OAKDENE HOLLINS

NOVEL LEAD RECYCLING TECHNOLOGY

Techno-economic and Environmental Evaluation

for

Cambridge Enterprise Ltd

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Executive Summary

A novel lead paste recycling technology has been developed by Dr R. Vasant Kumar at the Department of Materials Science and Metallurgy at the University of Cambridge. The competitive position of the new technology compared to existing technologies, especially in economic, environmental, carbon and energy saving and capital costing of a pilot plant, along with market research in selective countries and market entry strategies, was investigated.

The new technology has low carbon potential along with cost advantages in principle against the existing pyrometallurgical lead recycling plants. Its competitiveness largely depends on the low cost availability of consumables, mainly citric acid and sodium citrate. We conclude the following from this study:

- A number of criteria were developed and suggested for a viable market entry strategy for the implementation of this new technology, i.e. emerging enforcement of legislation, a trusted partner with an existing lead infrastructure, availability of consumables such as citric acid and sodium citrate at low cost and growing market potential for battery use.
- A pilot plant with one tonne per day of scrap battery is scalable and achievable at around $290,000.
- Among the countries researched, China and Turkey hold greatest promise for a pilot plant or implementation of full scale technology.

Further discussions are recommended with the battery manufacturers to cater for their needs in terms of the specifications of the final saleable product. Further potential exploitation or value addition opportunities also exist through the possible benefits of the final product (particle size, uniformity) to the battery manufacturer from efficiency improvements on batteries.

Abbreviations

BAT	Best Available Techniques
BEST	Better Environmental Sustainability Targets
BHMR	Battery Handling & Management Rules (India)
CO_2	Carbon Dioxide
EUROBAT	European Storage Battery Manufacturers Association
Fe	Iron
GRI	Global Reporting Initiative
HEV	Hybrid Electrical Vehicle
H_2SiF_6	Fluorosilicic Acid
H_2SO_4	Sulphuric Acid
HBF_4	Fluoroboric Acid
HCl	Hydrochloric Acid
IARC	International Agency for Research on Cancer
ILZSG	International Lead & Zinc Study Group
ktpa	Kilotonne per annum (capacity)
KWh	Kilowatt-Hour
LDA	Lead Development Association
LME	London Metal Exchange
Li-Ion	Lithium Ion (Battery)
mtpa	Millions of Tonnes per Annum
µg/l	Microgrammes per Litre
µg/dL	Microgrammes per Decilitre
Na_2CO_3	Sodium Carbonate
Na_2SO_4	Sodium Sulphate
NaOH	Sodium Hydroxide
Ni/Cd	Nickel-Cadmium (Battery)
NiMeH	Nickel-Metal Hydride (Battery)
NO_x	Nitrogen Oxides
OECD	Organization for Economic Cooperation and Development
OEM	Original Equipment Manufacturer
OK International	Occupational Knowledge International
PE	Polyethylene
Pb	Lead
$Pb(OH)_2$	Lead Hydroxide
$PbCO_3$	Lead Carbonate
PbO	Lead Monoxide
PbO_2	Lead Dioxide
$PbSO_4$	Lead Sulphate
PVC	Polyvinyl Chloride
RAPS	Remote Area Power Supply
RIR	Recycling Input Ratios
Sb	Antimony

SLI	Starting, Lighting and Ignition
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxides
tpa	Tonnes per Annum
UNECE	United Nations Economic Commission for Europe
WEEE	Waste Electrical and Electronic Equipment
Wh	Watt-Hour

1 Introduction

Lead is one of the most efficiently recycled metal commodities. Up to 90% of the lead from a scrap battery can be recovered and re-used to make new batteries, but conventional pyrometallurgical recycling technologies have a number of environmental impacts.

The lead acid battery is the world's most widely used electrochemical system (see Appendix 1 for a basic description); according to EUROBAT (the European Storage Battery Manufacturers Association), 70% of rechargeable batteries are lead acid batteries[a]. Rechargeable batteries are used in a wide range of automotive, industrial and portable applications (Table 1).

Table 1: Main applications for rechargeable batteries

Automotive applications (53% of the market)	Industrial applications (21% of market)	Portable applications (26% of market)
SLI batteries in conventional vehicles	Telecommunication systems	Utility vehicles
Powering electric vehicles	Emergency lighting systems	Tow tractors
Part-powering hybrid vehicles	Data communication systems	Trucks
	Security systems	Passenger carriers
	Cranking power for aircraft, railway locomotives and boats	Material handling equipment
	Railway crossing lights, gates and signals	Floor scrubbers
	Security energy for railway equipment, aircraft equipment	Airport ground equipments
		Golf carts, wheelchairs,

Source: EUROBAT.

Dr R. Vasant Kumar at the University of Cambridge's Department of Materials Science and Metallurgy has developed a novel lead paste recycling technology[b]. The new (hydrometallurgical) process potentially has less environmental impact than, and is technically superior to, existing

[a] Other rechargeable technologies include Ni/CD (Nickel-Cadmium), NiMeH (Nickel-Metal Hydride) and Li-Ion (Lithium Ion) batteries.
[b] The present innovation is described in detail in the UK priority patent application 0622249.1 filed on 8 November 2006.

recycling processes. Cambridge's innovation has only been carried out on a laboratory scale, so it is important to establish how such benefits would be translated to industrial-scale applications.

Consultants Oakdene Hollins Ltd have been asked to investigate the competitive position of the new technology with respect to existing lead acid battery recycling technologies, especially in technical terms. The potential carbon and energy savings obtained by using the new technology are also determined, as are any legislative and environmental issues arising from it. The capital and running costs for a pilot plant based on the new technology are estimated. Finally, an international market-entry strategy is developed.

2 Existing lead acid battery recycling technology

Currently, lead acid batteries are recycled using a high-temperature, pyrometallurgical process (Figure 1). Lead recyclers in the western world tend to have a large capacity. A 10kt per annum plant would be deemed small, with some plants processing 100kt or even 200kt of secondary lead per annum.

The process stages are as follows:

- **Collection:** At repair workshops, garages, decontamination centres, clean points. The batteries and other lead-containing scrap are consolidated at intermediate agents or scrap dealers.
- **Transportation**
- **Materials p reparation and sorting**
- **Breakage:** Lead acid batteries are composed of a variety of materials (Table 2).

Table 2: Typical composition of lead acid battery

Component	Wt %
Lead-antimony alloy components (i.e. grids, poles, etc.)	25 – 30
Electrode paste	35 - 45
Sulphuric acid	10 – 15
Polypropylene	4 – 8
Other plastics (e.g. PVC, PE, etc.)	2 – 7
Ebonite	1 – 3
Other (e.g. Glass, etc.)	< 0.5

Source: EC 2001. Integrated Pollution Prevention and Control (IPPC). Reference Document on Best Available Techniques (BAT) in the Non Ferrous Metals Industries.

- Scrap batteries are broken apart in a hammer mill. The plastic casing (typically made of polypropylene, ebonite and/or PVC) is shredded and recycled at extrusion plants. The sulphuric acid is also recovered and used in processes such as the manufacture of gypsum[a]. Meanwhile, paste comprising lead sulphate ($PbSO_4$), as well as the lead metallic grids is extracted. In conventional lead recycling, the grids are normally added to the smelter, however this is not always necessary,

[a] This occurs at the Enthoven plant in Derbyshire, UK

and instead can be melted and refined at lower temperatures. Table 3 shows the typical composition of the lead acid paste.

Table 3: Typical composition of lead acid battery paste

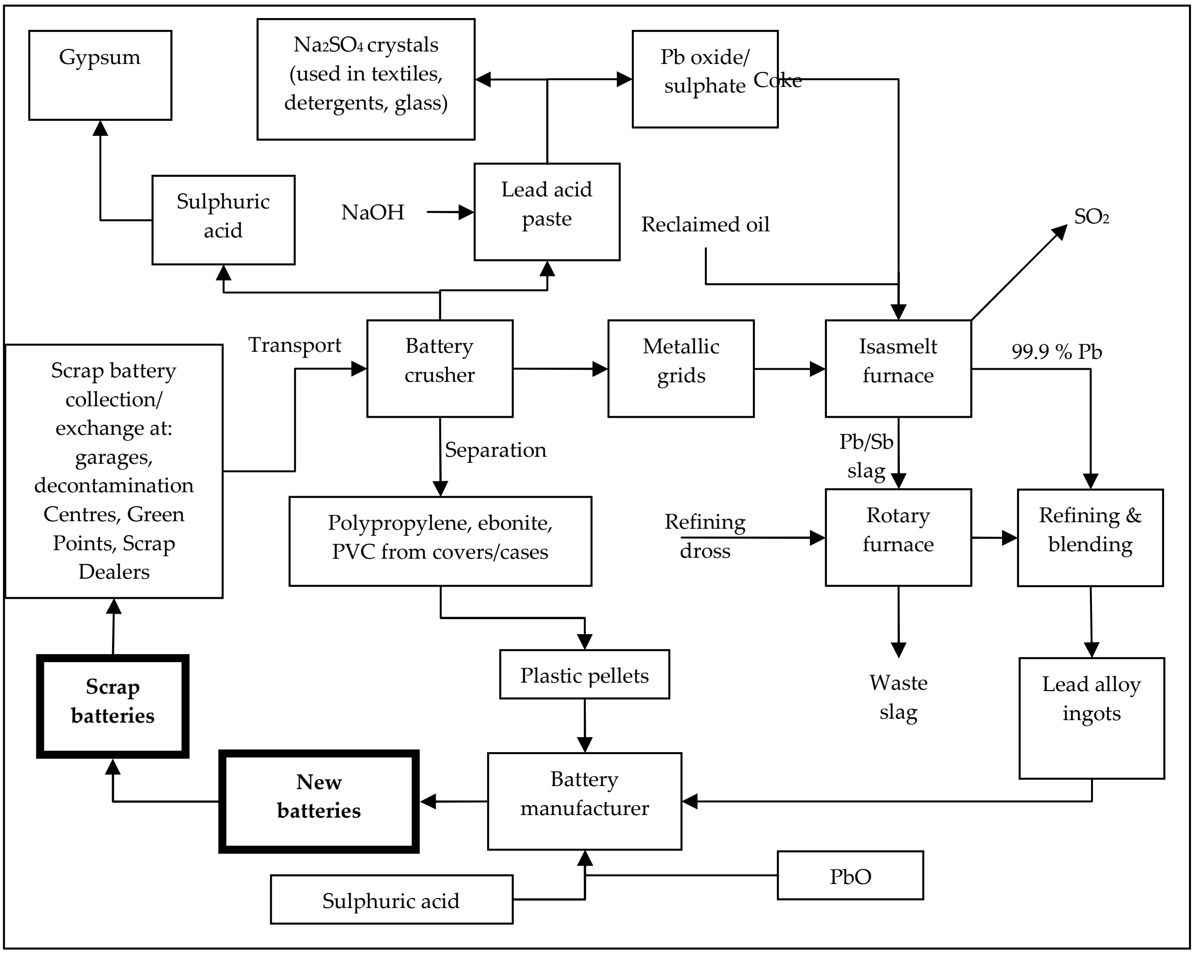
Material	Wt %
Lead sulphate	55-65
Lead dioxide	15-40
Lead monoxide	5-25
Metallic lead	1-5
Carbon black, plastics, fibres, other sulphates	1-4

Source: Kumar *et al.*

- **Neutralisation:** Sodium hydroxide is added to the discharged battery paste to neutralise residual sulphuric acid and desulphurise, which avoids sulphur dioxide (SO_2) emissions during smelting. Aqueous sodium sulphate, possibly containing some residual dissolved lead (II) together with colloidal particles is then discharged. Depending on the country, the consent concentrations for this discharge to sewers range from a few ppm down to zero; the upper limits are likely to be decreased in the future[a].
- **Smelting or Electrowinning:** The dry neutralised paste is usually smelted, along with the metallic grids, with a reducing agent in a high temperature Isasmelt or reverbatory or rotary furnace to produce lead. Coal or coke is the source of energy. The smelting takes place either in stand-alone reactors, or more often with lead concentrates derived from lead sulphide ores. Any lead or antimony slag is re-heated with refining dross in a rotary furnace producing lead-antimony (Pb/Sb) alloy and waste slag. Instead of smelting, some large-scale operations dissolve the lead sludge/filter-cake in powerful acids such as HCl, H_2SiF_6 or HBF_4 and recover lead by electrowinning.
- **Refining & Blending:** A finished alloy is produced by adding the Pb/Sb alloy to the almost-pure lead metal in a refining and blending process.
- **Transport:** Assuming recycling and manufacture plants are separate entities, the lead then must be transported from the former to the latter.
- **New battery manufacture:** Recovered lead is re-oxidised to PbO granules. Sulphuric acid (H_2SO_4) is added to the granules to form a paste applied to lead grids to manufacture new battery electrodes. After battery assembly, electrical energy is used to convert PbO to Pb in the anode and PbO_2 in the cathode.

[a] e.g. Brandon, N.P., Pilone, D., Kelsall, G.H., & Yin, Q., 2003. Simultaneous recovery of Pb and PbO_2 from battery plant effluents. Part II. Journal of Applied Electrochemistry, 33, 853–862.

Figure 1: Overview of the current lead acid battery recycling process flow



Source: Adapted from: Brandon *et al.* 2003; Exide/GNB Technologies Poster ("*Recycling for a Better Environment"*)

3 Lead acid battery flows

3.1 The Global Picture

3.1.1 Global Flows

Today, the global market for lead is now around US $1billion for mined ores and US $15billion for refined metal[a]. Despite the phasing out of dissipative applications of lead (e.g. as gasoline additives, in paints and solders, in ammunition), global consumption has been rising steadily for decades. In 1962, world demand stood at around 3.4 mtpa[b], in 1988 the figure was 5.6 mtpa, and in 2008 it is predicted to reach 8.6 mtpa[c]. Demand has risen in most countries.

The rise in consumption has resulted from the soaring demand for lead acid batteries. In 1960 batteries accounted for just 27% of lead end uses[d]; in early 2008, the ILZSG estimated that 82% of world consumption of lead is now used in this application[e]. Although demand for lead (and batteries) has increased steadily in many countries, the growth in China's economy since the mid-1990s has been the main driver.

Over 400 million batteries are now produced each year worldwide, with a market value of US$25bn[f]. Most are used for SLI[g] applications in the automotive sector, but also for traction as in milk floats, and for emergency power. The lead acid battery industry is also hoping to expand into the hybrid electrical vehicle (HEV) and remote area power supply (RAPS) sectors[h]. The automotive battery industry is fragmented, but key global players include Johnson Controls International (JCI) with 34% of market, Exide (14%) and GS Yuasa (10%)[i]. JCI has consolidated Delphi, Varta, Hoppecke and Gruppo Imsa businesses. In Europe, FIAMM, Banner, Moll, Midac and Mutlu have a major presence, while East Penn is the largest

[a] **International Lead Association**. *Lead Action 21. The Evolution of an Element.* Brochure.
[b] **White., P.** 2008. *Lead – A change in dynamics.* International Lead & Zinc Study Group. Presentation. *Metal Bulletin* International Lead Conference, London.
[c] **Cauley, I.,** 2008. *The art of primary lead smelting in today's competitive global environment.* Nyrstar, Australia. Presentation. *Metal Bulletin* International Lead Conference, London.
[d] **Cauley, I.,** 2008. *The art of primary lead smelting in today's competitive global environment.* Nyrstar, Australia. Presentation. *Metal Bulletin* International Lead Conference, London.
[e] **Karpel, S.,** 2008. Lead also rises. *Metal Bulletin Monthly*, Feb. pp26-30.
[f] **Kumar, R.V., Sonmez, S., & Yang, J.,** Sustainability of automotive batteries. *Unpublished Research*
[g] **S-**tarting the vehicle; **L-**ighting, etc. in the vehicle; and **I-**gniting the fuel.
[h] **Wilson, D.N.,** 2008. *Lead and the environment: Regulation and responsibility.* Lead Development Association. Presentation. *Metal Bulletin* International Lead Conference, London.
[i] **May. G.,** 2008. *Can the battery industry prosper with high and volatile lead prices?* FOCUS Consulting. Presentation. *Metal Bulletin* International Lead Conference, London.

North American-based company. In the Asia-Pacific region major companies include: Matsushita (Japan), Furukawa (Japan), Coslight (China), Exide Industries, Amara Raja (India) and AtlasBX (Korea).

Battery demand is expected to continue for the foreseeable future as the world market for cars shows little sign of slowing. Global production of light vehicles is predicted to rise from 66m in 2004 to 88m in 2014 according to JD Power Automotive Forecasting[a]. Moreover, the lack of suitable lead substitutes, the use of lead acid batteries in new hybrid technologies, and their potential in future automotive technologies[b], all ensure that the world's - and especially China's - appetite for the metal will remain high in the medium-term. In 2012, over 95% of all lead (10 mtpa) is predicted to be used in batteries for vehicles and emergency power supplies[c].

Due to the high value of lead and the relative ease with which the metal can be recovered, lead acid batteries are one of the most efficiently recycled products in the world – albeit with varying environmental standards. In developed nations a variety of organised schemes are in operation. For example, Sweden, Germany and Italy operate levy systems related to the lead market: when the lead price is so low that battery recovery is uneconomic, a levy is imposed on new batteries to finance recycling of used batteries. Italy and Ireland also have a national collection and recycling schemes. In the United States, many states require retailers to accept used car batteries when customers purchase new batteries. Several American states even require a cash deposit on new battery purchases which is refunded to the consumer once the used battery is returned to the retailer[d]. Elsewhere, battery collection is normally market driven[e]. In the UK, for example, where organised systems do not exist, car repair shops and scrap metal dealers collect used batteries.

Some claim the absence of formalized battery collection systems at the national level in the developing world causes battery recyclers there to seek illegal imports of scrap batteries as a cheap source of lead[f]. However, the widespread dumping of scrap lead acid batteries – and loss of lead from the domestic economy - in these poorer countries seems improbable. Given the lead's high value, even an informal infrastructure is likely to be highly efficient in getting used batteries back to smelters for secondary lead recovery.

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[a] **Karpel, S.,** 2008. Lead also rises. *Metal Bulletin Monthly*, Feb. pp26-30.
[b] The Advanced Lead Acid Battery Consortium recently completed a 100,000 mile test drive of a Honda Insight in the UK on lead acid battery power.
[c] **Kumar, R.V., Sonmez, S., & Yang, J.,** Sustainability of automotive batteries. *Unpublished Research*
[d] Basel Action Network. Lead Astray Again: The Ongoing Illegal Trade of U.S. Scrap Lead Acid Batteries to Brazil. http://www.ban.org/Library/lead_astray.html
[e] Ian Burrell, ILZSG
[f] Basel Action Network. Lead Astray Again: The Ongoing Illegal Trade of U.S. Scrap Lead Acid Batteries to Brazil. http://www.ban.org/Library/lead_astray.html

Over 90% of the lead from batteries can be extracted and re-used[a], so with such high recovery rates, the secondary lead production is now a huge business. According to official estimates, more than 40% of the world's refined lead is now derived from secondary production. Table 1 presents some recycling input ratios (RIR) around the world. RIR quantify the contribution recovered lead makes to overall production of refined metal.

Table 1: Apparent Recycling Input Ratios (RIR) for lead in 2006

Region	RIR
Europe	62.7%
Americas	74.2%
Asia	15.7%
World	41.6%

Source: Wilson, D., Burrell, I., & White, P., *Recycling ratios for lead.* Powerpoint Presentation. LDA International/ILZSG

These RIR figures are based on official data collected from governments around the world. As such they are likely to underestimate true lead recovery rates because in many countries, especially in the developing world, the informal nature of lead recycling makes obtaining reliable data on secondary lead usage impossible. This is particularly true for Asian countries: lead is so highly prized here that it is likely that almost 100% of the metal from batteries is reused[b]. The ILZSG has produced a directory of nearly 200 dedicated secondary lead smelters around the world, but the true number is probably far higher; China alone may have as many as 500[c].

In the western world, primary lead production has declined in favour of steady growth in secondary production. For example, just four primary lead smelters versus thirty secondary smelters now operate in the EU[d]. Instead, primary lead production has now shifted to the developing world where there are laxer environmental standards and less enforcement capacitye. This is especially true for China which, in 2007, supplied 35% of the world's lead metal supply, up from 12% in 1997 (Figure 2).

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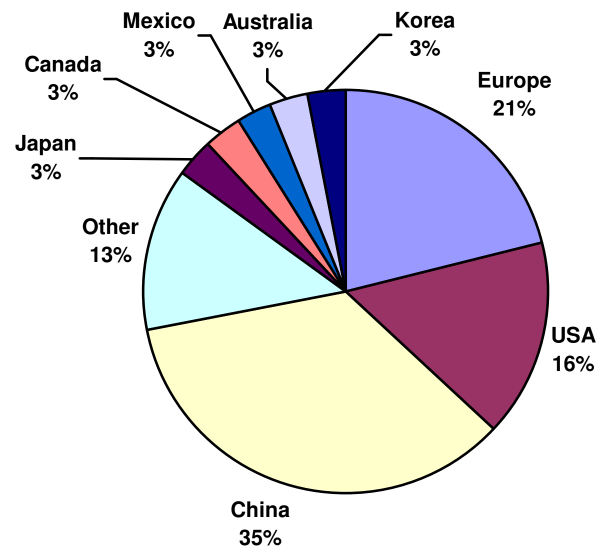
[a] **Kumar, R.V., Sonmez, S., & Yang, J.,** Sustainability of automotive batteries. *Unpublished Research*.
[b] David Wilson, Lead Development Association, Personal Communication.
[c] **Wilson, D.N.,** 2008. *Lead and the environment: Regulation and responsibility.* Lead Development Association. Presentation. *Metal Bulletin* International Lead Conference, London.
[d] **Frias, C.,** 2008. *It's time for clean lead mine production – seeking new technology options.* Técnicas Reunidas. Presentation. *Metal Bulletin* International Lead Conference, London.
[e] Occupational Knowledge International. http://www.okinternational.org/battery_facts.html

Figure 2: Distribution of lead metal supply 2007



Source: ILZSG

Among nine new major primary smelter projects currently "commissioned, committed and under construction", only one - the Magellan plant in Western Australia - is located outside China.

3.1.2 Global Regulation

Harmonised standards applying to lead at the international level have been pursued by the following organisations:

- UN Economic Commission for Europe (UNECE);
- UN Conference on Trade and Development - has worked with the lead industry on voluntary risk management projects
- International Agency for Research on Cancer (IARC);
- Organization for Economic Cooperation and Development (OECD).

Initiatives developed include[a]:

- general codes of conduct (e.g. UN Global Compact);
- management practices (e.g. ISO 14001),
- disclosure programmes such as the Global Reporting Initiative (GRI) have been developed.

[a] http://www.okinternational.org/lead.html

Historically, legislation was mainly driven by standards developed in the USA, particularly by the US Environmental Protection Agency (EPA), but today the European Union has become the driving force, along with Conventions, Protocols and Agreements adopted by intergovernmental organisations. In 2000, the lead industry volunteered to fund a €4m risk assessment on environmental, health and waste issues in conjunction with the European Commission and EU governments. Reports were submitted to the European Chemicals Bureau in 2005. The EU Scientific Committee on Health and Environmental Risks is also in the process of reviewing it[a] (but the results are not yet in).

At national level, even in the western world, no uniform limits apply to direct emissions from lead smelters or to other impacts from battery breaking and lead recycling plants. Instead, lead recyclers agree limits with regulatory bodies on a plant-by-plant basis depending on the specific local conditions of their intended operation, often under IPPC (Integrated Pollution Prevention and Control) frameworks. For example, limits for a plant close to where people live will be tighter than those applied to a factory away from dense human habitation.

Lead in Blood

Any set rules that do exist tend to apply indirectly to the effects of lead industry activities. Lead in the blood of lead workers, and the public at large is a prime concern as a health hazard. Allowable blood lead limits vary from country to country. In the USA, the legal limit is 50 μg/dL, but industry has a long-standing agreement by which workers are withdrawn from exposure at 40 μg/dL. In Europe the current limit is 70 μg/dL for male workers, although some are pressing for this to be reduced to as low as 10 μg/dL. The industry recently conducted its own risk assessment concluding that 40 μg/dL was a safe limit for male workers[b]. For women the limits are usually lower, at between 30 and 45 μg/dL, to protect a potentially developing foetus. They are likely to drop still further.

Non-occupational exposure blood lead limits are less often set, although since 1990, the WHO has had in place a standard of no more than 10 μg/dL as a safe limit for children from 0 to 4 years. This is is universally agreed as a "level of concern". The US National Ambient Air Quality Standard for Lead is being reviewed and may drop to 5μg/dL or lower for children.

Environmental legislation pertains to lead emissions to air and water, as well as to lead in soils and waste.

[a] **International Lead Association**. *Lead Action 21. The Evolution of an Element.* Brochure.
[b] **International Lead Association**. *Lead Action 21. The Evolution of an Element.* Brochure.

Air

In terms of emissions to air, restrictions apply both to direct emissions from plants and to ambient air. At the international level, the UNECE's 1998 Aarhus Protocol on Heavy Metals stipulates guideline limits for lead and total particulates for specific types of industrial process. The Aarhus limits are based on what can be achieved through Best Available Techniques (BAT). In 2001, the European Commission produced a reference note on what constitutes BAT for the non-ferrous metals industry[a]. But these are not binding and, as mentioned above, at the country level local conditions will dictate limit setting for plant emissions. Ambient air limits, which are designed to protect the local population, especially children, vary from country to country. In the EU the limit was set at 0.5 $\mu g/m^3$ in 1999, in the UK the limit is lower at 0.25 $\mu g/m^3$ with effect from 2009, while the USA has a limit of 1.5 $\mu g/m^3$ (quarterly average) but this is likely to be reduced.

Water

As with air, two types of limit are imposed for lead in water: emission limit values and water quality standards. Again the former varies with local conditions, normally within the range 0.01 to 0.5 µg/l. Water quality standards have not yet been set but when the EU's Water Framework Directive comes into force these may be as low as 30 to 50 µg/l above background for lead. For drinking water the limit is, understandably, considerably lower.

Soils

As with water and air, dual limits are applied to lead in the context of soil. Restrictions are set on both additions to soil and quality standards applying to the soil themselves, especially that used for specific purposes such as in farming or in children's playgrounds.

Wastes

Industrial waste containing lead can, in most countries, only be disposed of in controlled hazardous waste landfills. Such sites are increasingly rare leading to high disposal costs. In terms of municipal waste containing lead, new restrictions have come into force in several parts of world such as in new WEEE (Waste Electrical and Electronic Equipment) and the end-of-life vehicle regulations. In addition, rules now exist on the transportation of waste both within and between countries. The proximity principle that

[a] **European Commission.** 2001. *Integrated Pollution Prevention and Control (IPPC). Reference Document on Best Available Techniques (BAT) in the Non Ferrous Metals Industries.* Available from : http://www.epa.ie/downloads/advice/brefs/name,14509,en.html

waste should be disposed of as close as possible to its source normally holds.

The Basel Convention, originally drafted to prevent dumping of hazardous waste in developing countries, strictly regulates trans-frontier waste shipments and has been signed by 160 nations. The Convention applies to scrap lead batteries which are considered a hazardous waste.

Restriction of Use

A number of national and international bodies have attempted to reduce the use of lead in the first place, especially in dispersive applications. In many parts of the world, lead is now usually absent from paints, pipes, petrol and soldered food cans, but new initiatives seek to extend such bans to other products. For example, the OECD investigated further restrictions in the 1990s but concluded that this was best left to individual countries. In 2000 Denmark outlawed the use of lead in almost all applications except for where no alternatives exist. Similarly, the EU has introduced certain restrictions on the use of lead as part of the WEEE and end-of-life directives, in 2003 and 2006, respectively, while the UNECE has restricted the use of lead in gasoline to trace levels.

Developing World

While the lead industry in the western world, is subject to a number of environmental controls and restrictions, the picture in the developing world is very different. Poor environmental health standards and a predominantly manual approach tend to hold sway as anecdotal evidence indicates, notwithstanding examples of good practice in some surprising quarters[a]. Workers break batteries by hand using axes, untreated acid is simply emptied into sewers, and emissions from smelters can contain dangerous levels of lead and other pollutants. OK International is currently working to tighten up standards here by launching its Better Environmental Sustainability Targets (BEST) certification programme. The scheme rewards lead battery manufacturers that meet minimum emission standards and agree to take back used batteries for environmentally sound recycling[b].

[a] According to Brian Wilson from the International Lead Management Center, outstanding examples of good lead recycling practice were witnessed at two plants in Venezuela. Batteries with their full acid content arrived shrink-wrapped on pallets which were forklifted onto conveyor belts. The pallets and shrink-wrap was recycled (the latter used in the furnace), while the component plastic, acid, grids and paste were separated in a hammer mill and recycled as in the developed world.

[b] Personal communication, Perry Gottesfeld, OK International

3.2 UK

3.2.1 UK Flows

In the UK, the lead acid battery infrastructure is well organised, efficient and highly regulated. Here, as in the USA, the system is entirely market driven. Industry reports that almost 100%[a] of the some 130kt of automotive (SLI) batteries scrapped each year are collected and recycled, mainly as the lead they contain is so valuable. Assuming that each battery contains around 50% by weight of lead this represents around 65kt of lead per annum. A further 50kt of non-automotive batteries such as those used in telephone exchanges are also scrapped and recycled each year in the UK[b]. These have a lead content approaching 70% so an estimated 35kt of lead per annum is recovered from these sources. In 2007, 164kt of secondary lead was produced in the UK[c], the remaining 64kt not yet accounted for probably arising from recycled pipes and sheeting. In addition to secondary lead production, 111kt of primary refined lead was produced from ores (Figure 3).

Undrained automotive batteries originate from vehicle dismantlers, scrapyard breakdown services, civic amenity sites, battery producers, garages, distributors and waste management companies. Around a third of batteries are collected from small retail outlets and service garages by small-scale collectors[d] and are sold on to scrap merchants (e.g. Sims Metal, EMR). Industrial batteries such as standby batteries from telecommunications companies (e.g. BT) and power stations are also collected. A significant number come from submarines. The UK's leading battery collector is G&P Batteries, owned by Ecobat, itself the world's largest battery recycling company with a large presence in Europe, the USA and South Africa. According to unconfirmed anecdotal evidence, the current high value of lead has also encouraged a certain number of unlicensed dealers to "collect" (or even steal) lead acid batteries from garages, street furniture and other sources who then, allegedly, sell them onto less scrupulous scrap merchants. Depending on lead content, one tonne of scrap lead acid batteries can currently fetch anywhere between £50 and £200, so each battery is worth £1 or £2.

The industry reports that 95%[e] of UK batteries are recycled domestically at just one secondary lead smelter, run by Enthoven in Derbyshire – another subsidiary of Ecobat. Britannia until recently provided some competition with a secondary smelter at Northfleet in Kent but this has now closed,

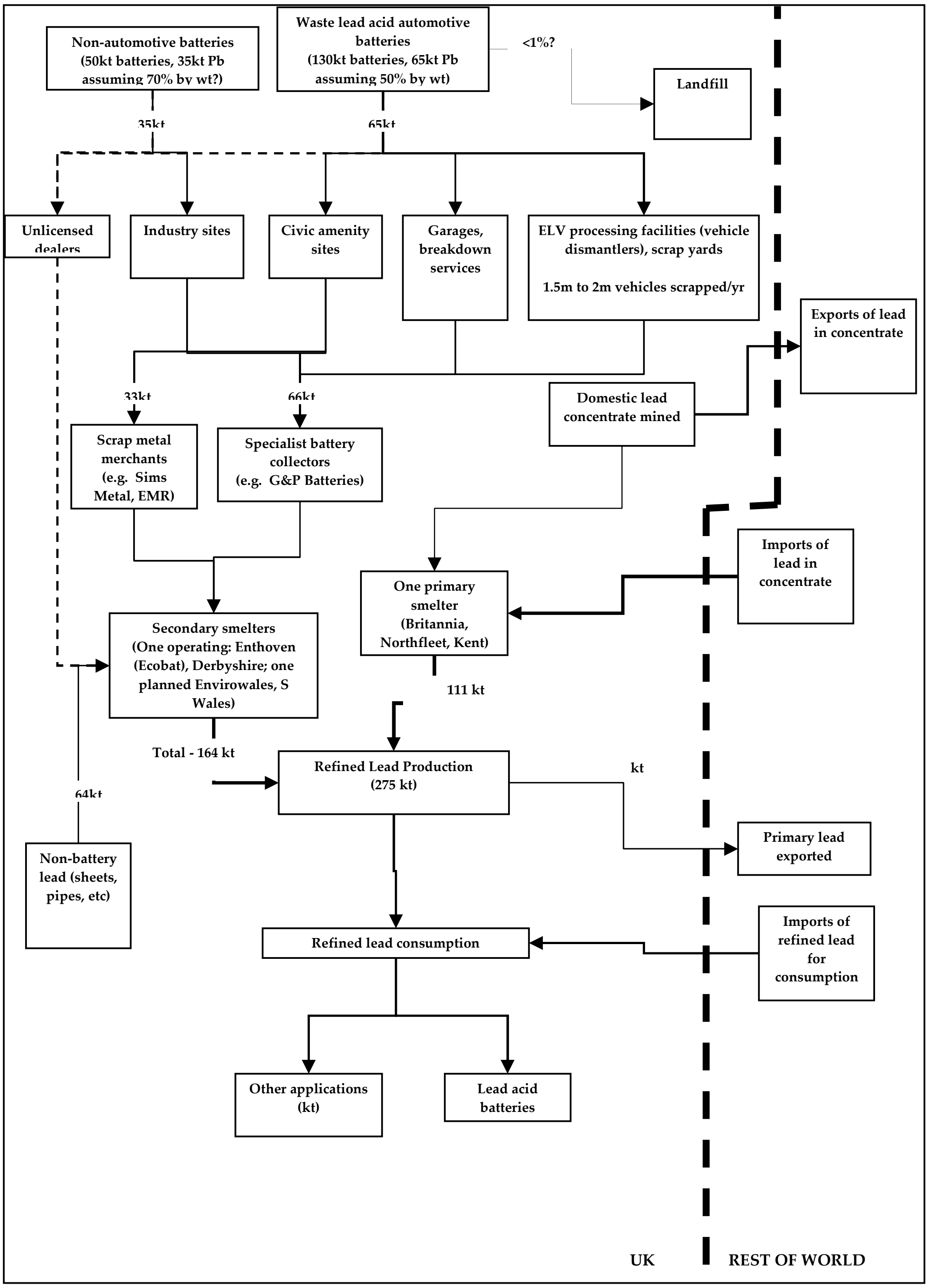
[a] G&P Batteries
[b] BERR
[c] Lead Development Association
[d] http://www.defra.gov.uk/ENVIRONMENT/WASTE/strategy/strategy07/pdf/waste07-annex-c13.pdf
[e] G&P Batteries

although the UK's only primary lead smelter still operates at the same site. Much of the lead concentrate it processes is imported from Australia, and also most of the refined product is then re-exported. Supported by a £2.5m Welsh Assembly grant, Envirowales Ltd has invested in a new 70kt lead acid battery recycling centre at Abergavenny on the Welsh/English border. Construction started in 2005, and a lead refinery plant has operated since 2006. Battery breaking, paste desulphurisation and secondary smelting is planned to start in July 2008[a].

The remainder of scrap batteries are exported to smelters such as those run by Campine Recycling in Beerse, Belgium, as well as plants in Spain. The Basel Convention prevents OECD countries from shipping batteries to non-OECD countries. However, anecdotal evidence suggests that at least some are going illegally to countries such as India, Pakistan and China. Dealers from such countries offer high prices to UK collectors on an almost weekly basis so the fact that some are tempted is perhaps unsurprising.

[a] http://www.tce-today.co.uk/JobsPDFs/802enviro.pdf

Figure 3: UK lead acid battery flows (2007)



3.2.2 UK Regulation

Scrap batteries are classed as hazardous waste so recycling them in the UK is subject to strict legislation at every stage of the system. As in the rest of the EU, sending lead acid batteries to landfill is outlawed, although the high value of the lead they contain would, in any case, make this an unlikely fate.

The existing EC Battery Directive (91/157/EEC) requires the separate collection of certain batteries, including those containing more than 0.4% lead by weight, which includes vehicle lead acid batteries. In some member states - but not the UK - a significant number of batteries are still not recovered and recycled. For example, many scrap cars still contain batteries when they are shredded so in May 2006 a revision of the existing battery legislation was agreed with implementation due to come into force in member states by 26 September 2008. The new EU Battery Directive proposals include a 70 - 100 % collection target for automotive lead acid batteries with a recycling efficiency target of:

> *"[a minimum of] 65% by average weight of lead acid batteries and accumulators, including recycling of the lead content to the highest degree that is technically feasible while avoiding excessive costs".*
> (Annex III Part B(a))

The UK is in the process of transcribing the new Battery Directive into national law. Industry expects the new rules to have little effect on the lead acid battery sector in the UK because it is already operating so well, with (legal) recycling rates exceeding 90%. The British government has inferred that it does not want this potentially costly and complex new legislation to interfere with an already efficient system[a]; the new rules are more likely to influence recycling of smaller and portable types of battery such as alkali cells.

The Environment Agency requires those collecting the batteries to apply for a bespoke Waste Carriers' Licence. Anyone transporting scrap batteries in the UK needs to abide by Hazardous Waste Regulations and Dangerous Goods Regulations.

If a collecting company wishes to break apart a battery to get at the lead plates prior to sale to a smelter, sometimes necessary for larger industrial batteries, then they also require the appropriate Waste Management Licence.

At the smelting stage, a full IPPC is required for any processing of lead acid batteries. In Europe, the current legal limit for lead in the blood for workers is 70 μg/dL for male workers, although some are pressing for this to be

[a] However, some measures are being considered as a safety mechanism in case the price of lead drops and the incentive to recycle lead acid batteries then diminishes. This is thought especially problematical for smaller non-automotive batteries with a relatively low lead content. One scheme might involve a producer compliance scheme to kick in if recovery of batteries becomes uneconomic (BERR, personal communication)

reduced to as low as 10 μg/dL[a]. As elsewhere, air, water and soil emissions limits for lead recycling plants are determined on a case-by-case basis dependent on local conditions under IPPC. In 2001, the European Commission produced a reference note on what constitutes BAT (Best Available Techniques) for the non-ferrous metals industry in order to achieve 1998 Aarhus Protocol guidelines[b].

3.2.3 UK Market Potential

As in the rest of the EU, breaking into the UK market would be extremely difficult. Ecobat dominates both the collection and smelting infrastructure. In the UK, it owns the country's largest battery collector (G&P Batteries) and in Enthoven, Derbyshire, the country's only operating secondary smelting company. Enthoven have invested very recently in a new smelter so may be unlikely to collaborate in a process which does not require one[c]. Setting up a new operation based around the new technology would be prohibitively expensive. Building a plant involving battery breakage and smelting from scratch would cost in excess of £20 million, and require compliance with strict IPPC regulations.

3.3 USA

3.3.1 USA Flows[d]

As in other industrialised nations, American lead mining and primary lead production has declined for much of the last 100 years[e] (Figure 4). In 2007, five lead-only mines were operating in Missouri, while lead-producing mines were also operating in Alaska, Idaho, Montana and Washington. Approximately 430kt of lead in concentrates was mined in the USA in 2007, of which about 300kt was exported. Most of the more accessible lead reserves are now exhausted, as is the US national lead stockpile[f]. Today, only one primary lead smelter refinery still operates in the country: the Doe Run Company's facility in Herculaneum, Missouri, which produced about 150kt of primary refined lead in 2007.

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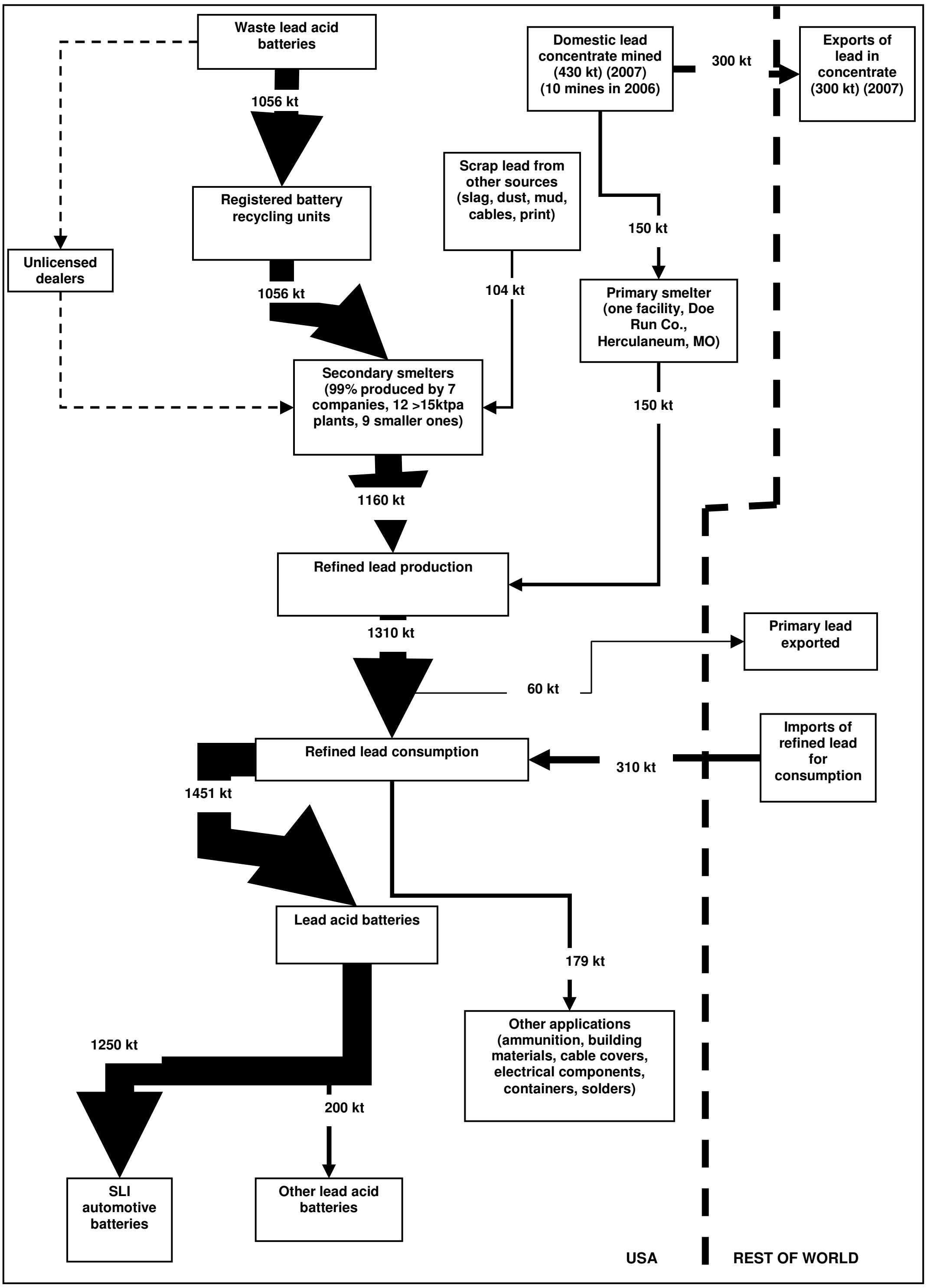
[a] **Wilson, D.N.,** 2008. *Lead and the environment: Regulation and responsibility.* Lead Development Association. Presentation. *Metal Bulletin* International Lead Conference, London.
[b] http://www.epa.ie/downloads/advice/brefs/name,14509,en.html
[c] Lead Development Association
[d] Much of the data in this section comes from a US Geological Survey Commodity Report: http://minerals.usgs.gov/minerals/pubs/commodity/lead/mcs-2008-lead.pdf
[e] **Socolow, R., & Thomas, V.,** 1997. The industrial ecology of lead and electric vehicles. *Journal of Industrial Ecology*, **1** (1), pp13–36.
[f] **White., P.** 2008. *Lead – A change in dynamics.* International Lead & Zinc Study Group. Presentation. *Metal Bulletin* International Lead Conference, London.

Figure 4: USA lead acid battery flows (2007)



The USA has, instead, successfully developed an efficient lead recovery and recycling infrastructure. In the USA, more than 97% of lead from batteries is recovered, and 60-80% of a new battery is recycled content[a]. Twenty one plants produced about 1,160kt of secondary lead in 2007, with twelve of them having a capacity of 15kt per annum or more and being responsible for 99% of production. Exide Batteries is a leading example of an American company adopting a closed-loop approach. Exide provides what it calls a "Total Battery Management" system whereby they both manufacture and recycle lead acid batteries.

In 2007, the USA exported 60kt of the refined lead it produced; the rest was consumed at 110 manufacturing plants. Reflecting the global picture, the use of lead in dissipative applications in the USA has declined, while the consumption of lead for batteries has grown steadily. Lead acid batteries of all types (i.e. SLI/automotive, industrial, traction, etc) were responsible for around 89% of lead consumption in 2007. The remaining lead consumed is used in ammunition, casting material, solder, oxides for glass and other applications.

Despite impressive lead recovery rates, the USA depends to a certain extent on imports; in 2007, 310kt of refined lead was imported, mostly from Canada. Battery imports are also high. The US International Trade Commission reports that battery imports more than trebled from 1989 to 2004[b]. Most enter the USA in new cars, accounting for almost half of all new car sales, but significant numbers are also imported for the replacement market[c].

3.3.2 USA Regulation

In most American states, almost any retailer that sells lead acid batteries must by law also collect used batteries for recycling. The 1996 Mercury-Containing and Rechargeable Battery Management Act makes it easier for rechargeable battery and product manufacturers to collect and recycle Ni-CD batteries and certain small sealed lead acid batteries. For these batteries, the 1996 Act requires that[d]:

- batteries must be easily removable from consumer products, to make it easier to recover them for recycling
- battery labels must include the battery chemistry, the "three chasing arrows" symbol, and a phrase indicating that the user must recycle or dispose of the battery properly

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[a] **Neil, A. B.,** 2008. *Ancient metal, today's market reality – What vision for the future?* The Doe Run Company. Presentation. *Metal Bulletin* International Lead Conference, London.
[b] **U.S. International Trade Commission.** 2005. *ITC Trade DataWeb* http://dataweb.usitc.gov.
[c] **U.S. Department of Transportation.** 2005. *National Transportation Statistics 2004, Bureau of Transportation*.
[d] http://www.epa.gov/msw/battery.htm

- there should be national uniformity in collection, storage, and transport of certain batteries
- the use of certain mercury-containing batteries should be phased out.

Handlers of large quantities of batteries are required to manage them in a way that prevents the release of any universal waste or component of a universal waste to the environment. Measures include:

- ensuring any leaking batteries are themselves carried in a suitable container
- ensuring any activity such as sorting, discharging electric current, or removal of electrolyte does not cause spillage
- determining whether the electrolyte and/or other solid waste exhibits characteristics of hazardous waste; if so it must be handled appropriately.

Those handling smaller quantities of used batteries must mark them, or their container, accordingly.

The US Environmental Protection Agency, mandated by the Clean Air Act, is responsible for national ambient air quality standards, is currently reviewing the lead standard and is expected to issue a proposed standard in early 2008[a]. In 1991, the US Center for Disease Control reduced its threshold definition of dangerous levels of lead in children's blood from 25 μg/dL (microgrammes per decilitre) to 10 μg/dL[b].

In the USA, waste disposal from lead recycling and secondary battery manufacture is regulated by the Resource Conservation and Recovery Act which stipulates that solid lead-bearing slag resulting from smelting must be treated to prevent leaching. Mixing the waste with Portland Cement is a typical method. In 1994, recycling wastes accounted for just 0.8% of secondary production[c].

3.3.3 USA Market Potential

As in the rest of the developed world, the new technology must be able to prove itself commercially in order to succeed in the USA.

[a] Occupational Knowledge International. http://www.okinternational.org/battery_facts.html

[b] **U.S. Department of Health and Human Services**. 1991. *Preventing lead poisoning in young children: A statement by the Centers for Disease Control.* Public Health Service.

[c] **Socolow, R., & Thomas, V.,** 1997. The industrial ecology of lead and electric vehicles. *Journal of Industrial Ecology*, **1** (1), pp13–36.

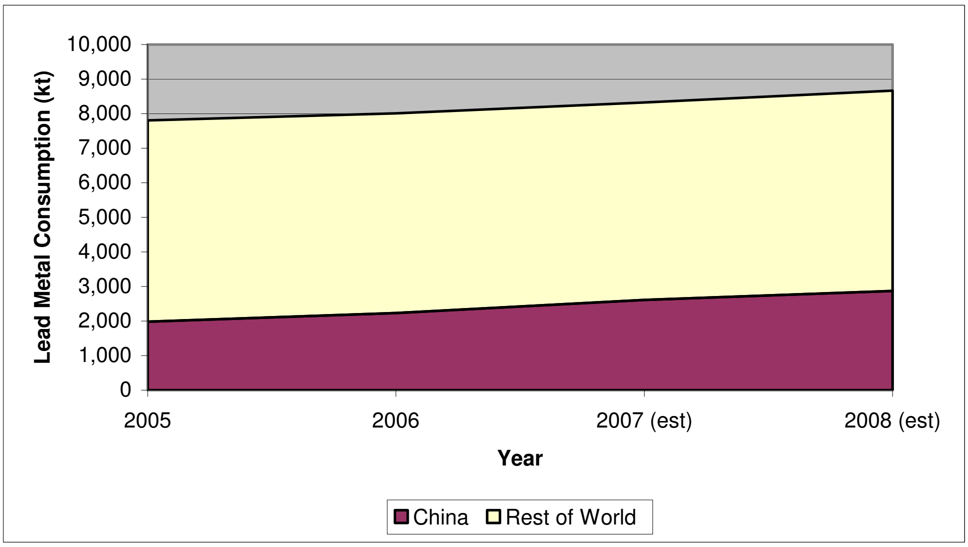
3.4 China

3.4.1 China Flows[a]

Whilst remaining fairly static elsewhere in the world, Chinese demand for lead is growing rapidly. Between 2000 and 2007, consumption grew by 16.9% per annum[b]. In 2005, China overtook the USA as the leading consumer with nearly 2m tonnes that year. Today the country consumes almost 3m tonnes of lead per annum, around 30% of world production (Figure 5).

Rocketing car sales underlie the growing demand in China. According to the China Association of Automobile Manufacturers, 8.7 million units were sold in 2007[c]. In addition, demand for electric cycles, mainly powered by lead acid batteries has soared. "E-bikes" and "e-trikes" are popular because of increased commuting distances, coupled with expensive licences for competing modes of transport such as cars and motorbikes. Almost 50 million e-bikes are predicted to be in use by 2010 (Figure 6), consuming some 500 thousand tonnes of lead per annum. In addition, a further 10 million e-trikes will be required within 3 to 5 years.

Figure 5: Chinese refined lead consumption against the rest of the world



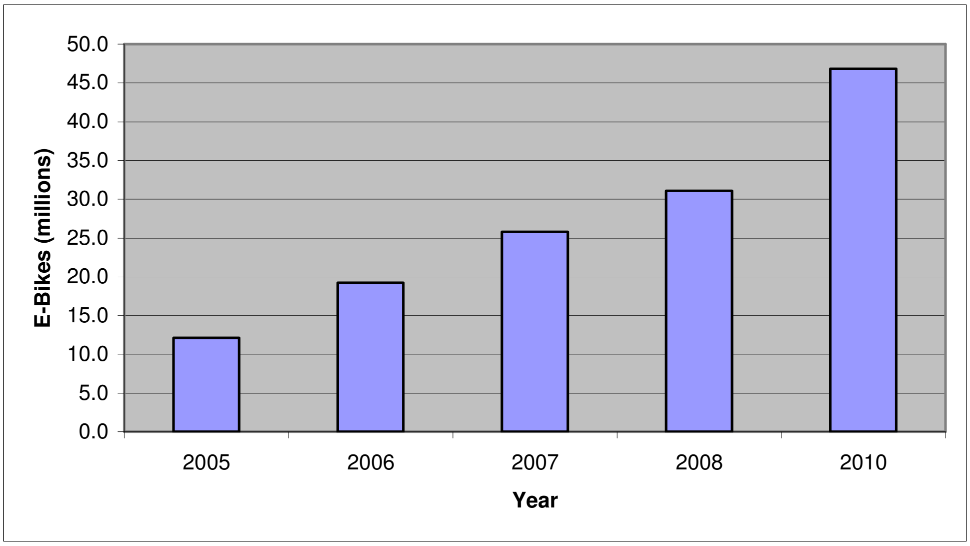
Source: World Bureau of Metal Statistics; ILZSG

[a] Much of the data in this section is from: **Hongyu, C.,** 2008. *China's lead battery sector: Players, products and markets – Can the growth continue?* South China Normal University. Presentation. *Metal Bulletin* International Lead Conference, London.

[b] **Roberts, H.,** 2008. *Can China withdraw from the global lead market? Implications for the industry elsewhere.* CHR Metals. Presentation. *Metal Bulletin* International Lead Conference, London.

[c] **Karpel, S.,** 2008. Lead also rises. *Metal Bulletin Monthly*, Feb. pp26-30.

Figure 6: E-bikes in use in China



Source: Hongyu (2008)

Rapid development of the communication and photovoltaic industries has also increased the demand for batteries. The Chinese Renewable Energy Law which came into effect in January 2007 is expected to lead to a growth rate of more than 50% in photovoltaics.

The Chinese government is now openly pursuing a policy for lead self-sufficiency by discouraging exports[a] and increasing lead production to keep pace with domestic consumption. Many mines are being opened and, in 2007 alone, a total of 340,000 tonnes of primary smelting capacity was added in China[b]. However, China's longer term primary lead production capacity is doubtful. In a recent sample of non-ferrous mines, more than 80% were either "nearly exhausted" or "facing a crisis". Chinese lead reserves are estimated to be able to last only another six to eight years based on existing consumption levels.

For this reason, China is now also seeking to increase secondary production and at the same time improve its environmental impact. Until recently China had been unusual in that, according to official figures at least, secondary lead production was relatively undeveloped. In 2006, of the 2.8m tonnes of refined lead metal produced, just 700kt (25%) was reported from secondary smelting, often of imported batteries. The rest came from primary smelting of lead concentrate; mostly mined domestically[c].

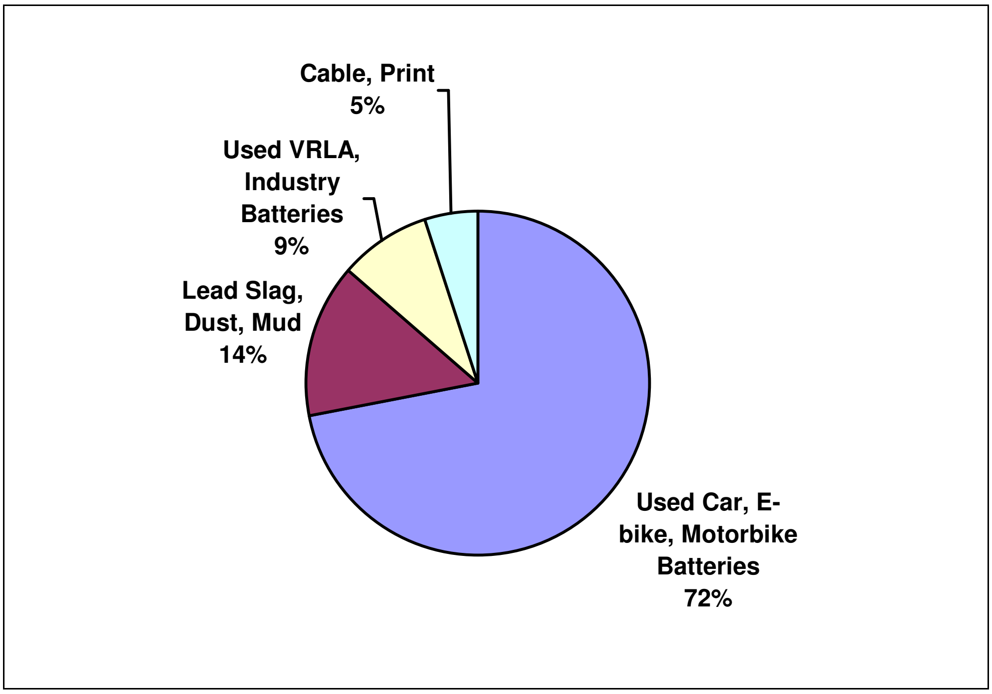
[a] In 2006, a 13% tax rebate on lead shipments from China was cancelled, and in 2007 a 10% export duty on lead ingots was imposed.

[b] **Cauley, I.,** 2008. *The art of primary lead smelting in today's competitive global environment.* Nyrstar, Australia. Presentation. *Metal Bulletin* International Lead Conference, London.

[c] http://minerals.usgs.gov/minerals/pubs/commodity/lead/mcs-2008-lead.pdf

As in other parts of the world, most (70%) of China's recovered lead comes from automotive batteries (Figure 7).

Figure 7: Sources of lead used in recycling in China.



Source: **Hongyu,** 2008.

Currently, about 300 secondary lead smelting plants operate in China ranging from 10 to 1000 tonne capacity. China is now only granting licences to larger, cleaner plants. Jiangsu Chunxing Alloy is China's leading lead recycler with 130kt per annum production[a]. In 2006, it set up a 50-50 joint-venture company, Jiangsu SembCorp Chunxing Alloy with a Singapore firm which expanded at facilities owned by Jiangsu in seven locations, increasing capacity to 315ktpa of lead and lead alloys by 2007. Other secondary smelters with more 10ktpa capacity include the Yuguang Gold and Lead Plant in Henan province opened in 2007, and plants owned by Jinxian Company in Hubei province, and Feilun Company in Shanghai.

The policies appear to be paying off: according to published data lead mining in China grew by 8.2% per annum between 2000 and 2007, while the rest of world experienced a 0.6% per annum decline over the same period[b]. Similarly, primary and secondary refined lead production in China grew by 12.1% per annum versus a -0.5% slump for the rest of the world[c]. In 2008,

[a] http://minerals.usgs.gov/minerals/pubs/commodity/lead/myb1-2006-lead.pdf
[b] **Roberts, H.,** 2008. *Can China withdraw from the global lead market? Implications for the industry elsewhere.* CHR Metals. Presentation. *Metal Bulletin* International Lead Conference, London.
[c] **Roberts, H.,** 2008. *Can China withdraw from the global lead market? Implications for the industry elsewhere.* CHR Metals. Presentation. *Metal Bulletin* International Lead Conference, London.

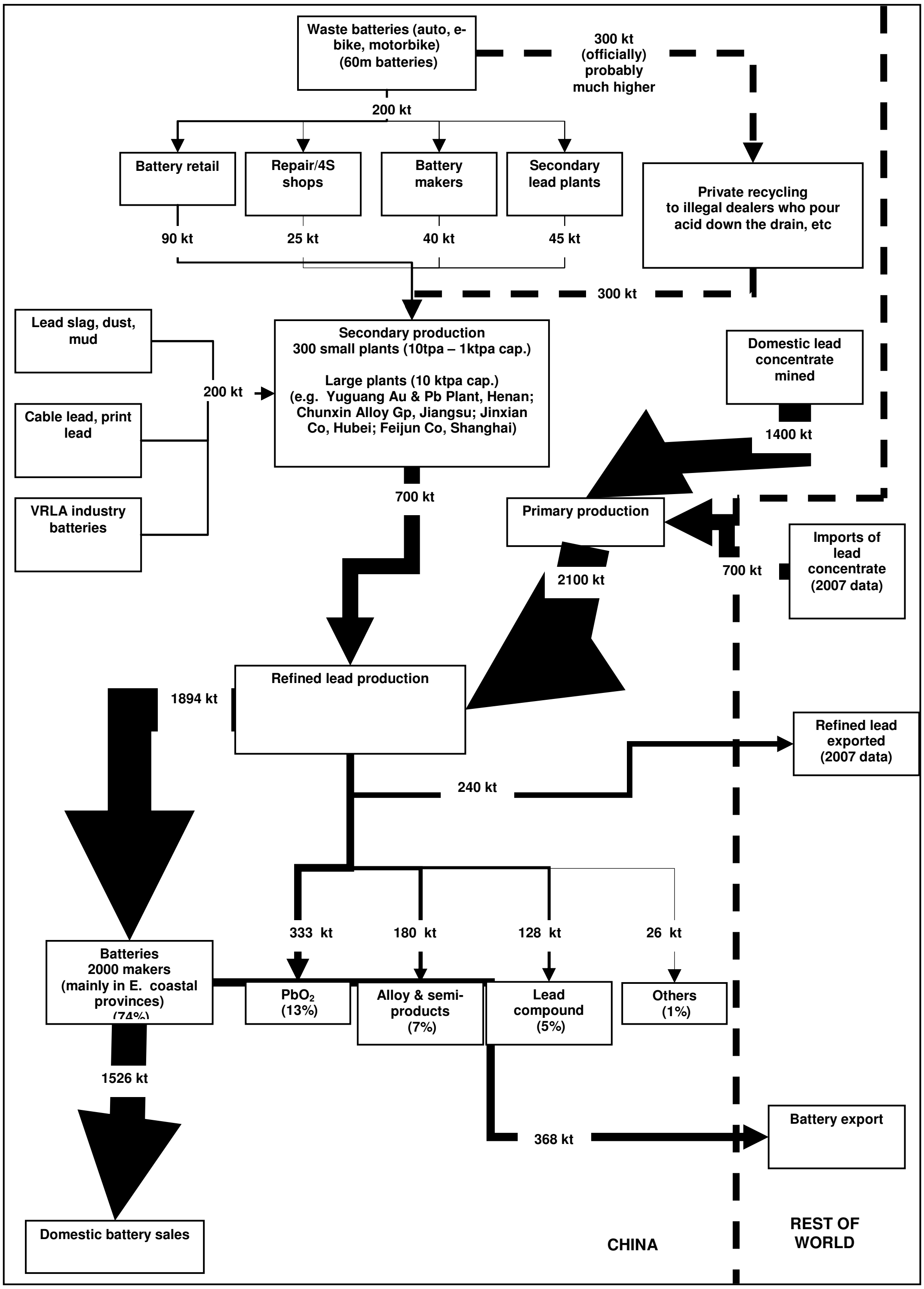
lead metal production in China is forecast to exceed 3mt which will match current rates of consumption[a].

China is also cleaning up its act. Chinese battery makers have tended to be small-scale, low quality operations. Smaller battery manufacturers are now being replaced by larger plants. Recently, Johnson Controls International, the world's largest battery maker, invested in a major smelter in China and is rigorously ensuring that all batteries come through authorised channels[b]. In 2003, there were an estimated 3000 enterprises, mainly based in eastern coastal regions; in 2006 the number had fallen by a third. By 2015 only about 300 larger-scale plants are expected to remain. Lead acid battery flow in China is shown in Figure 8.

[a] **White., P.** 2008. *Lead – A change in dynamics.* International Lead & Zinc Study Group. Presentation. *Metal Bulletin* International Lead Conference, London.

[b] Brian Wilson, International Lead Management Centre, Personal Communication.

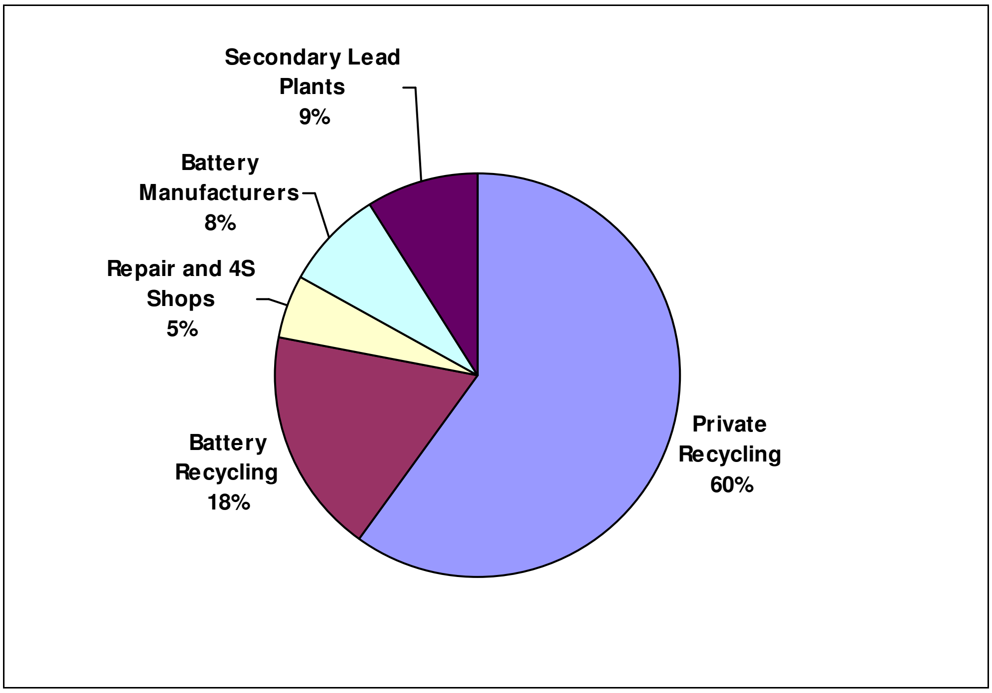
Figure 8: China lead acid battery flows (2006).



3.4.2 China Regulation

Until recently, existing central government regulations governing lead acid battery recycling in China have been poorly enforced at a regional level, resulting in some of the world's worst environmental performance at every stage of the process[a]. Indeed, lead pollution is said to be one of China's most serious environmental problems[b]. As elsewhere, the high value of lead in batteries encourages uncontrolled and environmentally damaging collection and recycling of batteries. Illegal battery recycling constitutes a large proportion of the secondary market. Even according to official figures "private" recycling stands at around 60% (Figure 9).

Figure 9: Where the recycling occurs in China



Source: Hongyu, 2008.

Anecdotal evidence indicates that after breaking apart the batteries to get at the lead, illegal dealers will routinely pour the acid straight down the drain. Traditionally, most secondary smelters are small, energy-intensive and polluting, producing high volumes of waste gas, water and slag. Many used traditional small reverbatory blast furnaces and cupolas.

[a] **Greenpeace**. 1994. *Lead astray: The poisonous lead battery waste trade.* Washington DC, Greenpeace USA.
[b] **Roberts, H.,** 2008. *Can China withdraw from the global lead market? Implications for the industry elsewhere.* CHR Metals. Presentation. *Metal Bulletin* International Lead Conference, London.

Unsurprisingly, workers and nearby communities suffer high levels of lead in the blood[a].

Keen to discourage energy-intensive, polluting and low added-value industries, the Chinese government is starting to close down the smaller, dirtier smelters, and is instead encouraging larger scale plants. New regulations stipulate that existing secondary plants must have at least 10 kt per annum capacity, upgrades must be 20ktpa and new plants must have greater than 50 ktpa capacity[b]. Some have predicted that, as China tightens up its environmental laws, lead acid battery manufacture may move abroad to countries such as Vietnam.

3.4.3 China Market Potential

China holds some potential for the new process. Clearly it is a massively growing market. The lead currently being used to make ever more batteries will soon need to be recycled. The main barrier to entry is that any new process would need to compete with the enormous informal sector. Moreover, as in other developing nations, a risk exists in China that new and potentially cost-saving processes might be copied, even when patented. In order to avoid this, Cambridge Enterprise would need to choose any partners particularly carefully. One way forward may be to deal with the China Metals Recycling Association who have a good reputation[c]. The fact that large multinational companies (e.g. the Doe Run Company, Johnson Controls International) have been prepared to invest in major secondary lead production in China is a sign of growing confidence. The Chinese central government, keen to encourage better environmental performance, is likely to support the new process.

[a] **Greenpeace**. 1994. *Lead astray: The poisonous lead battery waste trade.* Washington DC, Greenpeace USA.

[b] **Roberts, H.,** 2008. *Can China withdraw from the global lead market? Implications for the industry elsewhere.* CHR Metals. Presentation. *Metal Bulletin* International Lead Conference, London.

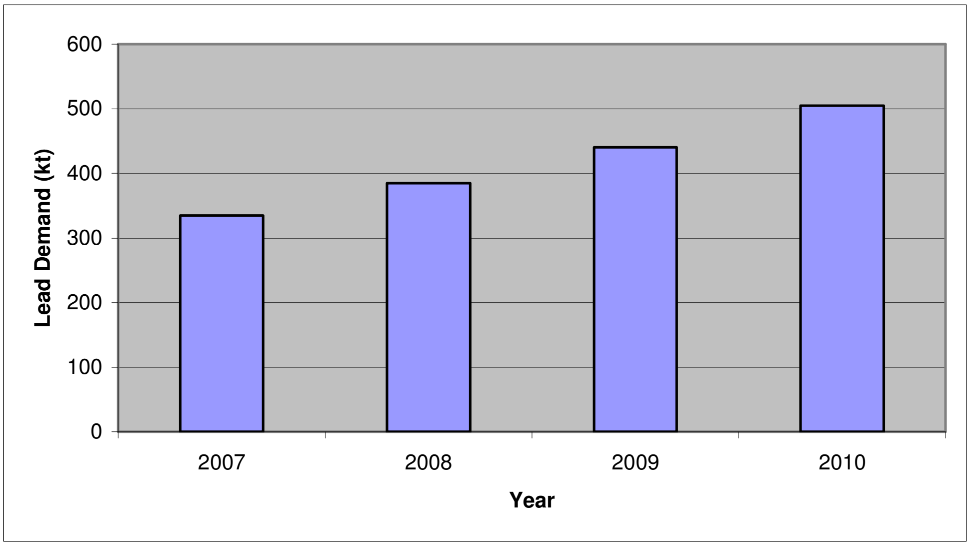
[c] Brian Wilson, International Lead Management Centre, Personal Communication

3.5 India

3.5.1 India Flows[a]

Lead consumption in India is large but not on the same scale as now seen in China. As urbanisation increases, however, so demand for lead - and batteries - is expected to rise steadily[b] (Figure 10).

Figure 10: Forecast demand for lead in India



Source: Gupta (2008)

In 2007, 335kt of lead was consumed, 78% of which was used to make new (mainly automotive) batteries, India differs from the rest of the world in that a significant amount (9%) is still used in dissipative uses such as paint.

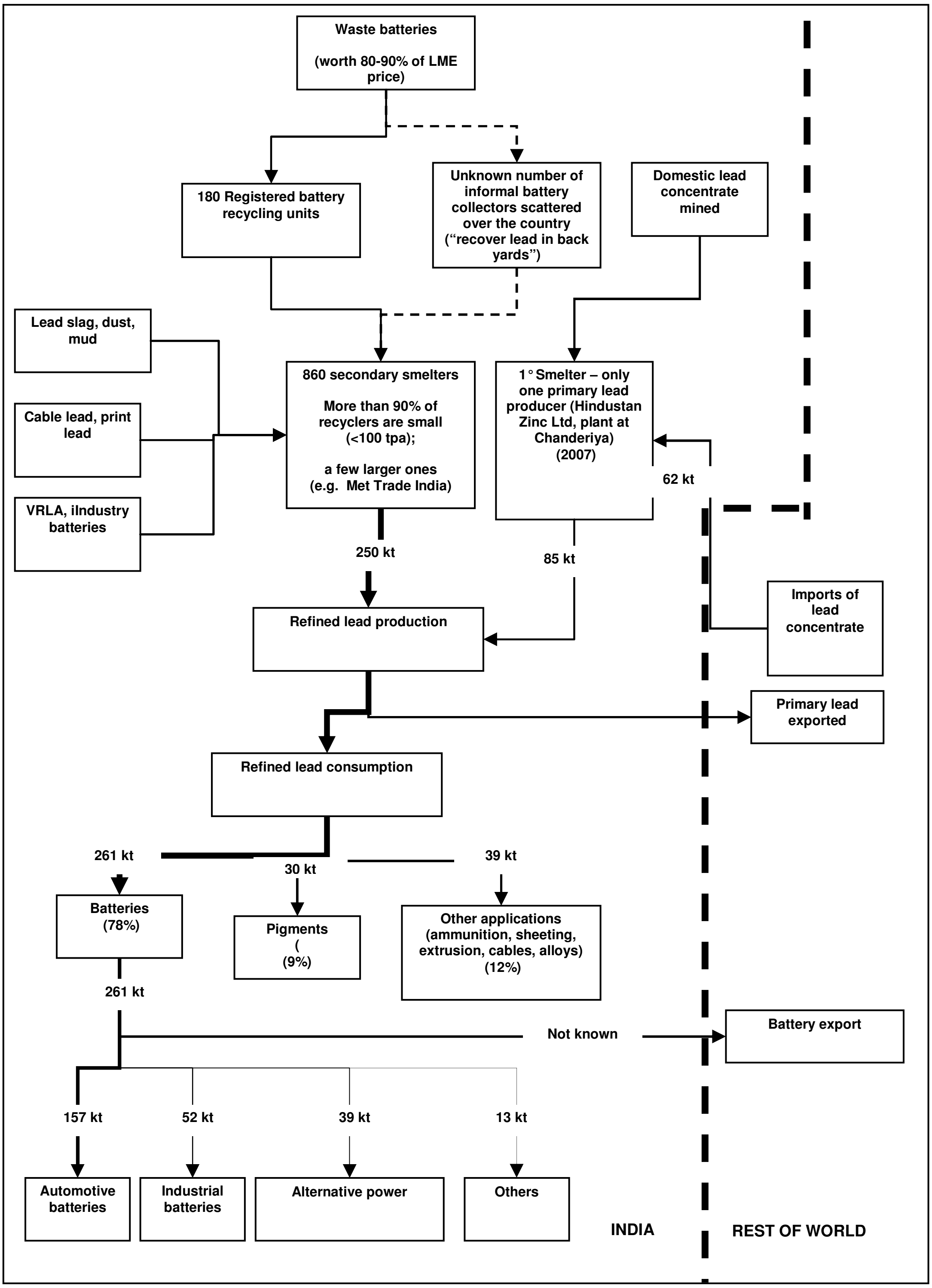
In India's traditionally thrift-oriented society a well established - albeit informal - secondary production infrastructure is in place. While only one primary lead producer currently operates (Hindustan Zinc Ltd, a subsidiary of Vedanta Resources plc), the secondary industry is highly disparate, consisting of numerous small producers scattered all over the country.

More than 90% of recyclers produce less than 100tpa. Reliable data are hard to come by as little formalised reporting is undertaken, but Met Trade India, the subcontinent's largest secondary producer, estimates that in 2007 primary lead production amounted to just 50kt as against 228kt of

[a] Much of the data in this section comes from: **Gupta, R.,** 2008. *Meeting lead demand in India.* Met Trade India Ltd. Presentation. *Metal Bulletin* International Lead Conference, London.
[b] **White., P.** 2008. *Lead – A change in dynamics.* International Lead & Zinc Study Group. Presentation. *Metal Bulletin* International Lead Conference, London.

secondary supply. The remaining approximately 60kt of lead India consumed that year was met by imports. Met Trade India predicts that as demand for lead continues to rise in India, so imports of concentrate will grow, alongside increased domestic prospecting and the re-opening of old mines. Lead acid battery flow in India is shown in Figure 11.

Figure 11: India lead acid battery flows (2007).



3.5.2 India Legislation

As in much of the developing world, poor environmental standards blight India's secondary lead industry. Batteries are meant to be collected locally and sent on to official regional recyclers, but in practice they are routinely broken apart on the street, the acid poured away and the lead extracted for onward sale to unregistered recycling units. Children are sometimes involved in the process.

Because labour is so cheap and standards so low, scrap battery prices almost match LME (London Metal Exchange) lead prices. At many secondary smelters where traditional methods hold sway, and direct manual handling of lead is the norm, workers and nearby communities unsurprisingly suffer high levels of lead in the blood[a].

The Indian government has attempted to improve the situation. In 2001-2 stringent new legislation, the Battery Handling & Management Rules (BHMR), introduced a formal battery take-back system authorising only special agents to collect used batteries for recycling, but implementation has been tardy. According to Met Trade India some companies are moving towards the organized sector but enforcement of BHMR has to date proven poor. The presence of many unorganized recyclers is perpetuating the current system. Currently, 180 units have been authorized to recycle batteries, with around 860 secondary smelters in operation. Met Trade India predicts that when environmental laws start bedding down and consumers begin to demand better quality batteries, so the secondary industry will eventually consolidate into a few large players.

3.5.3 India Market Potential

With little enforcement of environmental and safety regulations, lead recycling in India is extremely cheap. Secondary lead producers in India simply do not have to pay the full environmental and social costs that businesses in other parts of the world (including China) are increasingly being forced to bear. Until the situation in India improves, the new technology, however cheap, is unlikely to compete with the shoestring operations currently dominating India's lead recycling market. In the longer term, the potential in India is good however. Demand for batteries is likely to rise mirroring the current situation in China as car ownership levels increase.

[a] **Greenpeace**. 1994. *Lead astray: The poisonous lead battery waste trade.* Washington DC, Greenpeace USA.

3.6 Brazil

3.6.1 Brazil Flows[a]

In 2006, 222,214 tonnes of lead were consumed in Brazil; an increase of more than 16% on the previous year. Automobile batteries and accumulators consumed 199,336t or 89.7% of the total, while the industrial battery sector accounted for 13,200t or 5.34% of consumption. The remaining 10,000t or so was used in chemical, electronic, glass, ceramics and pigment applications (Figure 12).

In 2006, Brazil's only mine - Morro Agudo, Paracatu municipality, Minas Gerais state - produced around 25,764 tonnes of concentrate, realising 16,007 tonnes of refined metal. All of this primary lead is destined for export, with 13,945 tonnes of concentrate actually shipped abroad in 2006. Key markets for Brazilian lead include: Belgium (33%), Switzerland (30%), Morocco (23%), China (7%) and Germany (7%).

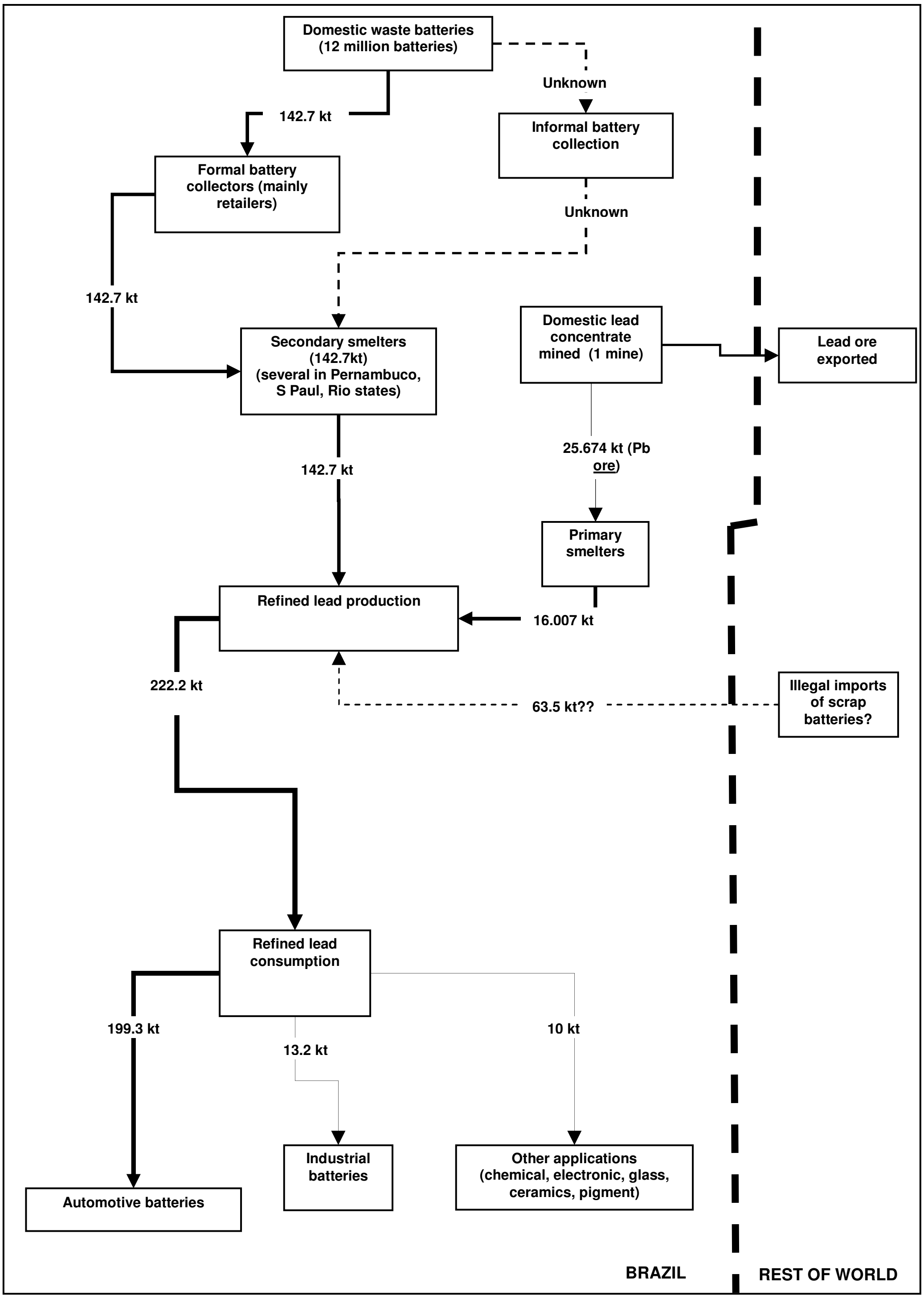
In Brazil, lead acid batteries recycling although a relatively recent phenomenon, is now a rapidly growing industry. Critics claim that is due to the reduction of secondary smelting capacity in the developed countries, especially the USA, where environmental standards and labour costs are higher[b]. A media campaign coordinated by the Brazilian Electrical and Electronics Industry Association (ABINEE) has been promoting lead acid battery recovery, recommending that the latter are returned to manufacturers through the original sale outlets. Approximately 12 million automotive and industrial batteries are now collected annually. In 2006, secondary production from used automobile, industrial and telecommunication batteries amounted to 142,653 tonnes, a rise of 36% on the previous year. Much of the secondary smelting occurs at refining plants in the northeastern state of Pernambuco and also in São Paulo and Rio de Janeiro states. As elsewhere, pyrometallurgy is the dominant technology, with Groupa Moura, the country's largest battery recycler, employing 2,000 people and headquartered in Belo Jardim, Pernambuco state.

Interestingly, with lead consumption in Brazil of 222,214 tonnes in 2006 and secondary and primary production officially amounting to a total of 158,660 tonnes, 63,554 tonnes is not accounted for. This suggests that additional lead is entering the system through informal channels, perhaps via illegal imports. This is subject to confirmation however.

[a] Much of this section is based on unpublished data collected by Benedito Célio Eugênio Silvae of Brazil's Departamento Nacional de Produção Mineral (DNPM).

[b] Basel Action Network. Lead Astray Again: The Ongoing Illegal Trade of U.S. Scrap Lead Acid Batteries to Brazil. http://www.ban.org/Library/lead_astray.html

Figure 12: Brazil lead acid battery flows (2006)



3.6.2 Brazil Legislation

Brazil was the first Latin American country to regulate the disposal and treatment of batteries. Since 1994, imports of lead acid batteries (viewed as a "hazardous waste") to Brazil for recycling have been banned under CONAMA (Brazilian National Commission for the Environment) resolution number 37. The trade also contravenes international law: the Basel Convention prohibits the export of lead batteries from OECD countries to non-OECD countries such as Brazil. Despite this significant imports have occurred; in 1997 Moura was accused by Greenpeace of importing 5,702 tonnes of scrap batteries, 88% of which came from the US (not at the time party to the Basel Convention). In 1996, the company was also criticized by Greenpeace for "dangerous lead contamination" in soil, water and sediment samples taken from close to its lead recycling facilities[a]. However, Brazilian legislation has not established maximum limits for lead contamination of soil. Judging from its website, Moura seems now to be taking its environmental record rather more seriously; it is ISO 14001 certified and has an active CSR department.

3.6.3 Brazil Market Potential

Discussions with Brian Wilson of the International Lead Management Centre indicate that, although significant, the Brazil market is unlikely to be receptive to the Cambridge process. The current pyrometallurgical process prevailing in Brazil is based on technology developed by a Mexican-based company and is highly effective and competitive.

[a] Basel Action Network. Lead Astray Again: The Ongoing Illegal Trade of U.S. Scrap Lead Acid Batteries to Brazil. http://www.ban.org/Library/lead_astray.html

3.7 Turkey[a]

Turkey is a country in transition and could represent a promising testing ground for the new process. With a population of 73 million, the second highest population in Europe, and a rapidly modernising economy, future car ownership and demand for batteries is anticipated to rise. At the same time, with an eye on EU membership, the Turkish government is tightening up environmental legislation favouring cleaner processes such as the Cambridge technology. In 2005, the Ministry of the Environment began issuing licences to lead recycling factories, outlawing unlicensed operations.

Although no primary lead production occurs in Turkey, the country has a significant secondary lead market. In 2007 between 80,000 and 90,000 tonnes of scrap lead acid batteries were collected and recycled, representing 45,000 to 50,000 tonnes of secondary lead production. There are 13 licensed recycling factories in Turkey with capacities ranging from 500 to 5000 tonnes/month capacity. Nearly half of the used batteries are collected as part of a state-controlled system, the rest via the informal market.

Although traditional pyrometallurgical approaches to lead recycling dominate in Turkey, alternative technologies are now being piloted here. No hydrometallurgical processes occur in Turkey although İnci Akü Sanayi, one of Turkey's largest battery manufacturing firms, has been working on a novel recycling technology for three years. The technology is similar to - but not the same as - electrowinning. They are currently recycling 300 tonnes per month.

[a] Much of the information for this section comes from a personal communication with Kadir Kaymakçı, Planning and Purchasing Manager of İnci Akü (a Turkish lead acid battery recycling company).

4 The new technology

4.1 How it Works

The preliminary steps of the new technology, such as taking apart used batteries to recover the PbSO4 paste, and neutralisation are identical to those in existing processes. Similarly, the end stages such as lead alloy refining remain. The novel (hydrometallurgical) approach departs from existing methods in obviating the need for high temperature smelting. Instead, the following steps take place:

- **Leaching-Crystallisation:** Non-toxic carboxylic acids and other additives, routinely used in the food industry and in the home, are added to the neutralised lead paste. Unlike other hydrometallurgical processes currently under development, the lead is not solubilized in the leachate for electrowinning, but is only transient towards crystallization. This leaching-precipitation technique forms a lead organic precursor at room temperature.

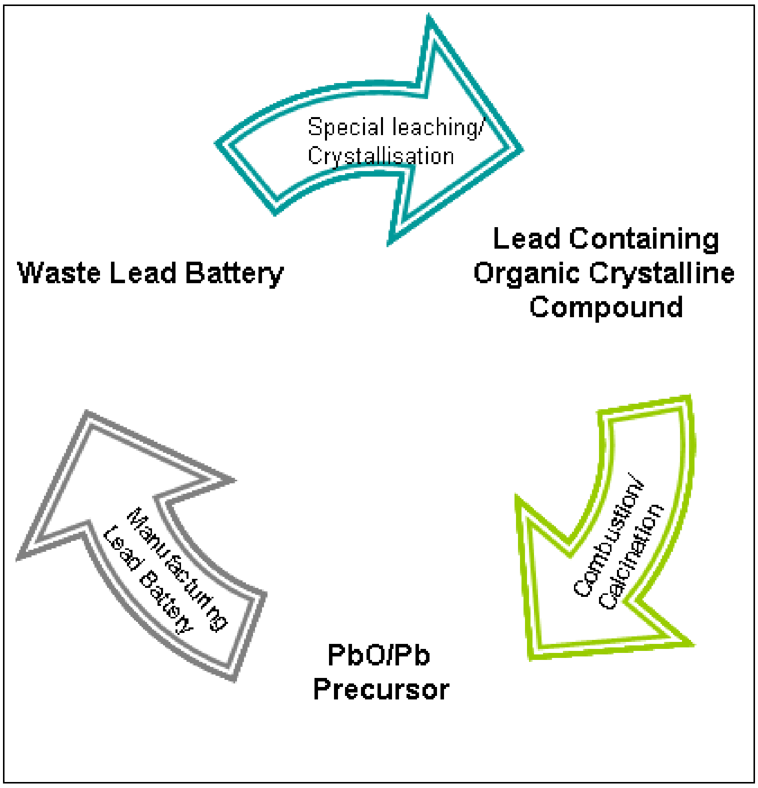
- **Combustion-Calcination**: The precursor is heated to between 300°C and 450°C to remove the organics embodied in the crystals, which themselves serve as the fuel by combustion to aid calcination. The decomposition liberates a mixture of metallic lead (Pb) and lead monoxide (PbO). The degree of oxidation depends upon the operating conditions. By varying the combustion-calcination conditions, it may be possible to directly create Pb or PbO or mixture of the two for the anode and cathode respectively of a new battery. Also, the PbO product can be produced in a nano-crystalline form.

- **Lead-sulphate Recovery:** Any residual $PbSO_4$ not fixed in the solution during leaching can be recovered in the calcined lead product in the form of binder for the preparation of the precursor for making new lead acid batteries. Thus, during the new recycling process, no sulphur oxides (SO_x) are released to the environment.

The new process has the advantage that the Pb/PbO mix produced can be used directly to produce new lead acid batteries. Other products, including lead sub-oxide and metal lead, can also be obtained using the same procedure and, at little extra cost, the chemical composition of these products can be controlled. Small to medium-scale recycling plants based on the new technology are anticipated to become profitable. Such plants may be more suitable for developing countries or regions where transport and collection cause major risks or costs.

The new process works easily with lead or lead alloys, the latter requiring additional refining steps.

Figure 13: Flow chart for the new process of recycling lead battery waste directly into PbO/Pb precursor for new battery manufacture



Source: Cambridge Enterprise

4.2 Claimed Benefits of New Technology

The new technology might enjoy a number of economic and environmental advantages over conventional lead acid battery recycling processes:

- **Lower emissions of pollutants:** The smelting operation integral to conventional recycling, but not the novel technology, results in significant volumes of hazardous fumes and dusts containing lead, NO_x and SO_x. Treatment of these gases is laborious, time-consuming and expensive[a], and legislation is getting stricter.

[a] More advanced smelting technologies such as Isasmelt use iron or soda to fix some of the sulphur in the furnace, forming a FeS-PbS matte or a slag containing Na_2SO_4; other technologies use NaOH or Na_2CO_3 (aq) solutions to fix the sulphur as soluble Na_2SO_4 - a saleable by-product. The insoluble $PbCO_3$ or $Pb(OH)_2$, collected as sludge or filter cake, is then routed to the smelter. Some sulphur remains, though, in the lead sludge/filter cake, so not all SO_2 emissions during smelting are prevented (Kumar *et al.*).

- **Lower energy inputs:** The new process has significantly lower energy demands than established technologies since much of the input would be provided by the combustion of organics used in the process. The main input in conventional battery recycling comes from the need for high temperatures (typically 1,100°C or more) during the smelting process or from energy-intensive electrowinning. Energy usage during smelting or electrowinning is estimated at 10 kWh and 5-12 kWh, respectively, per kg of lead. Such values are several orders of magnitude greater than the typical energy density of a lead battery (40[a] to 50[b] Wh per kg of lead). Based on thermal analysis data, the overall energy requirement in the new process is approximately 250 Wh per kg of lead, and so is of the same order of magnitude as the energy available from a new lead battery.

- **Lower greenhouse gas emissions:** Current lead smelters burn coke or coal as a fuel generating substantial emissions of CO_2. Emissions also result - albeit indirectly - from electrowinning if the purchased electricity is derived from fossil fuel power plants. The new process does not involve smelting or electrowinning hence does not generate such emissions.

- **Directly usable end-product:** Traditional recycling results only in lead metal which then needs to be oxidised in the manufacture of new batteries. The new process differs in that lead oxide is an end-product which can be used directly to make new batteries. The need to produce new lead oxide feedstock is potentially eliminated - along with its associated environmental impacts.

- **Small scale:** Smelting or electrowinning processes require large-scale operations to be cost effective, but the new solution should be viable at much smaller scales.

A key issue for the new process is how it would handle the solid and liquid waste products. The waste acid in particular is a cause for concern. Existing processes such as that at Enthoven recycle the sulphuric acid into gypsum. However, the gypsum can only be sold on if it contains no lead contamination. The new process must be able to produce lead-free sulphuric acid if the gypsum route is to be taken. If not, then an alternative outlet for the waste acid must be secured[c]. Sodium sulphate production for glass manufacture might be an option, but this product seems to have low value.

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[a] **EUROBAT.** 2005. *Battery systems for electrical energy storage issues.* Battery Industry RTD Position Paper, July.
[b] **Kumar, R.V., Sonmez, S., & Yang, J.,** Sustainability of automotive batteries. *Unpublished Research.*
[c] Brian Wilson, International Lead Management Centre

4.3 New Technology Process Flow

On the basis of information available to us we designed the process flow of the new technology as shown in Figure 14. The process is designed to handle 10,000tpa of batteries. The details of mass flow, waste streams and energy consumption are also shown in the flow diagram. The new process has similar initial stages common to conventional recycling operations and would cause similar environmental impacts – and hence may be subject to the same legislation. These stages and their possible impacts are as follows:

- **Transport:** Both to the recycling plant, and then on to the manufacturer (unless these are co-located).

- **Battery Crushing/Disaggregation**.

- **Neutralisation**: The new process shares the same neutralisation process as conventional lead recycling, and faces the same challenges in dealing with aqueous effluents containing Pb(II) species. Depending on the country, the consent concentrations for this discharge to sewers ranges from a few ppm down to zero. The upper limits are likely to be decreased in the future. Current industry practice involves treating the effluent with lime to precipitate a mixture of lead sulphate, hydroxides and gypsum, which may then be sent to a landfill site. This route is likely to be precluded by future legislation, because of possible mobilization of the Pb(II) contaminated watercourses. Scientists are therefore developing methods involving electrolytic reactors to recover lead species from the effluent[ab].

With the new technology the battery paste and all other metallic parts (grids, poles) are treated in different streams. If a clean separation of metallic parts is achieved (removal of any oxides or sulphates) then a kettle furnace would be adequate for melting and consequent refining/alloying stages. This would then avoid the need for implementation of a small rotary furnace which has a more complicated operation. Implementation of a rotary furnace - even a small one - would make the new process similar to existing secondary recycling technologies (Figure 15). The final product in this stream is pure lead which then turned into further grids and poles for a new battery.

In the other stream, lead paste is treated in a leaching tank with citric acid and sodium citrate. Lead citrate and sodium sulphate saturated solution is

[a] **Brandon, N.P., Pilone, D., Kelsall, G.H., & Yin, Q.,** 2003. Simultaneous recovery of Pb and PbO2 from battery plant effluents. Part II. *Journal of Applied Electrochemistry*, **33**, 853–862.
[b] **Cheng, C.Y., Kelsall, G.H., & Pilone, D.,** 2005. Modelling potentials, concentrations and current densities in porous electrodes for metal recovery from dilute aqueous effluents. *Journal of Applied Electrochemistry*, **35**, 1191-1202.

the product for the next stage. Lead residue leaves the process as waste and might be sent or sold to secondary pyrometallurgical plants to avoid waste disposal charges. The saturated solution is then precipitated as lead citrate monohydrate. The waste solution from this stream can be fed back into the leaching tank. The precipitated lead citrate is then calcined in a rotary kiln at various temperatures to produce Pb, PbO or a mixture as required by the battery paste specification to make new batteries.

Figure 14: Overview of the proposed process flow for Cambridge lead recycling technology

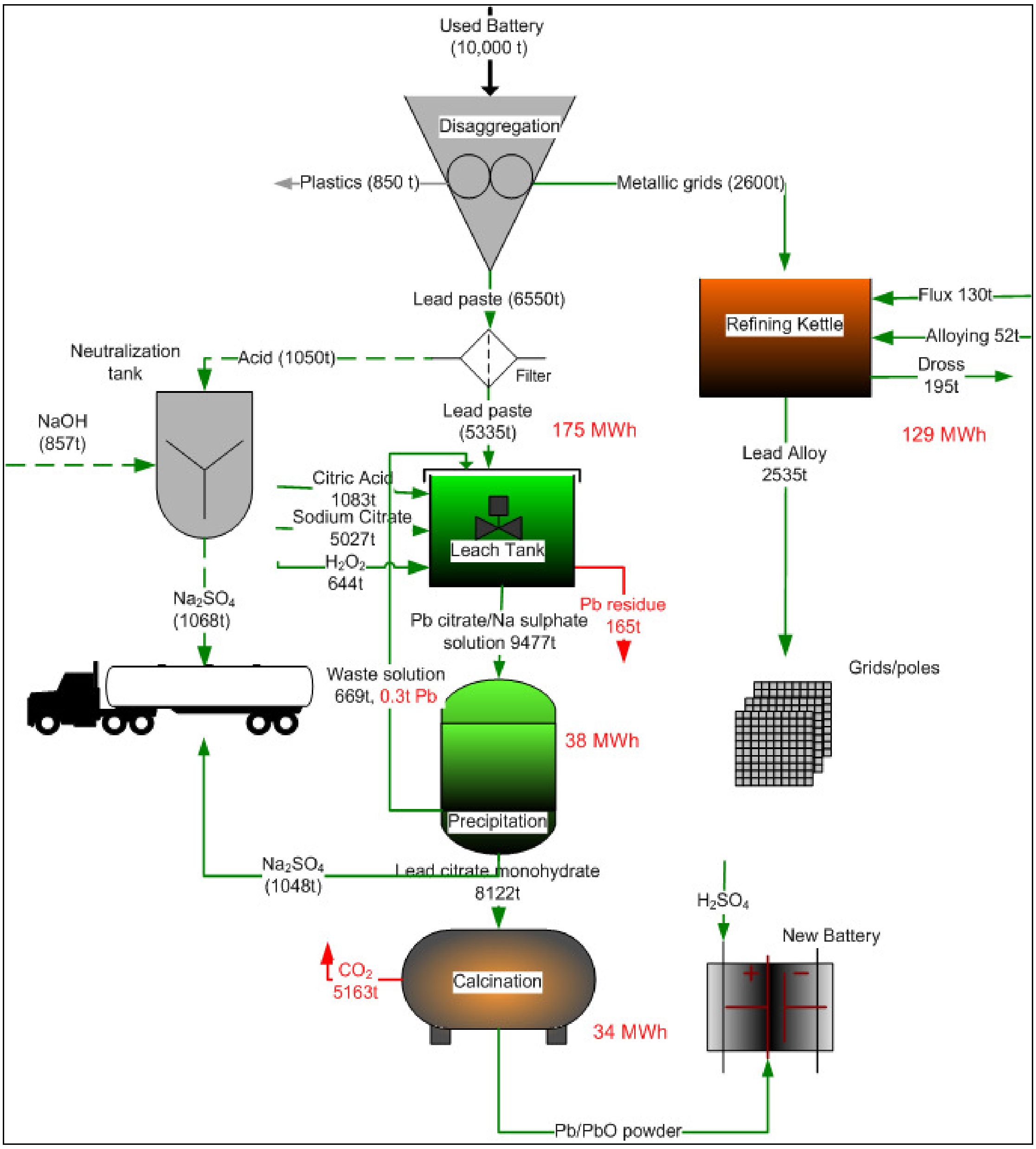
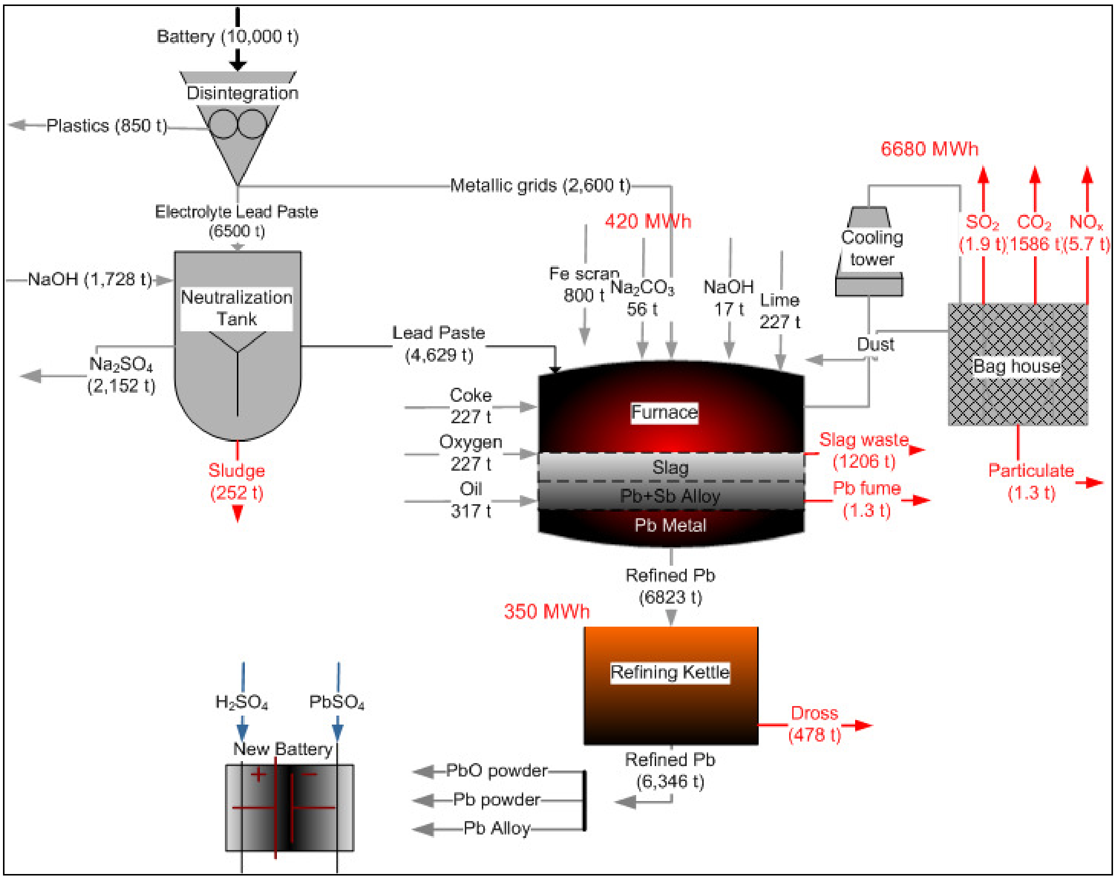


Figure 15: Schematic process flow of a pyrometallurgical lead recycling plant



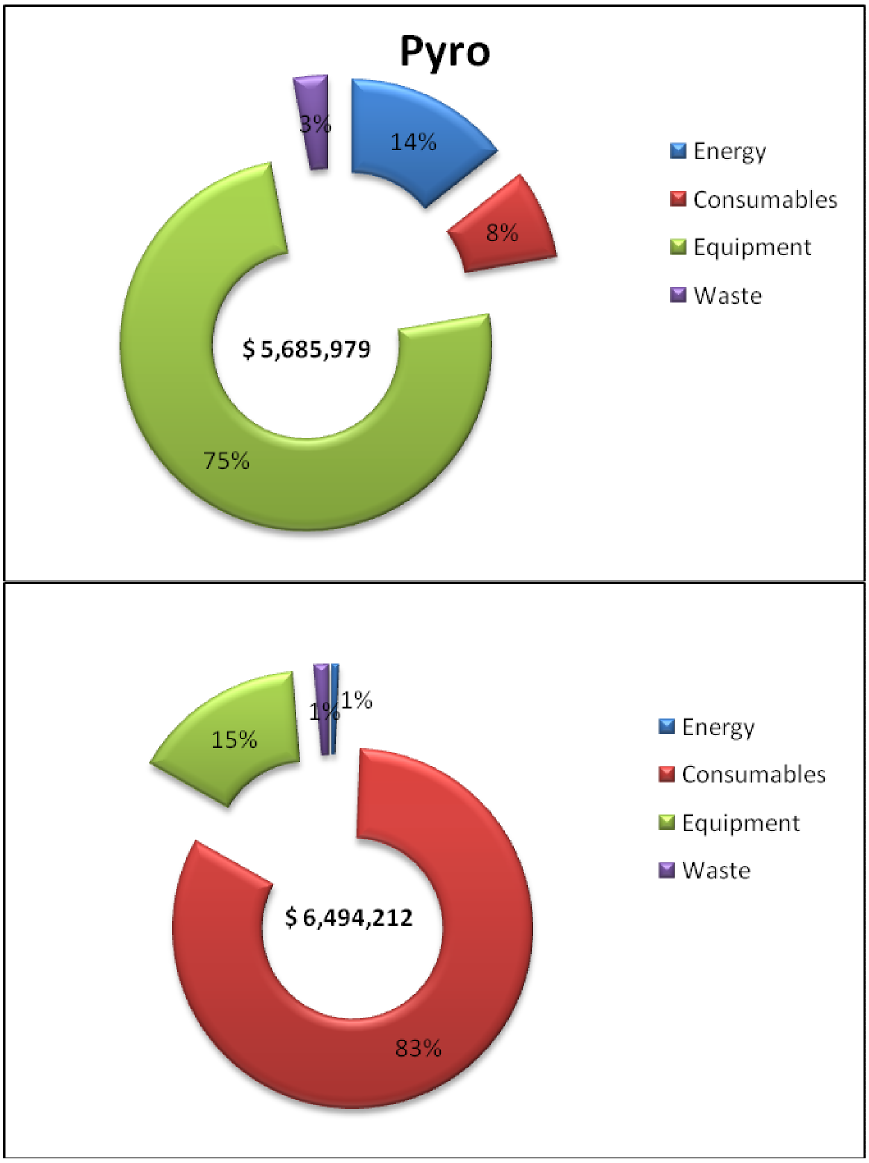
4.4 Economic Comparison

We have broadly analysed the cost of the two processes in terms of major cost items such as energy, consumables, equipment and waste (Figure 16). Equipment account for the majority of the total investment cost of 75% for the pyrometallurgical process, while consumables accounted for about 83% of the total cost. The new process requires large amount of citric acid and sodium citrate which are very expensive chemicals, both being used in the food industry. Citric acid is the most widely used organic acidulant and pH-control agent in foods, beverages, pharmaceuticals and technical applications. Tri-sodium citrate, on the other hand, is widely used in foods, beverages and various technical applications mainly as a buffering, sequestering or emulsifying agent. Over half of global consumption of citric acid is used in the beverage industry[a]. The food industry consumes

[a] http://en.wikipedia.org/wiki/Citric_acid

about 15–20%, followed by detergent and soaps (15–17%), pharmaceuticals and cosmetics (7–9%), and industrial uses (6–8%)[a].

Figure 16: Cost breakdown of pyrometallurgical and new lead recycling processes

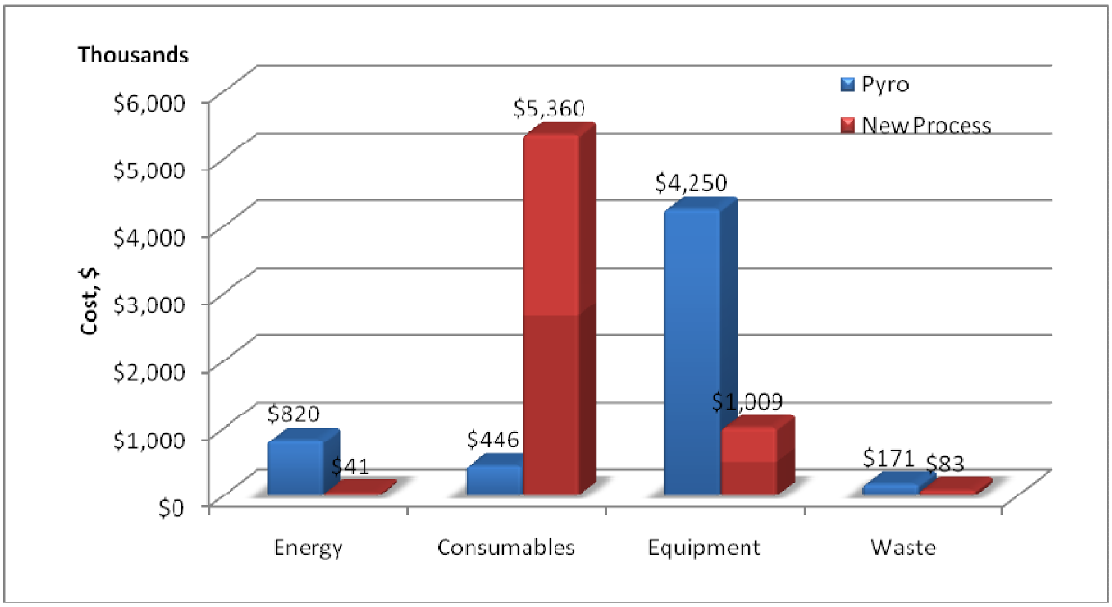


The prices of food grade citric acid and tri-sodium citrate were about $750-800 and $800-850 per tonne, respectively, at the time of writing this report. In the analysis we used these values to calculate the cost as this would represent a worst case scenario. Figure 17 shows a cost comparison of the

[a] http://www.sriconsulting.com/CEH/Public/Reports/636.5000/

two processes under these conditions. There is, however, an industrial grade of citric acid which would be considerably cheaper than the food grade due to its level of impurities. The new technology might accommodate these impurities allowing the use of cheaper alternatives, and hence reduce the cost.

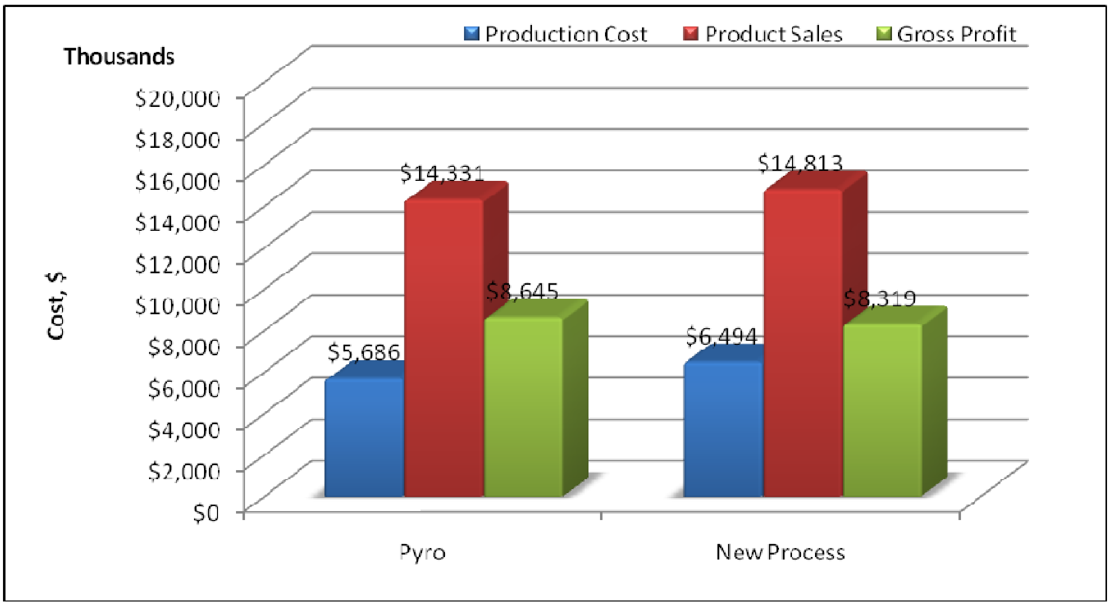
Figure 17: Comparison of major cost items for pyrometallurgical vs new processes



The overall investment cost on the basis of consumables, energy, equipment and waste is slightly higher for the new process mainly due to high prices of consumables (Figure 18). Assuming that both processes were set up to produce pure lead as final product, with the current value of $2,250 per tonne (15th May 2008) the sales revenue is slightly higher for the new process than for the pyrometallurgical process due to process efficiencies. However, the gross profit for the new process is lower, due to its higher running costs (consumables).

The main advantage of the new process is its ability to produce a lead paste composition ready for battery manufacturing. This would change the whole economics of the product revenues: see the sensitivity analysis discussed in Section 4.6.

Figure 18: Production cost versus product sales



4.5 Environmental Comparison

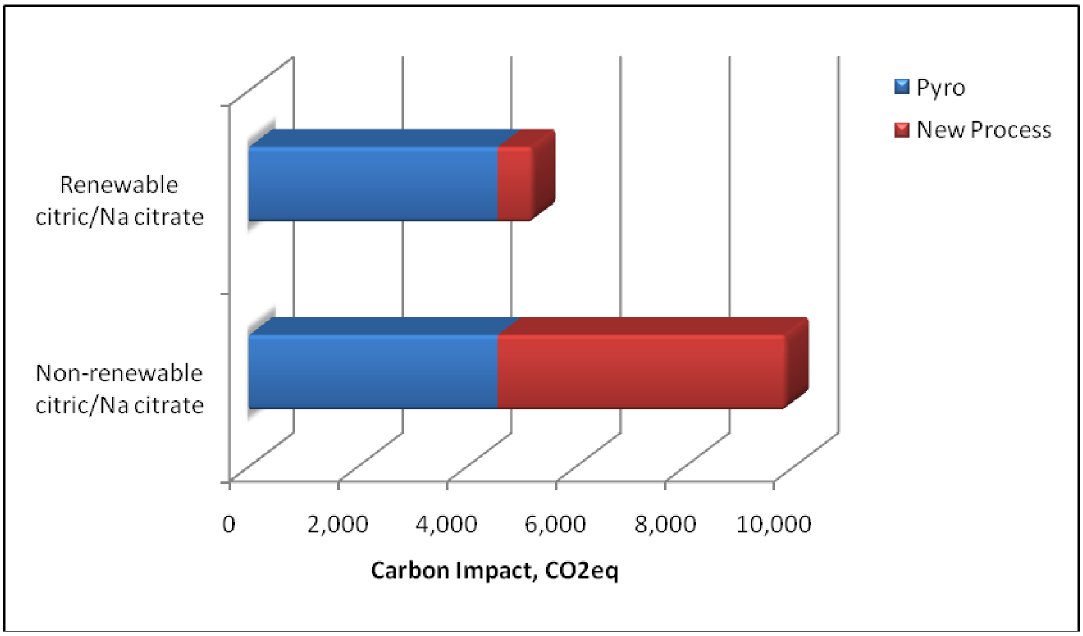
We analysed the new technology for its environmental credentials against the established pyrometallurgical secondary refining operations. We have looked at the energy and environmental implications of the each process to establish the possible environmental benefits of the new technology.

As discussed earlier, some of the initial battery dismantling and neutralization stages are common to both processes they are not included in the comparative analysis. The analysis is based on the process flow of a pyrometallurgical secondary lead recycling plant (Figure 15) with a capacity of 10,000t batteries per year, and the equivalent process plant with Cambridge technology (Figure 14). The energy requirements for each stage and waste stream are highlighted in red for both processes. Electrical energy consumption of the current technology is about 7,450 MWh while the new technology consumes ca. 376 MWh electricity. The new process consumes only about 5% of electrical requirements of the pyrometallurgical process. For the pyrometallurgical process there is an also thermal energy input which is calculated to be equivalent of 3,686 MWh of electrical energy. Combining the electrical and thermal energy the new process only consumes 3.4% of the total energy of the similar scale pyrometallurgical plant. Theoretically, there is also the additional energy available, in the hot gases from combustion-calcination, of nearly 4 kWh/ Kg of PbO produced. This energy can be harnessed for use in melting the lead grids. We did not take this into account in the belief that this energy might not be usable unless the process is designed to accommodate this.

As seen in Figure 15 there are also environmental issues with the pyrometallurgical process in the form of gaseous species, lead fumes, slags, particulates etc. Overall CO_2 release from the process is calculated to be around 4,561 tonnes (Figure 19). In addition, the final product from the process is pure lead which needs to be converted into lead oxide for the preparation of paste to make a new battery. This extra step in the process involves extra energy and cost.

For the new process, CO_2 emission from the calcination furnace is the major environmental issue. This is mainly due to burning of citric acid. The total CO_2 release for the proposed plant is about 5,291 tonnes which is higher than for the pyrometallurgical process. However, citric acid is mainly produced via fermentation of sugar canes with cultures of *Aspergillus niger*[a]. Therefore it can be treated as a renewable source, and it is carbon neutral. Hence the total carbon impact of the new process is about 645 t CO_{2eq} (Figure 19).

Figure 19: Carbon impact of new and pyrometallurgical processes



[a] Mustafa Yigitoglu, Journal of Islamic Academy of Sciences 5:2, 100-106, 1992

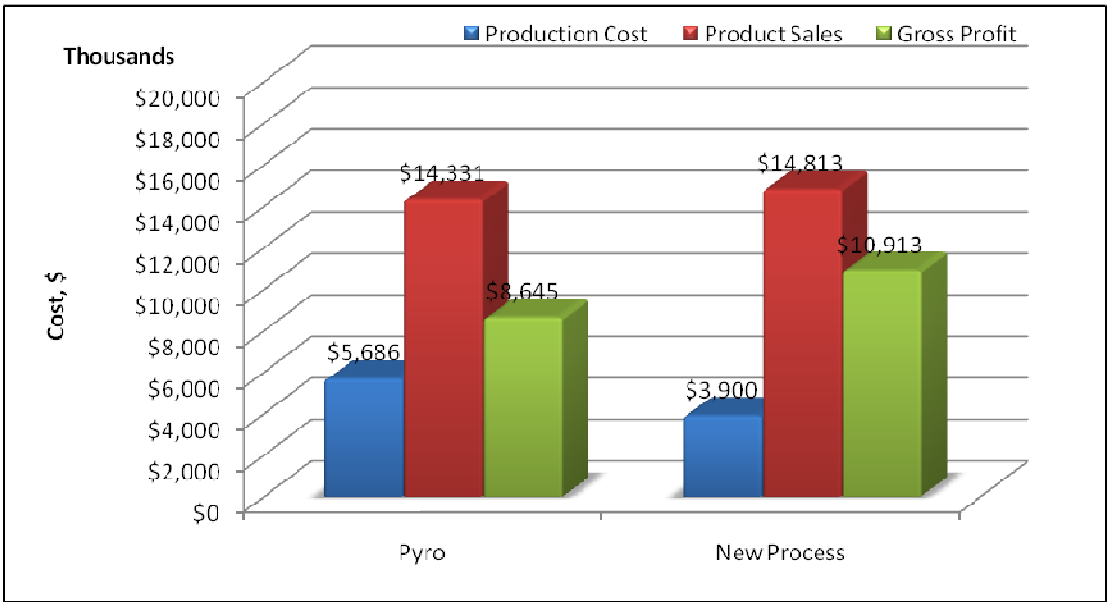
4.6 Sensitivity Analysis

We identified that the price of consumables and the types of final product are important parameters for the new technology. Hence a sensitivity analysis was conducted.

4.6.1 Scenario 1: Final product lead with low grade low cost consumables

Fluctuations in the price of citric acid and tri-sodium citrate, or in the grade of these materials used, would affect the financial viability of the new process. Industrial grade citric acid, which is used in cleaning products, fertilizers, textiles etc., is expected to be considerably cheaper than food grade. Assuming this grade is viable for the new process, the price of $400 per tonne would reduce the consumables cost from 83% to 81%. Similar prices for the tri-sodium citrate would further reduce cost to 71%. This is still a huge chunk of the total cost and can be an important factor in any investment decision. Accommodating citric acid with acetic acid is not a viable option as the prices for high grades of these are at similar levels. One way to get around this would be to source a waste stream that contains these chemicals but at very low grades. At these scenario conditions the overall profit has improved considerably for the new process, due to low running costs (Figure 20). Profit margins can be further improved if a waste stream were established for these chemicals where the prices would be very favourable. However, we found that the biofuel industry is also chasing for organic carboxylic acid. We identified one source of waste acidic acid (50% w/v) where the price was quoted at £50 per tonne.

Figure 20: Effect of using low cost low grade consumables on gross profit, with lead as the final product



4.6.2 Scenario 2: Final product battery paste with food grade consumables

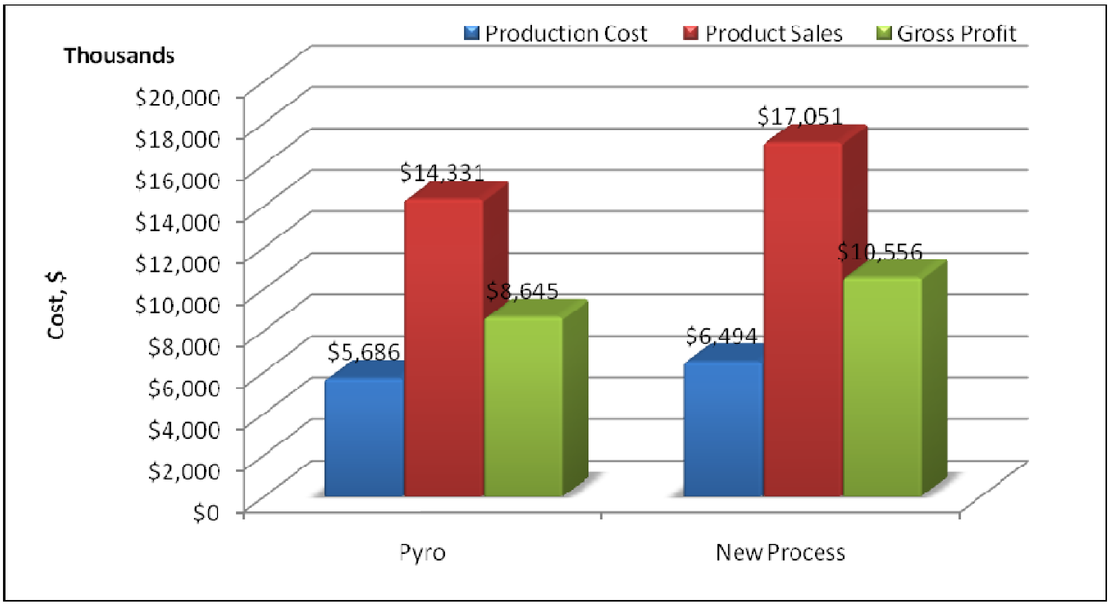
The new process claims to be able to produce a mixture of $Pb/PbO/PbSO_4$ depending on the requirements for a ready-to-use lead paste. This is unique in that lead compounds (litharge, red lead, lead oxide) used to form the active mass normally require additional production methods. The predominant processes are the 'ball mill' and the 'Barton pot' processes. These, and other methods, produce oxides with characteristics which are unique to each. The oxide properties (particle size and shape, surface area, crystal structure, purity, and degree of oxidation) can, individually or in combination, affect the battery. With today's manufacturers making mixed product lines that range from deep cycle to automotive lead acid to valve-regulated lead/acid (VRLA) batteries and everything in between, lead oxidation machinery and processes must be able to respond accordingly to produce materials that meet appropriate specifications. Oxide equipment and operating techniques are improving in response to those characteristics that the ongoing research by industry indicates are - or will be - beneficial to overall battery performance[a].

Our consultation with battery manufacturers indicates that mixtures of Pb/PbO or perhaps $Pb/PbO/PbSO_4$ at various ratios are very beneficial to a battery manufacturer. Battery manufacturers tend to make their own Pb/PbO mix by using one of the above or similar processes and adding $PbSO_4$ (or form in-situ during sulphuric acid mixing) and various binders. Details of this stage changes as the final composition of the battery paste itself changes depending on the manufacturer and type of battery.

We assume a 25%Pb / 75%PbO mixture as the final product composition. Battery manufacturers calculate the price of PbO on the basis of London Metal Exchange (LME) lead prices, normally $250-300 per tonne above the LME price for lead plus $100 manufacturing cost. We used $400 extra over the LME price for this analysis. Under this scenario conditions the new process is still considerably profitable even using high cost food grade consumables (Figure 21).

[a] Lead oxide technology—Past, present, and future, Journal of Power Sources, Volume 73, Issue 1, 18 May 1998, Pages 47-55

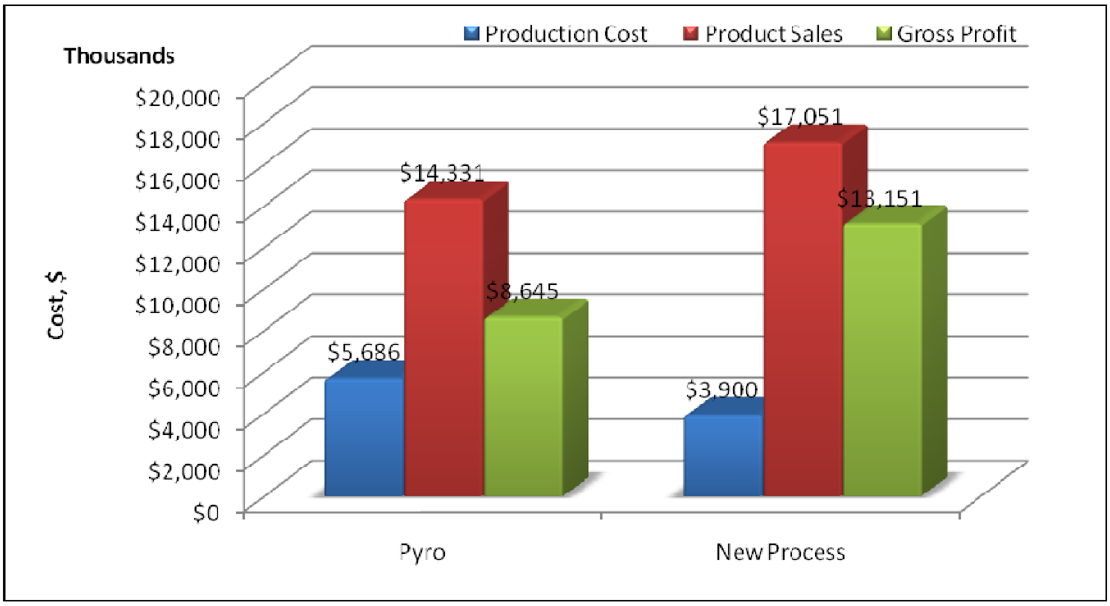
Figure 21: Gross profit using food grade consumables, with ready paste as the final product



4.6.3 Scenario 3: Final product battery paste with low grade consumables

In this scenario we assume that low grade citric acid and tri-sodium citrate at low cost ($400 per tonne each) is available to produce a Pb/PbO mix ready for the battery manufacture. In this scenario the new process achieved about 67% more gross profit than the pyrometallurgical process (Figure 22).

Figure 22: Gross profit using low grade low cost consumables, with ready paste as the final product



5 The pilot plant

5.1 Capital Costs

Due to legislation around lead production, we have costed the pilot plant on the basis that it would be a part of an existing plant. This will not only provide a low cost solution for the pilot plant but also shorten the time to commercialisation. As part of an existing plant, such as an existing battery recycler and manufacturer, the pilot plant utilizes the battery paste as starting material. The scale of the pilot plant not only depends on the cost but also the credibility of its production scale by the industry for full commercialisation. Cost estimation was done using our own experience of the costs of process operations, with additional information from industry and pilot plant process suppliers.

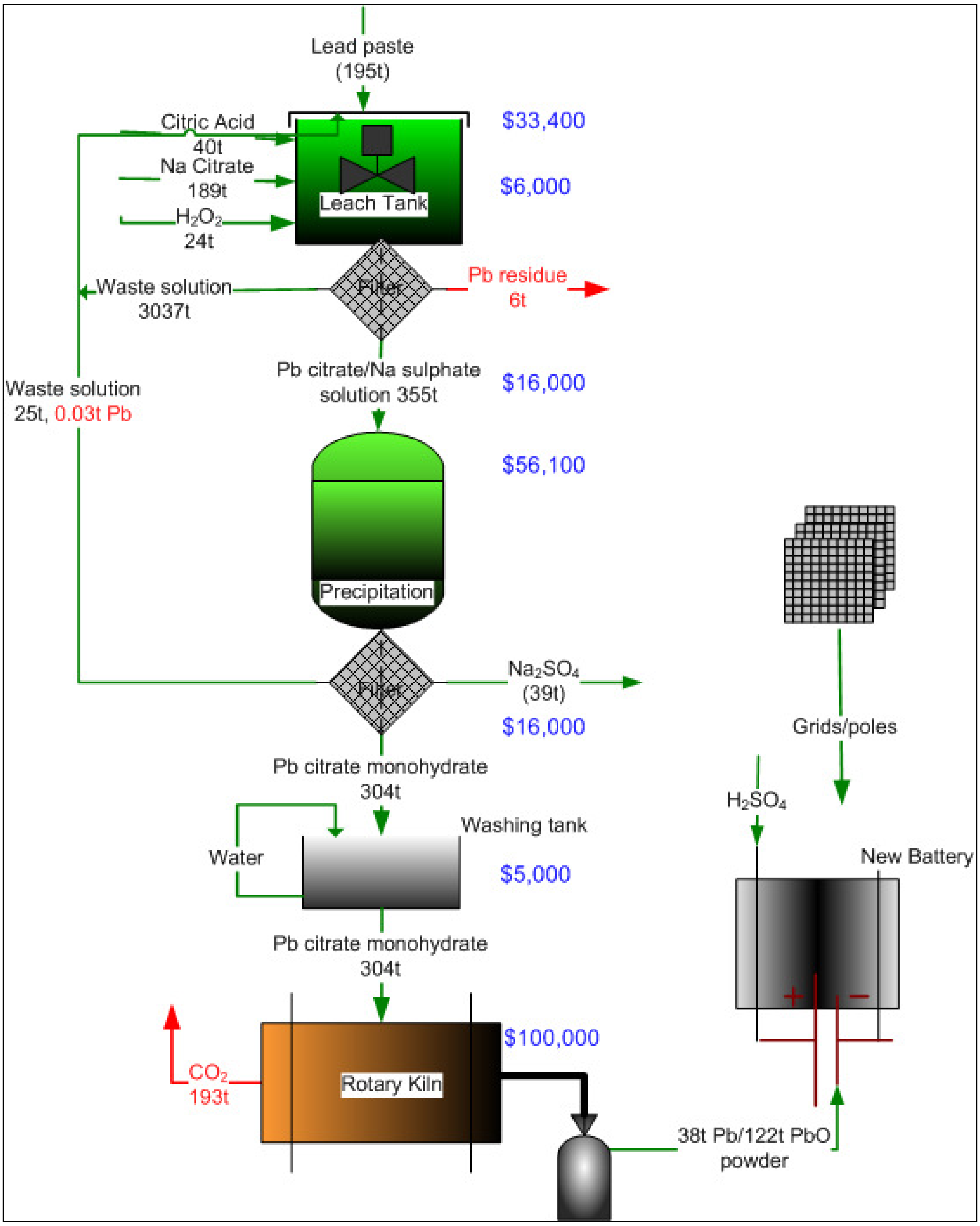
In line with process flow shown in Figure 14, the pilot plant requires the following equipment:

- Leaching tank for taking lead into citric acid solution
- Propeller type mixer for the leaching tank
- Filter for lead citrate solution/solid waste separation
- Precipitation tank for lead citrate precipitation
- Filter for lead citrate precipitate/waste solution separation
- Washing tank for the lead citrate precipitate
- Rotary kiln for calcination of lead citrate to lead and lead oxide.

The pilot plant is designed with a capacity of 365 tonnes battery per year. Assuming 55% of the recycled battery is paste with a composition of 3% Pb, / 12% PbO / 25% PbO_2 / 60% $PbSO_4$, 195 tpa paste is treated by the pilot plant (3% losses assumed during the separation stage). The process flow of the pilot plant, along with equipment costs, is shown in Figure 23.

The total cost of the pilot plant is estimated to be around \$232,500: including contingency premium of 25% the cost is about \$290,625.

Figure 23: Process flow and cost of a pilot plant



5.2 Potential Partners

Potential collaborators in building a pilot plant for the proposed new technology may be found either among existing battery recyclers or manufacturers. Partnership with recyclers has the advantage that the latter already have in place the necessary infrastructure for the preliminary steps common to established processes (e.g. battery recovery, breakage, neutralisation, etc.). On the other hand, battery manufacturers may also see an interest in investing in the new technology as access to its end-products (lead and lead oxide), will allow them to 'close the loop'. With growing pressure on 'producer responsibility', this is becoming an important consideration. There is also an economic case for recycling batteries given the very high prices of lead metal.

The current process requires access to the spent battery paste. In well-regulated regions such as the EU and North America this would only be feasible through forging partnerships with existing battery recyclers, as they will be the only entities with the capability (and licences) to break apart batteries, which is a complex business subject to health and safety regulations. Existing plants will already have invested heavily in smelters, therefore in order for Cambridge Enterprise's new process to seem attractive to potential partners it has to make commercial sense. This seems certainly to be the case in our broad evaluation of the investment cost for the new technology. The environmental or technical advantages of the process will be of limited interest to UK, EU or North American battery recyclers unless it can also save them money, as such companies will already be complying with all the relevant environmental legislation. The implementation of the new Battery Directive in EU member states in September 2008 is, in the UK at least, unlikely to have much impact on the lead acid battery recycling sector which is already seen to be operating to a very high standard. For example, Enthoven in Derbyshire, currently the UK's only functioning secondary smelter, is already recycling the lead, acid and plastic from batteries very efficiently.

Existing pyrometallurgical processes are unlikely to take up the technology in the short run, as being able to deal with both paste and metallic parts of the battery in one process seems appealing. Although the pyrometallurgical process is more energy intensive and polluting than the new process, the industry complies with the regulations for lead. For that reason we believe existing battery recyclers and/or battery manufacturers should be targeted as potential users of this new technology. The new technology:

- Provides an opportunity to add extra value to final products for an existing battery recycler.

- Provides opportunity for a low cost and environmentally sound recycling technology for an existing battery manufacturer. This would also serve for product end life legislations and reduce the manufacturing cost of batteries.

- Provides a low cost final product ready to use in the battery paste preparation for existing battery manufacturers and recyclers. Being able to modify the composition of the final product, particle size and distributions are extra benefits to explore for better battery efficiency.

We identified a battery manufacturer and recycler based in Turkey. İnci Akü San. ve Tic. A.Ş. is the second biggest lead battery producer in Turkey with a production capacity of three million units. The company is currently expanding to increase capacity to four million units. Due to high lead prices they have decided to recycle batteries and have been working on alternative recycling processes for three years. They have been using a modified version of electro-winning process for about one year. Currently, about 3,600 tonnes of batteries are recycled each year in the plant, but there is potential to increase this capacity further (up to 10,000t per year).

The company has been introduced to the new technology and has expressed an interest. The current set-up of their operation is perfect for the new technology, as paste and metallic parts are processed separately - as in our process flow (Figure 14).

In the UK, battery manufacturer Yuasa based in Gwent is aware of the technology. However, they currently do not recycle batteries. They might be convinced to implement the new technology if financial and environmental benefits are presented.

6 A market-entry strategy

Transferring a new technology from the lab bench to the market is extremely difficult. This is particularly true when attempting to introduce a hydrometallurgical process into an industry dominated by pyrometallurgy. According to Brian Wilson of the International Lead Management Centre, the secondary zinc industry is far more likely to be receptive to hydrometallurgical processes than their counterparts in the lead industry. A competing hydrometallurgical process claiming to be 'environmentally sound' developed almost a decade ago[a] has yet to reach market, despite the construction of at least one pilot plant in Madrid. Investment (from the Philippines) in this process, which is quoted as "excellent", was nearly completed but fell through recently.

The most fruitful areas to investigate for market entry would likely be in the developing world, where demand for lead acid batteries is rising. As well as China, Africa is a promising location as rates of car ownership are anticipated to rise rapidly in the near future. Small pyrometallurgical plants have recently opened in Kenya and Senegal.

Opportunities may also lie closer to home. In Eastern Europe, for example in Romania or Kosovo, many of the older lead smelters are starting to be upgraded, and scope may exist to apply for an EU grant to use the new process here[b]. Turkey also has good prospects as discussed above.

Overall, based on our work we are proposing the following key criteria for market entry strategy:

- Countries where environmental legislation is mature and fully established should be avoided (since existing lead recycling technologies will be well adapted to the legal landscape). Similarly, locations where legislation is either non-existent or ignored should also be avoided (because the proposed technology would not be competitive with existing 'dirty but cheap' operations).
- Trusted and enthusiastic partner with existing lead infrastructure for H&S (battery manufacturers or secondary lead refiners). Other partners may be possible, but should possess battery breaking facilities (large scale battery collectors/dismantlers).

[a] **Andrews D., Raychaudhuri A., & Frias C.** 2000. Environmentally sound technologies for recycling secondary lead. *Journal of Power Sources*, **88**, (1), May 2000, pp. 124-129(6).
[b] Brian Wilson, International Lead Management Centre, Personal Communication.

- Cheap source of citric acid/sodium citrate, preferably waste stream source.

- Growing major market segments such as automotive SLI, electric scooter, possibly off-grid energy storage.

We recommend pursuing the exploitation of this technology in China and especially in Turkey.

We also recommend extensive dialogue with the battery manufacturers to gain further understanding of their requirements for battery paste. It may be possible to further add value with the exploitation of the possible beneficial effects to the efficiency of the final product. Particle size and uniformity of the paste-ready powders are important parameters for the final efficiency of the battery. Lead oxide powders from the new process might have an extra edge for these properties over powders from existing processes since these are claimed to be tailored by controlling the process conditions.

The process provides versatility and flexibility, which can be implemented as a whole or part of an existing operation. It is a scalable, cost effective process and can easily be adapted to local industrial conditions and requirements.

Sustainability is fundamental to the development of the new Cambridge process, through lower waste emissions, obtaining savings in operating and environmental costs, and reduction of toxic wastes or slags generated by conventional smelting processes.

Although the prospect of producing paste-ready product from waste batteries is appealing at first sight, the very low cost of converting metallic lead into paste-ready powder (which is the current practice among battery manufacturers) limits this appeal. Moreover, a market for ready-to-use powder does not exist, perhaps because paste compositions change from one manufacturer to other. Another reason might be low cost production of powder from metallic lead.

7 Conclusion

We conclude the following from this study:

1. The new technology:
- Does have low carbon potential
- Does show cost advantages in principle
- Can be competitive, largely depending on the citric acid and sodium citrate pricing.

2. A viable market strategy can be developed (but use key criteria).

3. On the basis of our assumptions a one tonne per day pilot plant is a good scale to demonstrate the feasibility of the technology within a cost of $290,000.

4. Our market study suggests:
- USA and UK are not viable as they have mature and established markets
- India is not feasible due to lack of enforcement of legislation
- China and Turkey are very positive as developing countries: China due to its huge market and emerging legislation; Turkey because it is a potentially growing market with legislative measures, where we have established contact with an enterprise interested in the technology.
- Brazil is a possibility, but with stiff competition from established players; however there are openings to explore new technologies.

5. For future work we suggest:
- Creation of a consortium to evaluate the process at a pilot scale and to commercialise it internationally if successful (which may require different partners), including obtaining funding streams, either internal or external to the consortium.
- Further discussions with battery manufacturers on requirements for the final product.
- Exploitation of the possible beneficial effects of particle size and uniformity.
- Exploitation of the potential for process step reduction by the new product from paste making to final battery (conditioning, curing etc.).

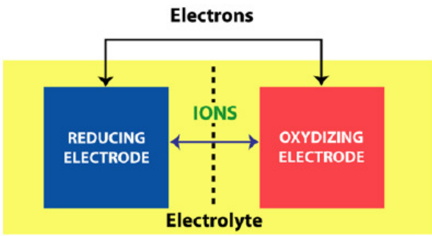
Appendix I: How Lead Acid Batteries Work

EUROBAT

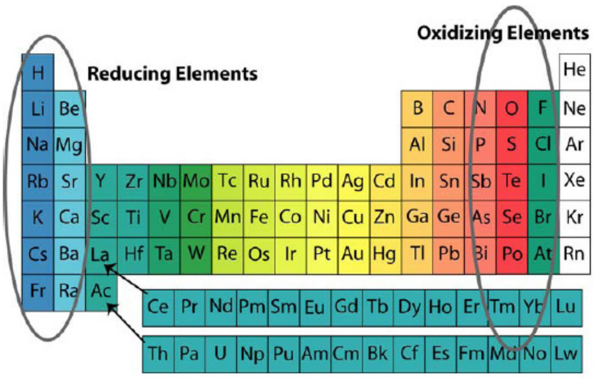
1 STATE OF THE ART

1.1 Battery basics

A battery is an energy storing system based on electrochemical charge/discharge reactions. During discharge the chemical energy is converted into electrical energy and during charge the energy is reconverted into chemical energy. In a primary battery system only the discharge reaction can be used. A secondary or rechargeable battery system is characterized by a charge/discharge reaction that is reversible.



The higher the reversibility the more discharge/charge cycles can be performed. The electrical energy stored in a battery is directly related to the chemical energy being stored. The cathode incorporates an oxidizing material, the anode a reducing component. The laws of nature have fixed limits to specific energy of electrochemical systems from the periodic table of elements:



The maximum theoretical specific energy is attained for Lithium and Fluorine at 6,085 Wh/kg. However, most chemical reactions cannot be used in a battery system because they are not reversible in an electrochemical cell.

Batteries have to be distinguished from fuel cells and capacitors. A capacitor is based on a reversible separation of charge with a significant lower energy, compared to a chemical reaction associated with a battery technology. Fuel cells convert chemical energy into electrical energy without the ability to be recharged by electrical power. Whenever energy has to be reversibly discharged and recharged at high energy density, and with high efficiency, a battery is the most suitable energy storage system.

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Source: **EUROBAT.** 2005. *Battery systems for electrical energy storage issues.* Battery Industry RTD Position Paper, July.

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1.2 Main Battery technologies

Although a broad range of different electrochemical systems and battery technologies exists today three systems dominate the current market:

- Lead-Acid battery technology
- Alkaline battery technology
- Lithium Ion battery technology

The selection of one of these technologies depends on the requirements regarding performance, life, safety and cost. As described in Section 2, the selection of the battery system depends on the application.

1.2.1 Lead-Acid battery technology

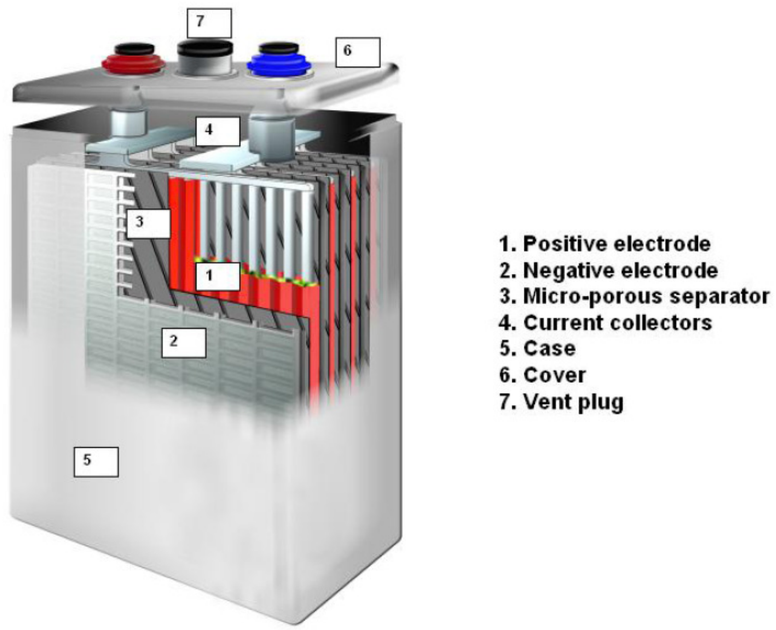
The lead-acid technology is the most widely used electrochemical system.

The lead-acid battery is based on:

- Lead dioxide as the active material of the positive electrode,
- Metallic lead, in a high-surface-area porous structure, as the negative active material,
- Sulphuric acid solution.

In fact, lead-acid technology is composed of several sub-technologies according to the battery design and the manufacturing process:

- Flooded lead-acid batteries,
- Valve-Regulated Lead-Acid (VRLA) batteries with electrolyte immobilized by a gel,
- VRLA batteries with the electrolyte immobilized in an absorptive glass mat (AGM)



Source: **EUROBAT.** 2005. *Battery systems for electrical energy storage issues.* Battery Industry RTD Position Paper, July.