Battery Recycling: Is it worth it?

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Abstract
An overview is given of the processes involved in recycling the various components of conventional portable batteries. These are assessed for their materials recovery rate, economic viability, and environmental impact. Nearly all metal content is recovered, but most of the rest is not valuable enough to recycle. Adverse effects on air, soil and water near battery recycling plants can mostly be avoided, however, the required measures are not always taken in developing countries. The battery industry will face challenges in the near future that require much greater throughput of battery recycling and more comprehensive collection of spent batteries from consumers.

Keywords: batteries, recycling, environment, pollution, economics

1. Introduction
The main aims of battery recycling at end-of-life are as follows:[1]
- To recover rare and valuable materials
- To save energy that would otherwise be used to mine and refine those materials
- To save landfill space, and to prevent heavy metals leaching from landfill into groundwater
- To prevent emission of dangerous substances into the air and soil, in the case of incineration

Despite the fact that certain materials used in batteries – cadmium, mercury, manganese, lead, nickel – have long been known to be toxic,[2] it was 1978 before a paper was published raising concerns over the degradation of batteries in landfill. The authors concluded that “the presence of domestic arisings of primary dry cell batteries in landfill presents no special threat to groundwater quality”![3]

Of greater concern in the 1970s and ‘80s was the danger to workers involved in the manufacture of batteries. Numerous publications highlighted the health risks to factory workers caused by inhalation, ingestion or dermal absorption of heavy metals.[4], [5], [6] Though studies were small and concluded that the dangers were caused by improper safety procedures, they indicate the preoccupation of the time.

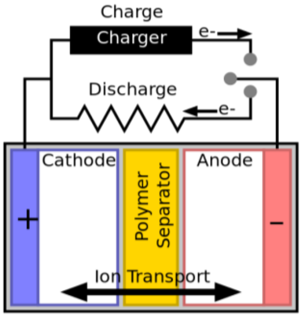
More recently Rydh and Karlström[7] have argued that the levels of heavy metals in landfill are a concern – they cannot degrade further than their elemental forms, and remain in the environment well beyond 100 years. Even small concentrations of heavy metals can accumulate in living organisms.

Meanwhile, the Clean Japan Centre had been developing a system to sort batteries and lightbulbs and recover the mercury contained in them, as well as zinc and scrap iron from the batteries.[8] Operations began in 1985 – a good few years ahead of the European Council’s directive of 1991 on batteries and accumulators containing certain dangerous substances.[9] The ‘90s saw much progress in development of processes to sort, separate, and recover valuable materials from used batteries.

After describing the structure and variety of batteries in Section 2, various recycling processes are discussed in Section 3. Costs, both economic and environmental, are analysed in Section 4. The future of battery recycling is speculated upon in Section 5. The conclusions are presented in Section 6.

2. Batteries: Structure and Variety
Batteries store chemical energy. This is discharged into electrical energy to power devices when a load is connected across the battery’s electrodes: a redox reaction at the negative electrode injects electrons into the circuit, while another redox reaction at the positive electrode absorbs electrons. The circuit is

completed by ion transport between the electrodes within the electrolyte (ion-conductive liquid or paste). A separator prevents short-circuiting between the electrodes. There may be several layers of electrodes and separators, or they may be rolled up into a cylinder. If an electrode material is not conductive enough, a pin and/or endcap is necessary. The entirety is contained within a package.[10]



Batteries may be categorised into primary (not rechargeable) and secondary (the products of the redox reaction are in a form such that the reactions can be reversed by applying a voltage across the electrodes, charging up the battery). Secondary batteries still degrade after a number of charge/recharge cycles, and also need to be recycled. The variety of battery chemistries is due to the demands for batteries for different applications: low cost of lead-acid batteries for starting automobiles, small size of lithium-ion for mobile phones, etc.

Figure 1 – Components of a Battery[11] (N.B.: separator need not be a polymer)

Table 1 – Different battery chemistries examined in this review.
Note that this is not a comprehensive list of battery types, nor of the materials contained within them.

Common Name	(+) Electrode	(-) Electrode	Electrolyte	Separator	Case	Additional End Products
Lead-acid, Pb-A [10] ch.23	PbO_2 paste (on Pb grid)	Pb (alloy grid)	Sulphuric acid, H_2SO_4 (aq)	PVC / other polymer	PVC / other polymer	$PbSO_4$, H_2O
Alkaline [10] ch.10	MnO_2 (mixed with C)	Zn powder (gel)	Potassium hydroxide, KOH (aq)	polymer	Steel, polymer seal, brass pin	ZnO, $Zn(OH)_2$, MnOOH, Mn_3O_4 , H_2O
Zinc-carbon, Zn-C [10] ch.8	MnO_2 (mixed with C)	Zn (the electrode is the casing)	Ammonium / zinc chloride NH_4Cl / $ZnCl_2$ (aq)	Paper / polymer	Paper, plastic, metal foil; tin-plated steel caps	ZnO, Mn_2O_3 , Mn_3O_4 , H_2O, Zn(OH)Cl
Nickel-cadmium, Ni-Cd [10] ch.28	$Ni(OH)_2$ (coated on Ni mesh)	Cd (paste/ deposited on Ni mesh)	KOH / NaOH (absorbed by separator)	Fabric / polymer	Ni-plated steel	NiOOH, $Cd(OH)_2$, H_2O
Nickel-Metal Hydride, NiMH [10] ch.29	$Ni(OH)_2$ (coated on Ni mesh)	M (metal alloy, e.g. $LaNi_5$, coated on Ni mesh)	KOH (absorbed by separator)	Fabric / polymer	Steel, paper, plastic	NiOOH, MH, H_2O
Lithium-ion [12]	e.g. $LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$ (paste, bound to Al with PVDF binder)	C (graphite paste deposited on Cu)	Li salts ($LiClO_4$, $LiBF_4$, $LiPF_6$) in organic solvent (gel)	Polymer	Steel, paper, plastic	Elements and groups that were in the electrodes and electrolyte

3. Methods of Battery Recycling

Recycling proceeds first by collection of used batteries, and transportation to a recycling facility. There, they are sorted into different streams – the processes used to separate the materials vary depending on battery type. Each process stream must be assessed for its economic value (compared to mining and processing raw materials) and its environmental value (how much is saved in terms of carbon emissions? Air pollution? Heavy metals entering the ecosystem?).

3.1 Pre-treatment: Collection, Transportation, Sorting

The average battery collection rate in the EU was a paltry 13.6% in 2009.[13] A lack of mature recycling infrastructure and market for recovered materials, along with lack of public awareness, lead to landfill disposal of many spent batteries, or more often hoarding.[14] Pb-A batteries are an exception, having a mature recycling route that began development as early as 1978.[15] Collection of Pb-A batteries exceeds 90% in many European countries,[16] and nowadays they are made of over 80% recycled materials, with a similar percentage of all lead sales destined for Pb-A batteries.[17]

Transportation of spent batteries contributes to greenhouse gas emissions and air pollution. It can take up to half the total energy cost of recycling, according to some life cycle analyses.[7], [18] However, that transportation would be needed whether the batteries went to a recycling centre or to landfill.

Sorting batteries is a labour-intensive process. A number of automated systems have been developed for recognising battery types.[19] It is unrealistic to expect consumers to sort their batteries into the many types before disposal. The ideal recycling system would accept any mixture of batteries. Indeed, the BATENUS,[20] Recytec[21] and BATINTREC[22] processes accept most portable batteries except Li-ion, and research is being done into the processing of NiMH and Li-ion together.[23], [24]

3.3 Separation of Components

To expose constituent parts, batteries are shredded or crushed using knife mills or hammer mills.[17], [20], [21], [23], [25], [26] Li-ion batteries are at risk of fire during this step (and indeed if exposed to moisture while corroding) – techniques proposed to reduce this risk include cryogenic freezing before crushing,[27] and cutting open the batteries with a high-pressure water jet under an inert atmosphere.[28]

Differences in physical and chemical properties of battery components are exploited to separate them:

- density relative to water (paper and plastics from separators and casings float on water and can be skimmed off, while metal compounds sink[17], [20], [25])
- magnetism (steel in the casing is recovered and sold as scrap,[21], [26] while nickel and cobalt are less strongly magnetic and can be separated in multiple stages[26])
- behaviour when heated in a reducing environment (i.e. pyrometallurgy, to obtain lead from Pb-A batteries,[17] ferromanganese from Zn-C and alkaline, and to vaporise contaminants[29])
- solubility in certain leaching agents (ammonium sulphate for Pb-A, sulphuric or nitric acid for the other types[12], [20], [22], [23], [26]) and reactiveness to precipitating agents (i.e. hydrometallurgy – after pre-washing, ball-milling to powder, chemical treatment and filtering, Pb-A batteries yield lead carbonate and sodium sulphate or calcium sulphate (gypsum);[17], [25] iron and rare earths are obtainable from NiMH; copper, cobalt and nickel from Ni-Cd, NiMH and Li-ion;[23] good-quality ferrite or ferromanganese is the result of processing alkaline and Zn-C batteries[20], [22])
- ability of solutions to permeate selective ion exchange membranes (as used in BATENUS[20])
- electrochemical properties (using electrowinning to extract metals[25]).

Industrial-scale battery recycling invariably requires some combination of the above procedures. The emissions from pyrometallurgy must be cleaned – with alkaline scrubbers, active carbon filters, or electrostatic precipitation – otherwise it is as bad for the air and soil as incinerating the batteries. Mercury, though its use is more restricted now, still infiltrates the recycling stream particularly in very old batteries, and can be recovered by distilling.[17], [20], [22], [29] Precautions are also needed to remove contaminants from hydrometallurgy wastewater and dilute it to a safe level before discharge.

Certain materials are particularly hard to recover – especially manganese,[13], [30] and PVDF polymer binder.[12] If much recycled material is used to make more of the same batteries, it may make sense not to refine them too much, but to leave them closer to the state they will be in the batteries.[17], [18], [31]

3.3 Dealing with the Remainder

Certain by-products of battery recycling are not recovered as the cost of doing so exceeds their market value. The goal is then to reduce the harm they can do to the environment:

- paper and some plastics are incinerated, with exhaust gases filtered of air pollutants - but not CO_2
- acids and alkalis are neutralised, diluted, cleaned and discharged into waterways
- metals too difficult to recover (manganese, rare earths) or too cheap on the world market (cadmium, lithium) may end up in slag which is used as a construction material on landfill sites

It is debatable whether the production of contaminated slag and the generation of energy from exothermic incineration count as recycling.

4. Analysis of Costs

Even though the energy cost of recycling a battery is a significant fraction of that needed to produce it,[18] it is still less energy-intensive to make batteries from recycled rather than virgin materials (for example, 16% less for Ni-Cd).[7] Recycling is good news for cutting carbon emissions.

More often than not battery recycling is a loss-making activity. For example, in Switzerland the cost of recycling in 1995 was 4750 Swiss francs per ton, compared to 770 per ton to send to landfill.[32] Marketable by-products (secondary metals, gypsum from Pb-A, ferrite from Zn-C and alkaline batteries) reduce the losses only somewhat.

Furthermore, battery recycling falls short when it comes to the proportion of materials recovered. Despite close to 100% recovery rates for some metals (filtrate and exhaust are routinely fed back through the system multiple times),[22], [23], [30] around half the weight of batteries goes un-recovered as it is not economical to do much better.[33] However, this may not matter because it is low-value materials that are lost – scarcity will provide the incentive to improve materials recovery if needed. And as long as the financing is sustainable, no matter what markets or financial mechanism it comes from, what remains is to meet the goal of environmental protection.

The problem is that this goal is not met in many parts of the world. Where in the ‘70s the research focused on health and environmental impacts of battery manufacture, now the same concerns are raised for battery recycling. Despite the Basel Convention of 1992 which restricts the export of spent batteries to countries that cannot guarantee environmentally sound recycling practices,[34] battery repair has become a widespread cottage industry in certain regions of Africa[35], [36] and the West Indies,[37] leading to dangerous blood lead levels in their populations. In light of this, one may ask, if spent batteries mustn’t be landfilled or incinerated, and if it is unsafe to recycle them, might it be better to put them into safe storage until circumstances change?[2]

5. Future Outlook

The battery industry is likely to see some drastic changes in the near future:

1. An explosion in phone ownership, and increasing frequency of discarding obsolete devices
2. The electrification of transport
3. A growing need for backup Grid storage due to penetration by intermittent renewable sources[38]

Only the first trend is certain; the other two depend on global willingness to meet carbon emissions reduction targets. Even so, an increase in battery production can be expected, with corresponding generation of spent batteries. Far from being an environmental calamity, such a growth in inputs to battery recycling operations might possibly make them more productive and economical.

Throughout the history of battery manufacture the different types have waxed and waned in market share. New battery chemistries – perhaps aluminium-ion, or lithium-air – may come to challenge the adaptability of battery recycling processes. On the other hand, they are an opportunity to design recyclability in from the start. It will be difficult to juggle yet another factor that will compromise quality, but in today’s sustainability-conscious world, it is a challenge that all engineers must face.

6. Conclusions

Except for a reduction in energy use compared to making new batteries, battery recycling is not as successful as the public awareness campaigns often (must) suggest. Collection rates are low, much material goes un-recovered, processes are unprofitable, and poor environmental protection standards in some countries lead to public health issues. However, the alternatives to battery recycling are also unpalatable: pollution would still occur at landfill sites and incineration plants, and safe storage of spent batteries is not sustainable, especially given the increase in battery production and disposal to be expected in the near future (as well as all the other things that will need disposal or sequestration: solar panels, nuclear waste, CO_2 , etc.). A better solution would be to tackle the existing problems of battery recycling.

A good start is greater provision of battery collection points in workplaces and supermarkets (as is happening in the UK today). The hoarding of spent batteries may be a sign of public awareness of the dangers of sending them to landfill while not knowing how to safely dispose of them. It may also be worth providing recycling services not just free of charge to the consumer, but to actually pay for the return of batteries. One option for funding this is an international levy on battery sales and imports, an extension of the Swiss BESO levy[32] – but in anticipation of people clamouring to return their hoarded batteries, the levy may need to be mandatory, and larger. Regulations must still go hand-in-hand with provisions to ease compliance – otherwise the result may be illegal dumping of batteries.[39]

The technical challenges remaining in battery recycling are not insurmountable. Ingenious solutions have been and continue to be found for extracting metals, and preventing fire risk while dismantling Li-ion batteries. Secondary materials that go un-recovered today may one day become productive income streams as extraction techniques improve, common metals become scarcer, and more batteries enter the recycling stream. Then again, metals that fetch a good price today might fall in value when recycling operations increase output.

Interestingly, the BATENUS plant initially required more energy to obtain secondary material than was needed to refine the same amount from virgin sources.[20] This could be seen to demonstrate the role of governance and public will in addition to bare economics. There exist international organisations that oversee battery recycling – the European Battery Recycling Association,[40] and the Portable Rechargeable Battery Association (a non-profit trade association of five battery manufacturers in the USA, Japan and Germany)[41] – however, there is no such active organisation in Africa and the rest of Asia. A lot of good could be done by establishing a global trade association to provide guidance and resources to help comply with regulations in all these regions.[35], [36]

Is battery recycling worth it? Yes and no, with much room for improvement.

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