

University of Wales Trinity Saint David's

A Feasibility Study on the Reusability and
Recyclability of Lithium-Ion Batteries
And Environmental Impact Analysis of
Associated Activities

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Declaration of authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date:

Abstract

The following report investigates the feasibility of the recyclability and reusability of lithium-ion batteries (LIBs) through firstly dissecting the components of a single battery and analysing the what materials are commonly used. Laying out governmental law on waste electrical and electronic equipment (WEEE) as well as policies on companies and other sources that produce electronic equipment containing LIBs. Culminating in a failure modes and effects analysis that tests the robustness of the recycling model. The report also includes analysis of the environmental impact that is associated with lithium-ion batteries, uncovering the effects with the use of a life cycle assessment.

Objectives

- To assess the current reusability and recyclability of lithium-ion batteries by carrying out a feasibility study. To do this the product must be assessed, analysis undertaken on the components that are preventing recycling or reuse, and then use the conclusions to make recommendations on how Li-ion batteries can best be regulated and reliably produced.
- Break apart the structure of a lithium-ion battery to create a comprehensive view of the product, listing its advantageous recyclable materials as well as identifying the polluting and harmful substances present in the battery compounds.
- Research the environmental impacts that the life-cycle of lithium-ion batteries has on the environment and its associated activities involving raw material extraction and what methods of disposal are chosen.

Reasons and Relevance of the Project

The global market value of Lithium-Ion Batteries (LIBs) in 2017 was £23.10 billion, an increase of £10.4 billion from £12.7 billion in 2015. The growing usage of consumer electronics, hybrid electric vehicles and new interest in national grid storage systems has rocketed the industry forward in both production and development. The demand for these batteries has increased the cost of most of the materials used in their production resulting in a greater potential value of the discarded portion of LIBs. The value which can be recovered if a practical and affordable end-of-life scheme can be developed; as currently, the profitability of recycling these materials does not make it a worthwhile enterprise.

In 2014, 1.55 million tonnes of e-waste, or waste electrical and electronic equipment (WEEE), was put into landfills by Britain alone, ranking fifth in the UN's report on the waste produced per-capita tally (Balde, 2015). From my own calculations, 7% of that waste was compiled of mobile phones, calculators, personal computers and printers, which is still 108,602 tonnes of hazardous waste being sent to landfill. In addition to its lack of sustainability, this process of waste disposal is not a safe

solution as chemicals from the disused products leak out into the surrounding area, causing water pollution and ground contamination.

Looking at pollution in the European Union the size of the issue becomes much clearer. Data gathered and analysed from the 2015 UN report revealed that the top nine countries accounted for 4.29 million tonnes of WEEE sent to landfill; this is just over 10% of the worldwide value for dumped e-waste in 2014. Products which contain Lithium-Ion batteries make up roughly 7% of this figure, as well as other types of batteries, totalling roughly 300,000 tonnes of battery materials that had the potential to be recovered (European Commission, 2018).

The cost of sending LIBs, which are classed as hazardous waste, to landfill can be very high, with variances across policies for different countries. According to the upper limits of the UK landfill policy and the proportion of the UK's WEEE that LIB's contribute to (7%), it would cost £9.66million to landfill all LIB containing products in 2014. Even with better schemes and cheaper landfilling rates in other European countries, this method of disposal still presents enormous costs; costs that could be redirected to subsidise recycling schemes that would effectively deal with the problem.

Metal deposits on Earth, as well as all other resources, must be used in a sustainable and responsible manner. The waste hierarchy has been developed as a guide for how best to reduce and manage the waste that is produced. (Environment Protection Agency, 2019) The main pillars of the hierarchy are: avoidance of material use, to begin with, resource recovery, and finally safe disposal. Most discarded LIBs contain reusable and recoverable materials which, instead of being channelled back into the industrial economy, are crumbling in landfills. This causes hazardous chemicals to penetrate into water sources and contaminate the land; endangering human lives and the surrounding ecology. By using this waste hierarchy structure, societies can better conserve the limited resources here on Earth, and there are numerous potential efforts to be made still with material recovery and the disposal methods of LIBs.

One issue with the recycling of batteries, in general, is that there is a multitude of material compositions for every kind of battery, not solely LIBs, and this creates a real problem when processing facilities sort them into their constituent parts. "Although the lead-acid battery recycling industry has advocated for labelling, there are no LIB labelling standards, so at this point, even the development of sorting and segregation technologies may not be able to improve the process" (Gaustad, 2018). This source discusses the implications of the development and widespread use of LIBs and the implications that rapid development has on the environment. It highlights the

importance of labelling all LIBs to aid the recycling facilities in their struggle against the growing variety of LIB compositions.

The Feasibility of Recycling and Reusing LIBs

Structure and Composition Breakdown of LIBs

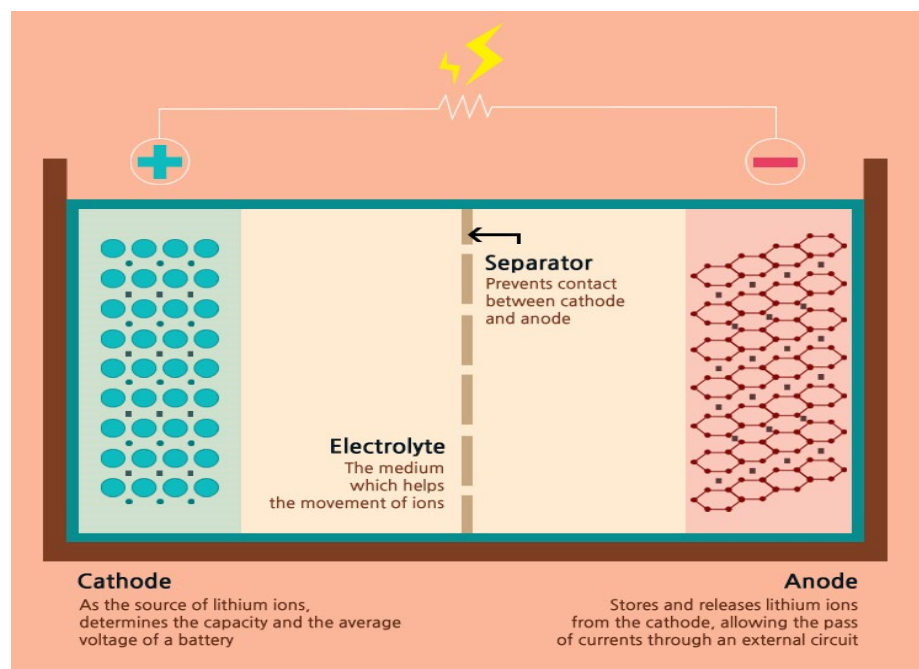
Component Breakdown

A LIB consists of one or more Lithium Ion cells comprised of four main components: the cathode, the anode, the electrolyte and the separator. The cathode is the section that holds and supplies the energy from the battery, in this specific case energy is stored as lithium-ions and is transferred from the cathode to the anode when discharging. The anode receives the ions (which are free electrons) and transfers these into the product that the battery is powering. The electrolyte is the medium through which the ions travel. The separator acts to split the anode and the cathode by allowing the ions to perforate through the electrolyte while preventing the cathode and anode from making a connection, which would otherwise short circuit the battery.

Structure and material details

There are three main cathode structures that LIB producers must use: octahedral, spinel and olivine. The variety of chemical mixtures within these materials are called generations, and there are about a dozen or more compositions currently available. The table below displays the typical values of the variation in specific capacity, specific energy amongst the different compositions and their

specific structures. With secondary (rechargeable) batteries, the designer must always follow a fine line: weighing up life-span of the battery (number of charging cycles) and the power that it can supply, as batteries with higher voltage capacity have shorter lifespans. Power must be sacrificed in order to achieve a longer life-span and vice versa, the designer's responsibility is to apply the right generation and structure to fit the specifications of the requirements for the product they power. The only commercialized anode materials are manufactured from natural graphite (carbon), and the layered structure of graphite means that the lithium-ions being transferred from the cathode to the anode during a discharge cycle allows for intercalation to occur (the process of lithium-ions locking



into the anodes structure). The anode is ionically conductive, allowing ion flow while also being electronically insulative to help stop the anode material from deteriorating irreversibly.

Cathode materials:

- Lithium cobalt oxide
- Lithium nickel oxide
- Lithium nickel manganese cobalt oxide (NMC)
- Lithium nickel cobalt aluminium oxide
- Lithium manganese oxide spinel
- Lithium iron phosphate

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M.M. Doeff

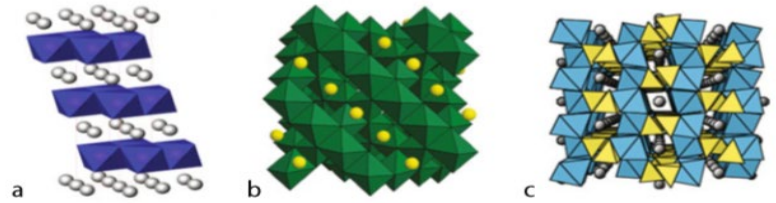


Fig. 2.2 Structures of common cathode materials: (a) The layered structure of LiCoO_2 with c -axis oriented vertically. The octahedrally coordinated Li ions in $3a$ sites are represented as spheres and CoO_6 (Co in $3b$ sites) as octahedra; (b) the cubic structure of LiMn_2O_4 spinel, with tetrahedrally coordinated Li ions (in $8a$ sites) represented as spheres, and MnO_6 (Mn in $16d$ sites) as octahedra; and (c) the olivine structure of LiFePO_4 , looking down the b -axis. Octahedrally coordinated Li ions are represented as spheres, and FeO_6 and PO_4 as octahedra and tetrahedra, respectively

Table 2.1 Characteristics of commercial Li-ion battery cathode materials

Material	Structure	Potential versus Li/Li ⁺ , average V	Specific capacity, mAh/g	Specific energy, Wh/kg
LiCoO_2	Layered	3.9	140	546
$\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ (NCA)	Layered	3.8	180–200	680–760
$\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$ (NMC)	Layered	3.8	160–170	610–650
LiMn_2O_4 and variants (LMO)	Spinel	4.1	100–120	410–492
LiFePO_4 (LFP)	Olivine	3.45	150–170	518–587

Anode materials:

- Graphite
- Lithium titanate

Energy Consumption of Batteries Worldwide

	NiCd	NiMH	Lead Acid	Li-ion	Li-ion polymer	Reusable Alkaline
Cycle Life (to 80% of initial capacity)	1500 ²	300 to 500 ^{2,3}	200 to 300 ²	500 to 1000 ³	300 to 500	50 ³ (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Cell Voltage (nominal)	1.25V ⁶	1.25V ⁶	2V	3.6V	3.6V	1.5V
Load Current						
- peak	20C	5C	5C7	>2C	>2C	0.5C
- best result	1C	0.5C or lower	0.2C	1C or lower	1C or lower	0.2C or lower

(Battery University, 2017)

The upper bounds of the cycle lives of the selected batteries were used in the calculations to find the total energy used by each battery in a single year. The following set of calculated results are therefore to be taken as upper bound estimates of what the real life values would be.

The amount of energy used by each battery type in their product lifespan is:

NiCd: 3.375MJ

NiMH: 4.5MJ

Lead Acid: 5.53MJ

Li-ion: 54.432MJ

Li-ion Polymer: 36.29MJ

Reusable Alkaline: 97.2kJ

Now, assuming that a li-ion battery lasts for its full life span of 3 years, then the yearly energy consumption is: $54.432 \times 10^6 \div 3 = 18.144 \times 10^6 \text{J}$

Or, 18.144MJ

The global phone use in 2019 was approximated at 4.68 billion, this estimation was made using data between 2015-2016 (Statista, 2016). Calculating the overall yearly energy consumption just from mobile phones is: $18.144 \times 10^6 \times 4.68 \times 10^9 = 8.49 \times 10^{16} \text{J}$

Or, 84,900TJ

What are critical raw materials for Lithium-Ion Batteries

Critical Raw Materials (CRMs) are so named, not for their scarcity on the planet, but because of their economic and strategic value to the European economy. They are essential for manufacturing in all areas such as consumer electronics, medical equipment, space exploration and aviation, steel making and environmental technologies. Without these materials, the functioning of the European economy would be unsustainable.

The key reasons that these materials are classified as 'critical' are as follows:

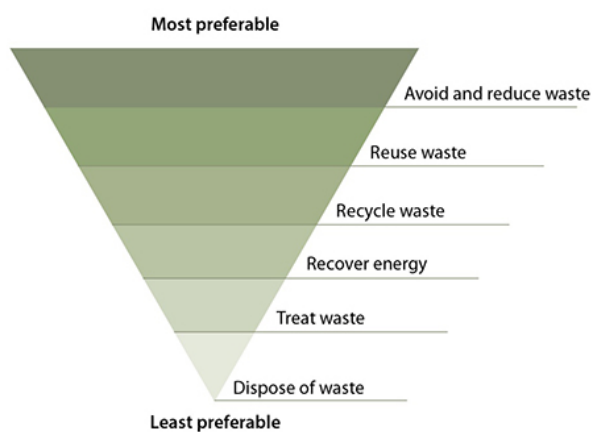
1. They have a high-supply risk which is due to Europe's dependency on importing the materials from usually far away countries. Also, the number of sources for these materials are limited because of the high level of concentration of CRMs in particular countries.
2. They have significant economic importance for key sectors within the European economy. A vast array of products and the companies that produce them relies on the steady supply of these materials.

3. Due to the unique and reliable properties of these materials, the number of viable substitutes is few to none. Meaning current and future applications rely heavily on CRMs.

As a result of the technological need for CRMs, EU industry, its environment and the quality and modern way of life is reliant on access and use of them.

(CRM Alliance, 2019)

The Waste Hierarchy



The waste hierarchy prioritises certain actions that must be carried out in order to minimise the amount of waste we produce as a society, on all levels. These set of priorities can be broken down into avoidance, resource recovery and lastly disposal. These are to apply to every level of society from the individual to large government, however, when it comes to disposal matters

become much more severe and should be undertaken by professional organisations to prevent environmental damage (EPA, 2017).

Avoidance

The avoidance stage of the hierarchy is the most important as it encourages the reduction of generation of waste, encouraging the community, industry and government to extract and use less virgin material. “The goal is to maximise efficiency and avoid unnecessary consumption” and ways to do that are:

- Selecting the items that use the fewest resources to fulfil its role and require the least amount of packaging
- Opting for resilient, long lasting products and avoiding disposable goods or single-use materials
- Buying products that are recycled, recyclable, repairable, refillable, reusable or biodegradable

Recovering Resources

The recovery stage focuses on maximising re-use, recycling, reprocessing and energy recovery. The resources that have been used would preferentially go on to be re-used without the need for further processing at the end of their life usage. Reuse is better for the planet than recycling because recycling involves processing and using up both energy and further material. Both re-use and recycling methods keep material within the productive economy and out of landfills. When either of these options is not feasible, there is a possibility to recover the energy form of the material. Although, not all materials can be recovered in this way meaning they must be sterilised and disposed of in a way that least impacts the environment.

Disposal

The final tier in the waste hierarchy is treatment and disposal. This option is reserved for those materials and substances that are hazardous to humans and cannot be safely recycled. Treatment and safe disposal is the most appropriate management option in these cases.

Waste Avoidance and Resource Recovery Act 2001

“This Act promotes waste avoidance and resource recovery to achieve a continual reduction in waste generation. The Act provides for the development of a state-wide Waste Strategy and introduces a scheme to promote extended producer responsibility for the life-cycle of a product” (EPA, 2017).

Recommendations for Advancing the Waste Hierarchy Structure

It has been suggested by The Environmentalist.com that a waste hierarchy with seven steps instead of five will decrease the percentage of material lost to disposal methods, like landfill or unregulated dumping. The new layout would differ from the old hierarchy by aiming to produce no waste at the disposal end and keep materials within the economy in one form or another; a ‘cradle to cradle’ approach rather than a cradle to grave one. The approach starts at remove, which is, in essence, questioning ‘Why is this material needed?’ and ‘Can this service be delivered by a different means?’; the next step being reduce just like for the present waste hierarchy. Re-source is the third step that encourages analysis of the resources used to consider alternate more ecological options. Reuse and recycle follow, which are obvious strategies for handling end-of-life products, reuse options being more preferential to recycling due to the higher energy consumption involved in most recycling processes. When materials cannot be reused or recycled part of the value they hold can be recovered through waste incineration and recovery as energy. This may mean that the economy loses out on the materials physical functionality, but their energy value is retained. Lastly, the materials are opted to be returned to the earth in an environmentally benign way, differing greatly from landfilling the unusable products. The aim at this stage would be to enrich the environment with these materials rather than burdening large areas with piles of it; this means

maintenance costs could be eliminated along with associated hazardous landfill risks like chemical leaks into the soil and gaseous build ups that release into the atmosphere.

The feasibility of the final step appears questionable as to whether it would wholly have a positive environmental impact or a negative one. The added processing that would be required to convert end of the line waste into neutral substances that can be returned to the soil would undoubtedly use much energy. Also, considering the capabilities of companies to continually distribute converted waste to fresh land seems like it would create more work. Although comparing this option with present landfilling for environmental impact and costing it may prove beneficial.

Factors Preventing Recycling

At present the business model for current recycling models is not robust enough. Ongoing growth in commercialized technologies is small as the profits made in these areas are small. In general, the products of recycling processes are less valuable than the untouched batteries prior to recycling and some of the most valuable components in the batteries are not being recovered from separation techniques.

The anode chemistries remain the same and differ between a handful of materials, but the cathode chemistries are constantly evolving making it difficult for companies who recycle Li-ion batteries.

New separation techniques have to be developed to account for the tweaked mixtures.

Government legislation for WEEE in Europe and America are attempting to keep up with the expanding battery industry, but in many countries there is no existing mandate for the recycling of them. Even though end-of-life LIBs are classified as hazardous and pose a serious threat to the environment (Heelan, 2016).

UK Laws and Legislation for WEEE

There are specific responsibilities for companies who sell electrical and electronic equipment (EEE) and dispose of five tonnes or more worth of WEEE. They must provide a means of disposal to their customers, and when they are selling a new version of the same unit, the older units must still be accepted for disposal. The waste electrical and electronic equipment (WEEE) regulations still apply regardless of how you sell the product, whether it is directly or indirectly through the internet, mail order and telephone.

You must either provide a free in store take back service or set up an alternative free take-back service. If you do not have your own take back service, you must join the distributor take-back scheme (DTS). Failure to comply with these regulations and you will be prosecuted.

Companies are required to provide free information to their customers on:

- Which take back service they provide
- How they can reuse and recycle electrical and electronic equipment
- Why this waste needs to be separated from other waste
- The damaging effects of not recycling electrical and electronic equipment
- The meaning of the crossed-out wheelie bin symbol

Shops can provide this information through posters and informational leaflets to describe the services and schemes they utilise. Also, information leaflets on the electronic goods that are sold.

Online retailers can publish this information on their website and if they are members of DTS they can get free customer downloadable information from the chosen scheme. The scheme provides set information to help producers determine what Government legislation requires them to do with WEEE.

If you are an EEE producer, you have other responsibilities. An EEE producer is one that:

- Manufactures and sells EEE under your own brand in the UK
- Import EEE into the UK on a commercial basis
- They are established outside of the UK and supply EEE directly to the UK market by distance selling; online, mail order or phone.

EEE producers: What Producers are Bound by Law to do with regards to disposal

If you place less than 5 tonnes of EEE on the UK market every calendar year/compliance year, then you can register directly with your environmental regulator and register as a small producer. If you place more than 5 tonnes of EEE then you must join a Producer Compliance Scheme (PCS).

Collection, treatment, recovery and environmentally sound disposal of WEEE must be financed and the PCS takes on these obligations.

EEE producers must also:

- Provide information on the reuse and environmentally sound treatment of the products and components.
- Make sure that the distributors you supply have your producer registration number.
- Mark products with the crossed-out wheelie bin symbol and a date mark.

According to the GOV.uk website producers should aim to improve design to facilitate recycling and reuse of components and materials.

If you produce more than one tonne of waste battery material on the market each year in the UK, then you must sign up to a Battery Compliance Scheme (BCS). You pay the BCS an annual fee and it takes on your duties.

What the BCS will do:

- Register you annually with the correct environmental regulator
- Pay the environmental regulator £600 annually for each member
- Send information to the regulator about the batteries you have placed on the market in the last two years and previous year
- Get evidence notes for the collection, treatment and recycling of waste batteries
- Send information to the regulator about the waste batteries they collect and deliver for treatment and recycling

Products placed on the UK market must have reported the weight of the EEE excluding the batteries and the weight of the batteries in the EEE.

There are different types of schemes based on whether you are a producer or a distributor. They work to protect the producers and distributors from prosecution and alleviate some of the manual work with relation to dealing with the environmental regulators (GOV.UK, 2016)

EU Legislation on Dealing With WEEE

WEEE has the potential to cause serious environmental and health problems, due to its hazardous content and diverse material make-up. It is important to note that the production of current electronics requires the use of CRMs and other scarce resources such as gold, and in 2014 roughly 15% of gold produced that year ended up in landfill. To cope with this global issue and contribute to a circular economy proper environmental management of the waste is mandatory. Improvements on the current collection, treatment and recycling of electronics will be key in eradicating WEEE pollution.

Two pieces of legislation have been put in place in the EU to address this wide issue: The Directive on waste electrical and electronic equipment (WEEE Directive) and the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS Directive). In December 2008, the Directive was revised for the purposes of tackling the rapidly increasing waste stream.

“EU legislation restricting the use of hazardous substances in electrical and electronic equipment (RoHS Directive 2002/95/EC) entered into force in February 2003. The legislation requires heavy metals such as lead, mercury, cadmium, and hexavalent chromium and flame retardants such as polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) to be substituted by safer alternatives. (European Commission, 2018)

In December 2008, the Directive was revised and the RoHS recast Directive 2011/65/EU became effective on the 3rd January 2013.” (European Commission, 2018)

To see the EU legislation on WEEE pertaining to its use and disposal treatment expectations visit appendix A.

Environmental Impact Assessment

The goal of an environmental impact assessment is to ascertain and gauge how impactful an activity is on the environment around it. By using severity ratings, the degree to which this activity degrades the environment can be assessed.

The complex nature of the earth’s atmosphere and its biological habitat is continually toyed with by large companies with the intent to destroy it for the sake of profit. Only monetary profit, however; in terms of world-wide consequences the effects are dramatically ‘unprofitable’, including to the companies who substantially add to the problem. People all over are passive and complacent in this system.

“Even with the continued rise of Li-ion battery development and commercialization, the recycling industry is lagging; approximately 95% of Li-ion batteries are landfilled instead of recycled upon reaching end of life” (Heelan, 2016)

Since 2016, efforts to recycle more LIB waste have been made, which has been backed up by legislation and numerous recycling schemes. However, large scale recycling is still far from being able to deal with global WEEE.

Life Cycle Assessment

An LCA is an important part of an environmental impact assessment, breaking apart the different stages of the chosen product’s life cycle to identify the resources, energies and fuels and polluting outputs from the related processes. By collecting information on the different life cycle stages, the assessor can accurately interpret which of them are essential and which have the potential to be switched out for more eco-friendly methods. To do this, a comprehensive view of alternative processing methods must also be built up and compared.

The life cycle can be broken down into these main stages:

- Extraction of materials
- Transportation
- Processing of materials

- Manufacturing of product
- Disposal and waste treatment

Inventory Analysis

Extraction of raw materials

Extracting raw materials for use in LIBs can create a number of polluting gases to be released into the atmosphere and chemicals leaked into the surrounding area. Cobalt cannot be extracted as a pure element rather it must be extracted as a by-product from other compounds, e.g. copper-cobalt sulphide concentrates, nickel-cobalt sulphide concentrates, copper-cobalt oxide concentrates.

When considering open pit mining for copper ore there are many outputs from the process like waste rock, tailings, spent ore, mine water and sludge. The activities involve tearing up large areas of ground to get at the desired mineral, clearing forests and habitat alike. The improper outlets for all of the by-products from mining involve dumping them into nearby rivers or lakes. These by-products can have a high propensity for leaching into water and soil in cases where they are moved into piles to rest on the ground. The leaching effect is amplified when rainwater arrives to mix with the compounds and carries this sludge mixture downstream or underground where it is stored in the soil.

Copper is ranked third amongst the five major basic metals for specific energy consumption making it a highly energy intensive extraction method. Somewhere between 0.086-0.112MJ of energy are spent extracting a single tonne of copper (Greenspec, 2019).

Aluminium is made from aluminium oxide, which is made from bauxite (aluminium ore). Extracting aluminium from aluminium oxide is done through electrolysis. For this process to take place the aluminium oxide must be made molten first but due to aluminium oxide's high melting point, this process would be insanely expensive. Therefore, to circumvent this issue, it is dissolved in an aluminium compound which melts at a lower temperature than aluminium oxide. Both the anode and cathode of this process are graphite (carbon) and the aluminium metal is drawn to the cathode and collects at the bottom; this is then tapped off as pure aluminium metal.

Transportation

The CRMs are transported from countries far outside the EU, having to be carried up to thousands of miles around coastlines and across vast oceans by cargo ships. Cargo ships can carry on average 8,000 containers at a time, although they vary in size vastly, and are quite efficient in comparison with trains, planes and trucks. Once goods have arrived into a port, they are transported by multiple

trucks to refining facilities where the materials are processed for product standard. These modes of transport burn fuels and release carbon dioxide, carbon monoxide and hydrocarbons.

Raw material processing

Processing the raw materials, generally, ores or chemical compounds, to manufacture battery grade material requires multiple types of processes for separate materials, with many stages to some processes. Methods like electrowinning and electrolysis are used to refine the compounds into purer forms of the element, and the purity standard depends on the desired properties. These processes can be energy intensive and also require mixtures of chemicals, which take energy to be created. The energy content that a material will consume to be made is around 110MJ/kg for copper and between 80-600MJ/kg for nickel depending on the quality and methods of refinement used (Materials Group, 2019).

Product usage

During the time that the battery is in use, it experiences a number of charge and discharge cycles until the charge capacity is worn from use and replaced. Every time a single charge cycle occurs energy is drawn from a socket connected to the national grid, which gets provided energy from a range of sources like combined cycle gas turbine (CCGT), renewable, solar, wind, nuclear and biomass. On average the energy consumed from these sources is 18.144MJ per annum for a single lithium-ion battery powered device. Of course, the size and power requirements vary from one application to another, but this focusses mainly on mobile phone batteries. Conversion from MJ to CO₂ is as follows;

Converting to kWh first, $18.144 \times 0.2778 = 5.04$

Next into kgCO₂, the equivalent weight of CO₂ that is produced from the consumption,
 $5.04 \times 0.5246 = 2.644\text{kg}$ of CO₂ per annum based on **grid electricity** conversion rates.

The use of fuels leads to emissions of carbon dioxide (CO₂) and small quantities of other greenhouse gases – including methane (CH₄) and nitrous oxide (N₂O) (Carbon Trust, 2011).

Waste treatment and disposal

Current Industrial Recycling Techniques

Several companies have developed predominately in North America and Europe to handle the flux of end-of-life batteries entering the waste stream every year (Table II). The majority of Li-ion batteries come from consumer electronics and electric/hybrid electric vehicles. The two major mechanisms for Li-ion battery recycling are pyrometallurgical and hydrometallurgical processes. Pyrometallurgical treatment uses high temperature smelting procedures to recover cobalt and nickel as alloys. Hydrometallurgical techniques use chemical leaching to facilitate materials recovery (Heelan, 2016).

Companies that recycle lithium-ion batteries include Retrie, Umicore, Recupyl, Xstrata Nickel, Batrec and Accurec. Their techniques for recycling LIBs make use of pyrometallurgical and metallurgical methods, or even combinations of the two to achieve as high a recovery rate as possible. The high-value metals are targeted for separation and extraction from plastics and other profitless materials.

Impact Assessment

Extraction of raw materials

The most common method of extraction for metals used to LIBs is open pit mining, and many outlets from these practices can be harmful to both the environment and people.

“Lithium-based batteries also require raw materials like cobalt, nickel and graphite, which further complicate the supply chain. Labour injustices in the extraction of cobalt are well documented. Over 20 percent of exports from the Democratic Republic of Congo, the world’s top producer, come from unregulated artisanal mines that often employ children. For raw materials like nickel and graphite, producing countries cope with water contamination and deforestation.” (Merchant, 2017)

In the case of copper mining aquatic life is adversely affected when the element finds its way into lakes and oceans connected to streams adjacent to mining sites causing elevated levels of copper. When chronic toxicity is occurring in aquatic communities, there are reductions in survival, reproduction and growth. Reduction in fish stocks could also lead to a knock-on effect in human populations who rely heavily on them for survival.

In small quantities, copper levels are essential for good health in humans but if ingested in high doses can cause nausea, vomiting and diarrhoea. Breathing in high levels of the element can cause throat and nose irritation.

“Very-high doses of copper can cause damage to the liver and kidneys and can even cause death” (U.S. Department of Health and Human Services, 2004, *cited in*, Greenspec, 2019)

“Measuring the energy content of a material is difficult, but includes:

- the energy required to collect/mine the material
- the energy required to refine, extract or synthesise it” (Materials Group, 2019)

Transportation

A single giant cargo ship pollutes as much as near to 50 million cars, produced by their enormous combustion engines which are 1000 times the size of a car engine. The types of pollution they produce, e.g. carbon dioxide, hydrocarbons and carbon monoxide etc. have an added effect to the

global warming of the planet as the molecules retain the heat sent from the sun. The entire shipping industry pollutes more than most small countries and 15 of the large containers equal the same amount of pollution as all of the cars in the world (Piesing, 2018).

Raw material processing

The impact that raw material processing has on the environment largely comes from the generation of energy for running them. Refining techniques tend to be high in energy demand and if the energy originates from non-renewable sources then there is an increase in the tonnes of pollutant gases expelled into the atmosphere. Effects such as acid rain, retained sunrays and weakened O-zone layer are caused through this.

Product Usage

The impact of usage of LIBs is sourced from the energy mix that keeps them powered. The only energy source that does not emit greenhouse gases into the atmosphere are renewables, and its carbon footprint only becomes 0 when it is generated on site (Carbon Trust, 2011). Manufacturing a kg of Li-ion battery takes energy equivalent to 1.6 kg of oil.

Waste Treatment and Disposal

The treatment of end-of-life LIB metals takes a lot of energy and only becomes profitable when there is a bulk continuous supply of them. Some processes are more energy intensive than others and this is why hydrometallurgical methods are more attractive because of the use of chemicals and solutions to achieve extraction from collected waste products rather than melt them at high temperatures.

Landfilling WEEE impacts the local area surrounding the landfill site and contributes polluting gases at a slow rate to the atmosphere. Due to the variance of complex materials and chemicals used in the production of electrical goods makes for a volatile mixture within the heaps on these sites.

Reactions

“Five common exothermic degradation reactions can occur:

- Chemical reduction of the electrolyte by the anode.
- Thermal decomposition of the electrolyte.
- Chemical oxidation of the electrolyte by the cathode.
- Thermal decomposition by the cathode and anode.
- Internal short circuit by charge effects.”

(Voelker, 2015)

FMEA of recycling processes

A failure mode effects analysis is a method for gauging impact in the hypothetical situation that one event or step in a process fails, and the system would be affected by this failure mode. FMEA is a reliability improvement method designed to help assess the flaws in a product or system and be able to identify the effects. The goal being to remove or diminish the possibility of failure.

There are two main kinds of commonly used FMEA: a process failure and mode and effects analysis and a design failure mode and effects analysis. A process FMEA takes apart the steps that make up a process and analyses what is likely to go wrong and how this might affect the results that the process is trying to achieve, and a design FMEA reviews a product or system to mark out where failure is likely to occur and what impact this will have on the consumer. Since it is the recycling process that is being assessed a process FMEA will be undertaken. The goal of which is to quality check the stages of recycling and verify, where necessary, the improvements that could be made.

Current Separation Methods

Current recycling methods that are designed to separate WEEE to extract primarily the Critical Raw Materials that hold more significant economic value than the rest of the battery composition.

Table 4
A summary of separating situation for the physical separation technologies (Ruan and Xu, 2016).

Physical separation method	Character of separation	Main advantages and disadvantages
Magnetic separation (MS)	Separation of ferrous metals	MS was most suitable separating steel or iron but not suitable for separating of non-ferrous metals
Eddy current separation (ECS)	Separation of ferrous and non-ferrous materials	ECS was encouraged to recover non-ferrous metallic particles and hard to separate ferrous metals/other metals
Air current separation (ACS)	Separation of light particles from heavy particles	Wind velocity, particle size, particle density, etc. were the critical influences for ACS
Corona electrostatic separation (CES)	Separate metallic particles (size from 0.2 mm to 1 mm) from non-metallic particles	The movement trajectory and collection position of metallic particles in CES were hard to predict and compute

(Lingen Zhang, 2016)

Magnetic Separation

“Mobile treatment plants are a typical application for permanent suspension magnets. Multipolar magnet systems and neodymium iron boron magnets increase the separating performance and efficiency. At the same time, the weight of permanent suspension magnets can be substantially reduced [...] Suspension magnets are often self-cleaning and equipped with a circular conveyor belt; the extracted iron is conveyed out of the magnetic field by carrier bars and then discharged” (Magnetic Separations, 2019).

WEEE waste is passed underneath through the magnetic stream of a powerful suspension magnet, capable of extracting only ferrous metals: usually iron and steel components. By removing metal

from the waste stream early on grinders, mills and other treatment equipment avoid damage from wear and tear.

Eddy Current Separation

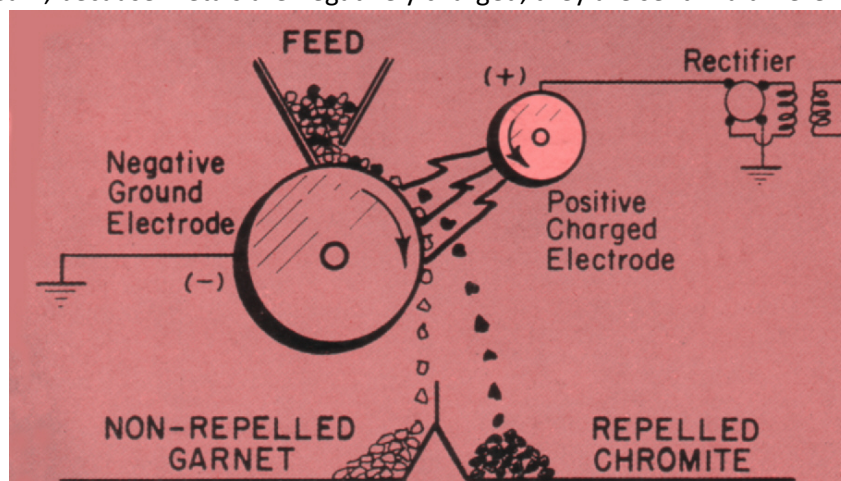
Eddy Current Separation (ECS) is a technique for separating metals and non-metals, the working method being based on Lenz's law. A rotating eddy current generator sends eddy currents through the non-ferrous pieces of metal which induces a magnetic field within the component that opposes that of the generator's field, so these metallic parts become repelled away from the conveyor belt that feeds the waste mixture. This technique allows for the formation of three different sorting streams; any non-metallic waste can fall under the force of gravity, and the ferrous metals are magnetically attracted to the belt so can be transferred to a separate collection point. Thus, allowing the separation and sorting of metals and non-metals (Morecambe Metals, 2017).

Air Current Separation

Air Current Separation (ACS) makes use of accelerated air currents inside a chamber with a conveyor belt carrying the waste stream to disrupt the direction of flow of lightweight materials, like paper, and barely altering the course of heavier weight parts like plastic bottles and metals. Air currents are sent from underneath the waste stream displacing the lightweight waste into the air where it falls onto another conveyor belt and into a separate collection point; the heavier parts fall under the weight of gravity into another channel.

Corona Electrostatic Separation

Corona Electrostatic Separation (CES) works in a similar way to ECS in that it makes use of electrostatic forces to separate out small metallic particles from non-metallic particles (0.2-1.0mm in size). "Electrostatic separations made with a corona device are called High Tension Separations" (Mine-Engineer, 2012). The process works by using electrostatic to repel metallic particles from the waste stream, because metals are negatively charged, they are sent in a different direction to that of



the non-metallic ones; although the movement trajectory of the metal is hard to predict making it a less reliable method.

Views on Recycling Technologies and the Current Recycling Model

“After a decade of effort, the recycling technologies for metals from WEEE have gained obvious improvements. However, there is no denying that current technologies still have some challenges for further promotion. For example, these new and novel recycling processes for metals are relatively single and dispersed. They are difficult to independently and efficiently separate metals from WEEE” (Lingen Zhang, 2016).

“There are three considerations that ought to be noticed and ensured for the future recycling technology innovation: (1) Technologies in the future should be prepared to face commercialisation, and suit for small and medium-sized enterprises in terms of investment or equipment; Further research should focus on the development of pilot scale tests to generate operational and cost data with the ultimate aim of commercialisation; (2) Single technology cannot solve all the problems because WEEE is a complicated system. So, recycling technologies would be more varied, and technology should be integrated according to the physical and chemical properties of all kinds of WEEE; (3) Future technologies should own high separation efficiency, recovery rate and greater sustainability” (Lingen Zhang, 2016).

Current Recycling Methods

Hydrometallurgy- Involves 3 distinct stages, which are leaching, solution concentration and purification and lastly metal recovery. It uses chemical combinations along with the use of water, oxygen and other substances to dissolve metal from its ore, concentrate or an intermediate product. To achieve higher purity beyond this requires further processing. The process uses a lot of water but is relatively eco-friendly when compared with similar technologies and does not liberate the same amount of polluting gases.

Pyrometallurgy- Uses high temperatures in a blast furnace to melt materials to a point where they can be refined from waste products into higher purity metals. The pyrometallurgical method of metal recovery has fast rates of processing material due to the high temperatures used, but this is also why it produces more green house gases making the option less preferential when regarding sustainability. For this reason, pyrometallurgy is being used less and less making hydrometallurgy the dominant method of practice for recycling LIBs.

Rating of Failure Modes

Drawing from sources, I will be using the severity, occurrence and detection ratings as laid out by Six Sigma (Six Sigma, 2019). The Six Sigma definitions lay out each degree of the rating scale that will be used to assess the WEEE recycling process and once ratings have been assigned to a failure mode a risk priority number (RPN) is calculable. An RPN number makes it easier to prioritise one failure mode over another, providing the FMEA with a clear focus at the end and valid recommendations for improvement can be made.

Severity Ratings

Severity Rankings			
Ranking	Effect	Design FMEA Severity	Process FMEA Severity
10	Hazardous-no warning	affects safe operation without warning	may endanger machine or operator without warning
9	Hazardous- w/ warning	affects safe operation with warning	may endanger machine or operator with warning
8	Very High	makes product inoperable	major disruption in operations (100% scrap)
7	High	makes product operable at reduced performance (customer dissatisfaction)	minor disruption in operations (may require sorting and some scrap)
6	Moderate	results in customer discomfort	minor disruption in operations (no sorting but some scrap)
5	Low	results in comfort and convenience at a reduced level	minor disruption in operations (portion may require rework)
4	Very Low	results in dissatisfaction by most customers.	minor disruption in operations (some sorting and portion may require rework)
3	Minor	results in dissatisfaction by average customer.	minor disruption (some rework but little affect on production rate)
2	Very Minor	results in dissatisfaction by few customers.	minor disruption (minimal affect on production rate)
1	None	No effect	No effect

Occurrence Ratings

Occurrence Rankings				
Ranking	Effect	Failure Rates	Percent Defective	Cpk
10	Extremely High	> 1 in 2	50%	Cpk < 0.33
9	Very High	1 in 3	33%	Cpk ~ 0.5
8	Very High	1 in 5	10-15%	Cpk ~ 0.75
7	High	1 in 20	5%	
6	Marginal	1 in 100	1%	
5	Marginal	1 in 400	0.25%	Cpk ~ 1
4	Unlikely	1 in 2000	0.05%	
3	Low	1 in 15,000	0.007%	Cpk > 1.33
2	Very Low	1 in 150,000	0.0007%	Cpk > 1.5
1	Remote	< 1 in 1,500,000	0.00007%	Cpk > 1.67

Detection Rating

Detection Rankings			
Ranking	Effect	Design FMEA Detection	Process FMEA Detection
10	Absolute uncertainty	No chance that design control will detect cause mechanism and subsequent failure.	No known process control to detect cause mechanism and subsequent failure.
9	Very remote	Very remote chance that design control will detect cause mechanism and subsequent failure.	
8	Remote	Remote chance that design control will detect cause mechanism and subsequent failure.	Remote chance that process control to detect cause mechanism and subsequent failure.
7	Very Low	Very low chance that design control will detect cause mechanism and subsequent failure.	
6	Low	Low chance that design control will detect cause mechanism and subsequent failure.	Low chance that process control to detect cause mechanism and subsequent failure.
5	Moderate	Moderate chance that design control will detect cause mechanism and subsequent failure.	
4	Moderately High	Moderately high chance that design control will detect cause mechanism and subsequent failure.	
3	High	very remote chance that design control will detect cause mechanism and subsequent failure.	High chance that process control to detect cause mechanism and subsequent failure.
2	Very High	Very high chance that design control will detect cause mechanism and subsequent failure.	
1	Almost Certain	Design control will almost certainly detect cause mechanism and subsequent failure.	Current control almost certain to detect cause mechanism and failure mode.

Failure Modes:

1. Collection points fail to correctly identify lithium-ion cells that are still usable meaning at least 80% of their charge capacity still remains. (Effects- Valuable products will be dismantled before their life-span has been fully utilized, which is a waste of energy gone into manufacture. Therefore, recycling treatment will take place instead of reuse options such as grid level storage systems (GSS).)
2. Metallic objects are not split up from non-metallic objects by the intended separation process and subsequent steps in the recycling chain are affected. Heavy weight particles become caught up in grinders designed for lighter/softer materials. (Effects- The machines that deal with waste after separation suffer wear and damage, potentially stopping the machines functioning. This will cause any further waste processing to be slowed or halted completely. The damaged machine will either have to be repaired or replaced depending on the level of damage; incurring costs to the treatment facility. Also, the contaminated stream is unable to be recycled then so it is taken to landfill; so, the impacts of landfilling are amplified)

3. Each separation technology used cannot on its own filter the multitude of components from a general waste stream 100% into their distinct categories of type and size. If unable to separate out particular streams, then more waste is sent to landfill and is unable to be identified for reuse or recycling. (Effects- Materials are lost from the economy and are no longer useful, so fresh materials must be extracted. As discussed in the LCA battery materials are mainly sourced overseas and their transportation accounts for a large proportion of greenhouse gases produced.)
4. The waste mixture contains a great degree of impurities due to poor separation prior to recycling treatment and so the treatment/refinement processes demands more energy to achieve the same quality of metal purity. (Effects- More energy is taken in by the process and as a result of the production methods of that energy there is a proportional amount of greenhouse gases produced. This adds to the effects of global warming and air pollution.
5. Lawful requirements to dispose of the final tier waste into a landfill is not fulfilled. Instead the waste is deposited onto a natural site or into a river, lake or sea. The uncontained WEEE is now free to stagnate and poison the immediate area or drift into open waters where it will contaminate animal or human drinking supplies. (Effects- Fish stocks are reduced as a consequence of polluted water and their reproduction rates could fall. Human populations living nearby to the dumped area may experience mild illnesses from ingestion of contaminated water; this is not a likely scenario in the UK where the majority of water is treated before human populations can consume it, however, a greater concern in third world countries.)

Failure Mode	Severity Rating	Occurrence Rating	Detection Rating	Risk Priority Number
1	5	6	3	90
2	7	5	4	140
3	5	7	2	70
4	3	5	3	45
5	8	2	5	80

Conclusions and Recommendations

The conclusions drawn from the life cycle assessment were that the activities associated with raw material extraction processes and transportation of those materials into the EU and UK had the greatest impact on the environment. Mining operations destroy acres of land in order to acquire the desired ore and the quality of health and safety practices vary widely from country to country, meaning the data analysed is a conservative estimate of the environmental effect they have. Emissions made by transportation are highly unsustainable and contribute to the greenhouse gas effect all year round. If focus can be directed on utilising the waste hierarchy to conserve materials in the economy, then the impact from attaining raw materials will be minimised. Although, this metaphorical gas bleeding can only be stemmed, as demand for electrical products rises more materials will have to be extracted eventually.

What was gathered from the FMEA was that the failure mode with the highest risk priority number was that linked with the separation techniques. The analysis revealed that a single separation process was unable to tackle the task of fully distinguishing between all of the components in WEEE, into their distinct streams of material type and size; RPN number of 140. A recommendation for tackling this issue would be to utilise multiple separation technologies in series of one another to filter and sort the waste streams into more identifiable recyclable products. Specifically, combinations of eddy current separation and air current separation techniques because of their reliability and predictability in results. Helping to mitigate the likelihood of inseparable electronic waste.

Appendix

Appendix A

DIRECTIVE 2012/19/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 4 July 2012
on waste electrical and electronic equipment (WEEE)
(recast)

(Text with EEA relevance)

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty on the Functioning of the European Union, and in particular Article 192(1) thereof,

Having regard to the proposal from the European Commission,

Having regard to the opinion of the European Economic and Social Committee [\(1\)](#),

Having regard to the opinion of the Committee of the Regions [\(2\)](#),

Acting in accordance with the ordinary legislative procedure [\(3\)](#),

Whereas:

(2)The objectives of the Union's environment policy are, in particular, to preserve, protect and improve the quality of the environment, to protect human health and to utilise natural resources prudently and rationally. That policy is based on the precautionary principle and the principles that preventive action should be taken, that environmental damage should, as a priority, be rectified at source and that the polluter should pay.

(3)The Community programme of policy and action in relation to the environment and sustainable development (Fifth Environmental Action Programme) [\(4\)](#) stated that the achievement of sustainable development calls for significant changes in current patterns of development, production, consumption and behaviour and advocates, inter alia, the reduction of wasteful consumption of natural resources and the prevention of pollution. It mentioned waste electrical and electronic equipment (WEEE) as one of the target areas to be regulated, in view of the application of the principles of prevention, recovery and safe disposal of waste.

(4)This Directive supplements the general waste management legislation of the Union, such as Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste [\(5\)](#). It refers to the definitions in that Directive, including the definitions of waste and general waste management operations. The definition of collection in Directive 2008/98/EC includes the preliminary sorting and preliminary

storage of waste for the purposes of transport to a waste treatment facility. Directive 2009/125/EC of the European Parliament and of the Council ⁽⁷⁾ establishes a framework for setting ecodesign requirements for energy-related products and enables the adoption of specific ecodesign requirements for energy-related products which may also be covered by this Directive. Directive 2009/125/EC and the implementing measures adopted pursuant thereto are without prejudice to the waste management legislation of the Union. Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment ⁽⁸⁾ requires the substitution of banned substances in respect of all electrical and electronic equipment (EEE) within its scope.

(European Commission, 2018)

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