understanding of the material composition of products in the waste stream and to be able to feed back information on the ease of recyclability of specific products; disassembly information for products needs to be made more readily available
- The development of innovative new products that can be manufactured from recycled materials is necessary. Detailed consideration must be given to the development of markets for recycled materials from WEEE
- There is need to develop technical qualifications for professionals handling and working with WEEE

6. Possible future work

The spreadsheet has been developed to meet the requirements set out in the current project and was tested with three case studies (washing machines, CRTs, mobile telephones) in order to confirm its suitability. However, it has potential to be upgraded and developed further. The following ideas are suggested:

- Transports to be broken down further to include multiple methods and site internal transports.
- Disassembly and sorting costs to have some standard methods built into the program e.g. shredding, grinding, etc.
- User defined recycling options to be included. This would allow users to calculate and use various recycle methods more easily. It would be especially useful for items which do not have an industry standard recycle method.
- Allow users to define some of their own specific output graphs.

Further work should explore the development of simplified and therefore more practical Life Cycle Analysis tools that offer the benefits of full life cycle analysis, but focused on the assessment of specific new processes or improvements to existing processes, while substantially simplifying the time and data requirements.
Some technology areas have been identified by the project group and other potential collaborators for future research initiatives: Radio frequency identification (RFID), Ionic liquid solvents for plastics separations and Microwave/RF pre-treatment of heterogeneous WEEE.

7. **Actions resulting from the research**

- Commercial development of the economic spreadsheet is planned, following further validation and case studies.
- Dissemination activities are continuing with publications and presentations.