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Lithium Ion Battery Recycling Technology 2015

Current State and Future Prospects

ESA REPORT # 2015:18

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Document Purpose and Use

This document assembles key results from work during the Realize project, and references to state-of-the-art literature and data on lithium battery recycling processes. The document itself is not peer reviewed, but most of the primary sources are.

The intent is to function as a quick reference suitable for use by researchers and engineers. An overview of many topics relevant to lithium battery recycling is presented, along with links to primary sources.

- Duncan Kushnir, curator

Realize
Realizing resource-efficient recycling of vehicles

MISTRA
Stiftelsen för miljöstrategisk forskning

Realize is an interdisciplinary project aimed at finding viable paths to resource-efficient recycling of vehicles.

Realize was funded by MISTRA, and ran from 2012-2015 with a consortium of industrial partners

LIST OF ACRONYMS

ADP	Abiotic Depletion Potential
AP	Acidification Potential
BMS	Battery Management System
DMC	Dimethyl Carbonate
EBRA	the European Battery Recycling Association
EC	Ethylene Carbonate
EEC	European Economic Community
EES	Electric Energy Storage
ELIBAMA	European Li-Ion Battery Advanced Manufacturing
EOL	End of Life
EP	Eutrophication Potential
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
GHG	Green House Gases
GREET	GReenhouse Emissions and Energy in Transport (Argonne Lab Model)
GWP	Global Warming Potential
HTP	Human Toxicity Potential
LCA	Life Cycle Analysis
LIB	Lithium ion Batteries
NMP	N-Methyl-2-pyrrolidone (common solvent)
PHEV	Plug-in Hybrid Electric Vehicle
POCP	Photochemical Ozone Creation Potential
PVDF	Polyvinylidene fluoride
RECHARGE	the International Association for Advanced Rechargeable Batteries
UN	United Nations
WEEE	Waste Electrical and Electronic Equipment

Contents

Introduction

This section contains a concise introduction to lithium battery technology with a focus on the material contents of various components and battery chemistries. Cells are the focus because other components in a battery pack have well established recycling chains.

Estimates of future battery production are included, along with links to relevant legislation regarding recycling them.

i. Brief introduction to lithium batteries

ii. Contents of a lithium battery

iii. Lithium chemistries and scarce materials

iv. Battery trends and projections

v. Legislation regarding lithium batteries

On recycling lithium ion batteries

Lithium batteries are at present the dominant potential solution for ending the dependence of transport systems on fossil fuels. Vehicles containing lithium batteries account for only a tiny fraction of vehicles put on market today, but their share seems set to grow rapidly. In time, lithium batteries may represent fairly large material flows in the ELV system, and, as they may contain a number of strategic metals, the question of how to recycle them and ensure circular flows of materials deserves some foresight. Alongside this reason, batteries also contain a number of potentially hazardous materials, making recycling an imperative for other reasons as well.

There are some 'off the shelf' solutions for recycling at present, but the actors involved charge gate fees of approximately 4€/kg of battery, and the processes used can not reclaim all of the metals in batteries. What are the prospects of reclaiming these metals? Of achieving cost effective recycling?

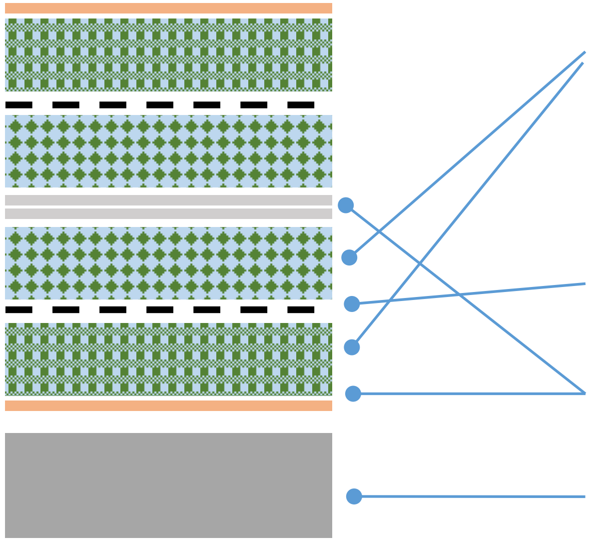
i. Brief introduction to lithium batteries

Lithium ion batteries are an ideal system for electricity storage

- LIBs (Lithium-Ion batteries) are rechargeable batteries that store energy through reversible intercalation of lithium ions.
- LIBs do not involve full redox reactions and thus manage to avoid many of the lifetime and power limiting problems of fully chemical battery mechanisms
- The ratio of ionization potential to atomic weight for lithium is higher than that for any other element, resulting in energy densities that will be difficult to match with any other electric storage technique

ii. Contents of lithium batteries

The main elements of a lithium cell are:

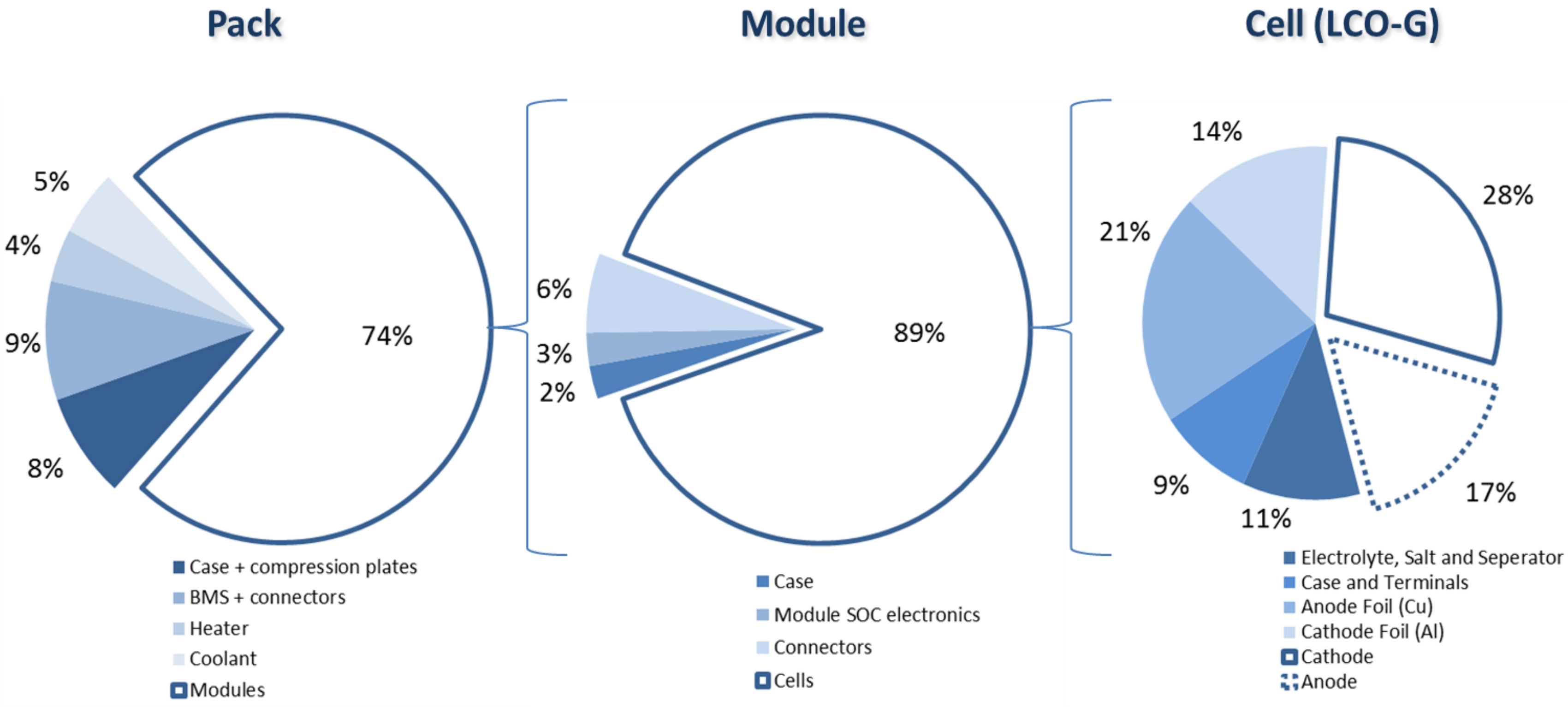


Cathode/Anode:	’Active materials’ intercalating Li+ ions (*various*)
Electrolyte:	solid or liquid allowing movement of Li+ ions (*DMC/EMC or solid polymer*)
Separator:	restricts movement of other species (*Polymer e.g. Nafion*)
Current collectors:	conduct electrons to and from cathode, anode *(Cu, Al)*
Casing:	holds other items together *(Steel, Al, Plastic)*

Most cells share common components in terms of the electrolyte, separator, foils and casing. What ultimately differentiates cell technologies is the material chosen for the ‘active materials’, e.g. the cathode and anode.

ii. Contents of lithium batteries

The remaining components in battery packs are to encase, cool, control, and distribute loads to the cells



Pack

Module

Cell (LCO-G)

Cathode materials are typically chosen to match the application

Material	Abbrev.	Voltage vs Li/Li$^+$	Specific Capacity (mAh/g)	Advantages	Disadvantages
LiCoO2	LCO	3.9	140	Performance, well understood	Safety, uses nickel and cobalt
$LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$	NMC(333)	3.8	160-170	Better safety and performance than LCO	Cost, nickel and cobalt
$LiFePO_4$	LFP	3.4	170	Excellent power, lifetime and safety, abundant materials	Low energy density
$LiMn_2O_4$	LMO	4.1	100-120	Cheap, abundant, high power	Lifetime, low capacity means low energy density
- *future possibilities* -					
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	NCA	3.8	180-200	High capacity and voltage, high power	Safety, cost, uses nickel and cobalt

ii. Contents of lithium batteries

A carbon is nearly always chosen for the anode. Materials such as LTO offer lifetime and power at the expense of energy density and cost.

Material	Abbrev.	Voltage vs Li/Li$^+$	Specific Capacity (mAh/g)	Advantages	Disadvantages
Graphite	G	0.1	370	Decent lifetime, well understood, abundant	Inefficiency due to SEI formation
Li4Ti5O12	LTO	1.5	170	Excellent power and cycle life	Lower voltage means less energy, cost
- future possibilities -					
LiFeSiO4	LFS	0.3	up to 2000+	Vastly better energy density than traditional anodes	Very short lifetime at present

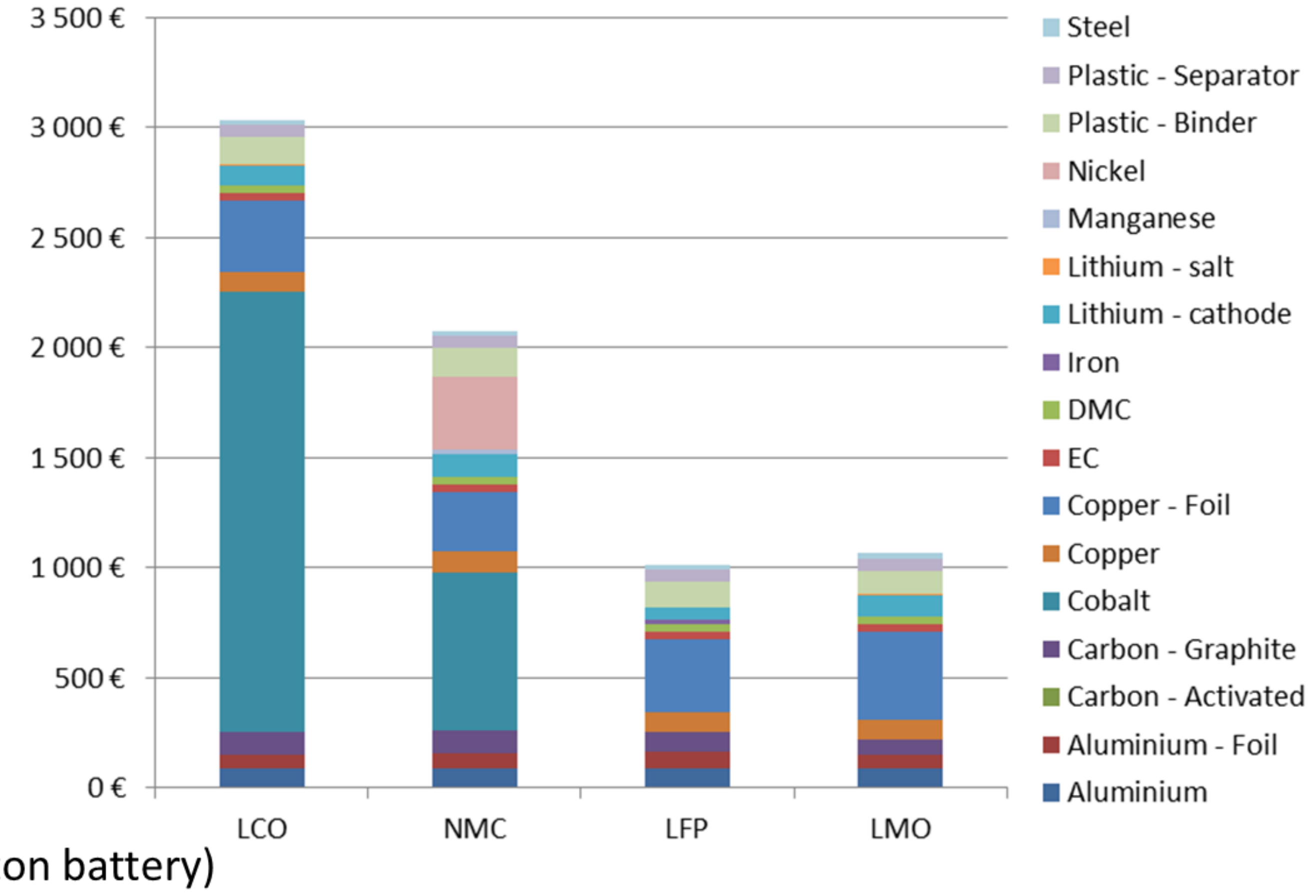
ii. Contents of lithium batteries

Material value in several cell chemistries

Calculated by taking the market price of the pure material (Dec 2014) multiplied by the mass percentage in the cell.

The majority of value in cells comes from Cobalt or Nickel. Copper represents about half of the remainder.

(Source: can be reconstructed from appendix B)



iii. Lithium batteries and scarce materials

Cobalt and Lithium are the most constrained materials. Nickel is important to recycle for environmental reasons.

Calculated by taking the USGS estimates for resource base and annual production, and comparing it to the material contents in the cells for NMC batteries which are estimated to be the most produced variant in 2025.

Can be reconstructed from appendix B. Table links to USGS.

Material	Availability (Mt, resource base)*	Production (2012, kt)*	Supply Constrained Stock (kWh)	Production Constrained Rate (kWh/y)
Cobalt	13	110	13×10^9 (LCO) 28×10^9 (NMC)	110×10^6 (LCO) 260×10^6 (NMC)
Nickel	150	2100	375×10^9	$5\,250 \times 10^6$
Lithium	30	26	60×10^9	152×10^6
Manganese	5200	16 000	$5\,777 \times 10^9$ (LMO) $14\,900 \times 10^9$ (NMC)	$13\,900 \times 10^6$ (LMO) $42\,000 \times 10^6$ (NMC)

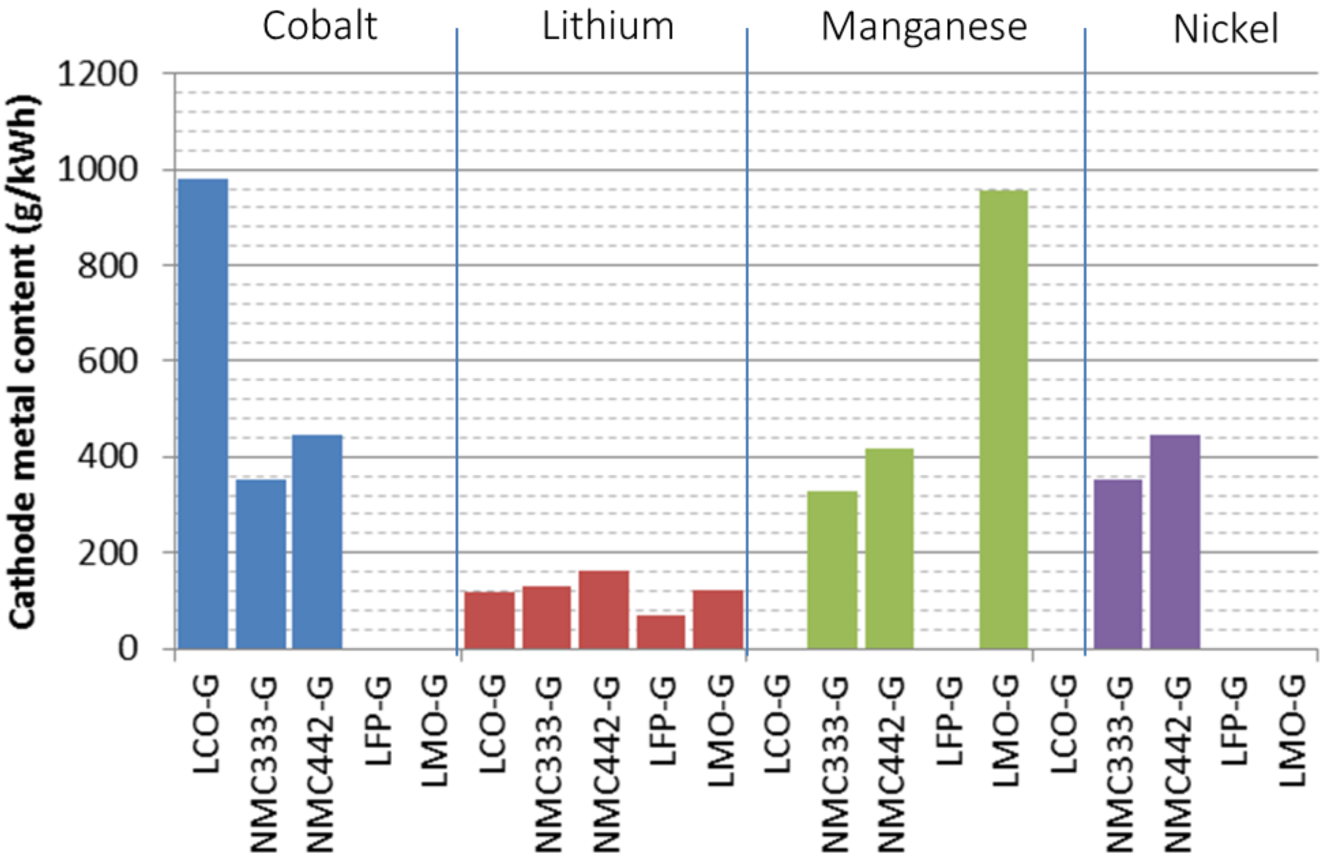
Table Sources: *USGS 2013 Resource Handbooks: stock and rate calculated with data from this document

These estimates should not be taken as immutable; as demand and price rise, more production will occur and more resources will become available.

Other potentially constrained metals vary by chemistry

Cobalt and Lithium are the most interesting from a scarcity perspective. Nickel is highly toxic in the environment. Manganese is a lower order of worry in both scarcity and environmental terms.

Can be reconstructed from appendix B.

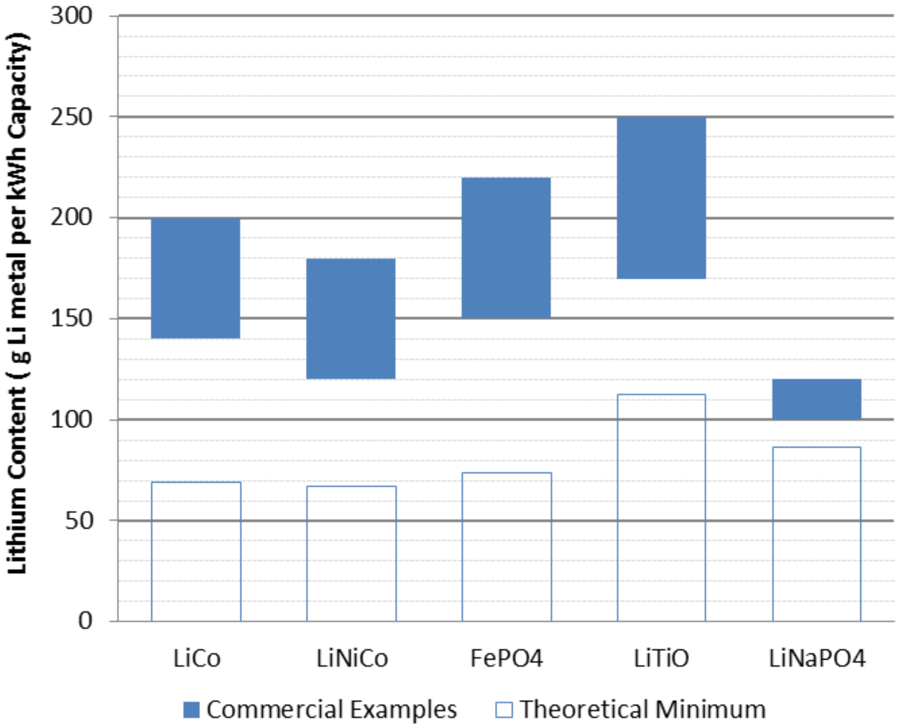


iii. Lithium batteries and scarce materials

Lithium content of batteries is mostly a function of voltage and cathode thickness.

- 160 g Li / kWh as an all-chemistry average estimate for BEV batteries
- Possibly 250-400 for PHEV batteries (Gaines, ANL., GREET MODEL)
- No clear way to use less metal without less life or lower energy chemistry

(source: Kushnir & Sandén 2012, linked from graph)



iv. Trends and projections

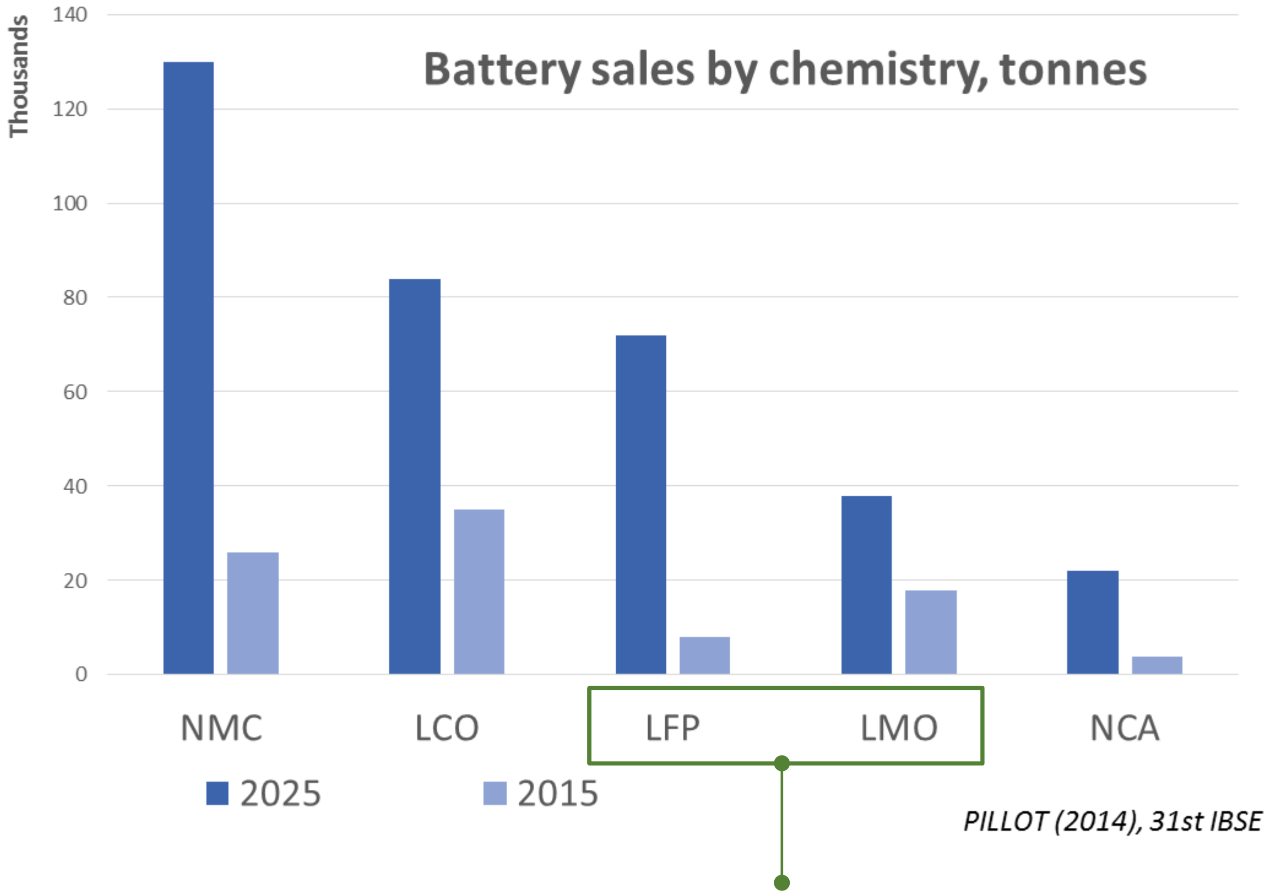
Anticipated sales by chemistry, in tons

Nickel and Cobalt containing chemistries seem likely to remain dominant for at least another decade.

This has more to do with mobile devices than vehicles. LFP batteries are used in EVs and power tools and are anticipated to have the fastest growth rate.

(*graph contains link to latest source*)

Virtually all projections indicate similar results: fast growth and a mix of technologies



PILLOT (2014), 31st IBSE

Very low material value in batteries

v. Legislation regarding lithium battery recycling

The EU has much more stringent laws than the US regarding battery recycling. However batteries can not be landfilled in either region, and advanced recycling companies and voluntary recycling networks exist in North America .

In addition, all OECD nations have regulations considering the transport of batteries by road, rail, or sea transport.

EU Battery Directive (2006/66) (Link)

- 45% batteries recovered by 2016
- 50% of mass recovered by recycling
- Energy recovery does not count

North America

- Patchwork of state level laws in US
- Mandatory recycling in BC,QUE,SAS in Canada

Common

- Hazardous waste cannot be landfilled

Recycling Processes

This section describes the physical process and theoretical potential of each recycling process for cells. Recycling for other components of a battery pack, such as electronics is excluded. Such components have well defined recycling pathways (e.g. WEEE), and are easy to separate.

i. Pyrolysis

ii. Hydrothermal recycling

iii. Direct physical recycling

iv. Process comparisons

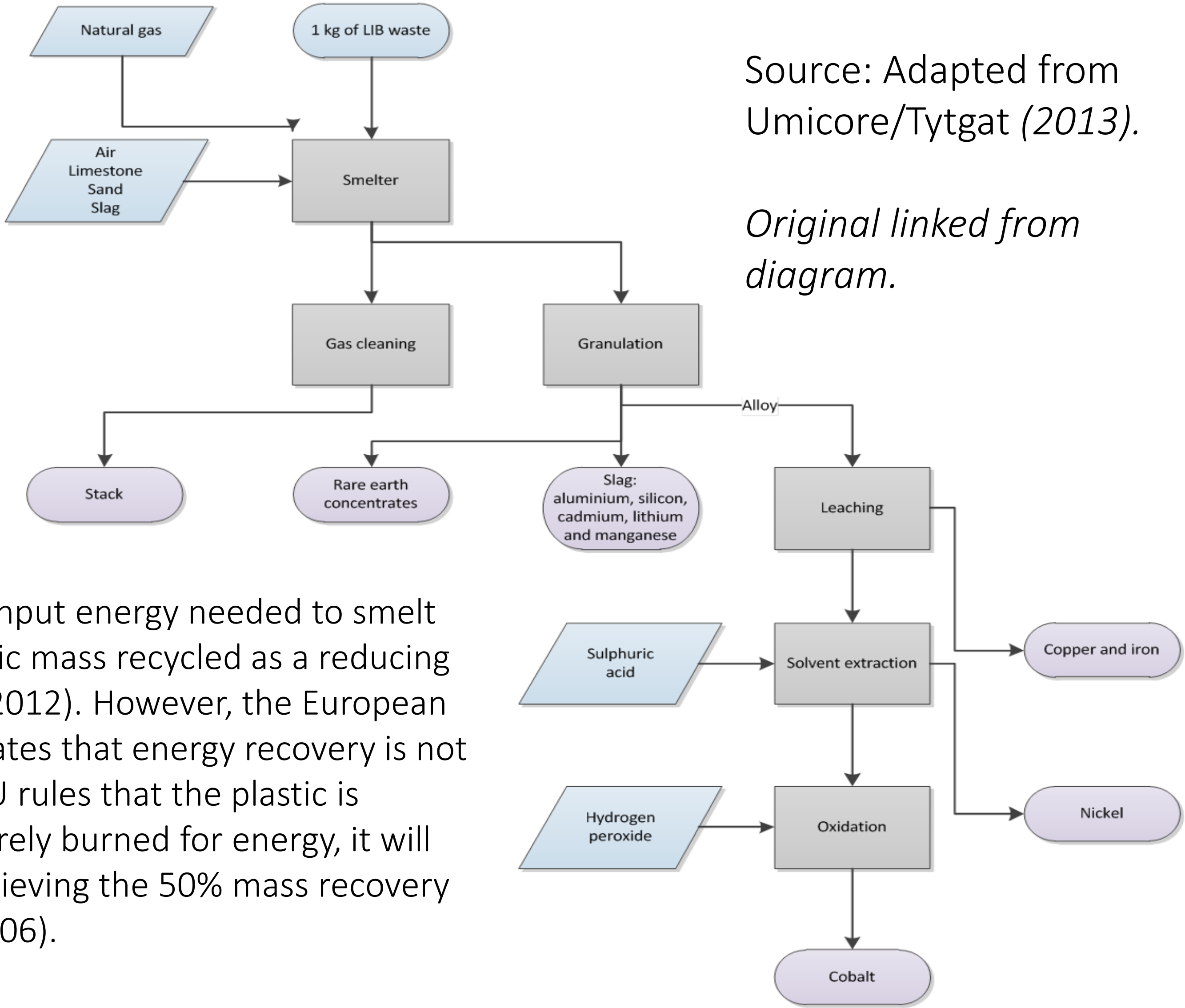
i. Pyrolysis

Pyrolysis means melting and reducing the battery materials to obtain metals

The process used by Umicore is a good illustration of pyrolysis approaches in general, both because Umicore is one of the largest battery recyclers at present, and because they have been transparent releasing process data (Tytgat 2011, Umicore 2013).

i. Pyrolysis

Batteries are shredded and smelted in a furnace where limestone is added as a slag-forming agent. The furnace has three heating zones. First, by slowly heating the battery waste, the risk of explosion reduces and the electrolyte evaporates. In the next zone with a higher temperature, all the plastic and solvents in the battery are burned.



Source: Adapted from Umicore/Tytgat *(2013).*

Original linked from diagram.

The energy released greatly lowers the input energy needed to smelt the battery. Umicore considers the plastic mass recycled as a reducing agent in the process (Dunn and Gaines 2012). However, the European Union (EU) battery directive explicitly states that energy recovery is not considered recycling (EU 2006). If the EU rules that the plastic is indeed a reducing agent rather than merely burned for energy, it will place the pyrolysis method closer to achieving the 50% mass recovery target for batteries (European Union, 2006).

i. Pyrolysis

Advantages

Pyrolysis is highly effective at recovering Nickel, Cobalt, and Copper in a concentrated and relatively clean alloy, with high efficiency. Other toxic solvents are burned, providing much of the process energy and removing their toxicity.

Pyrolysis processes can take more than one battery chemistry at the same time, leading to economies of scale, and simplified logistics.

Pyrolysis already exists at industrial scale, and is a mature metallurgical technique. It is an 'off-the-shelf', proven option.

Disadvantages

The inherent chemistry of the smelter traps other elements in the slag. Lithium and Manganese are the most relevant of these. The slag itself is a fairly complex material and recovering lithium from the slag is only a theoretical possibility, and even then, would be expensive and inefficient.

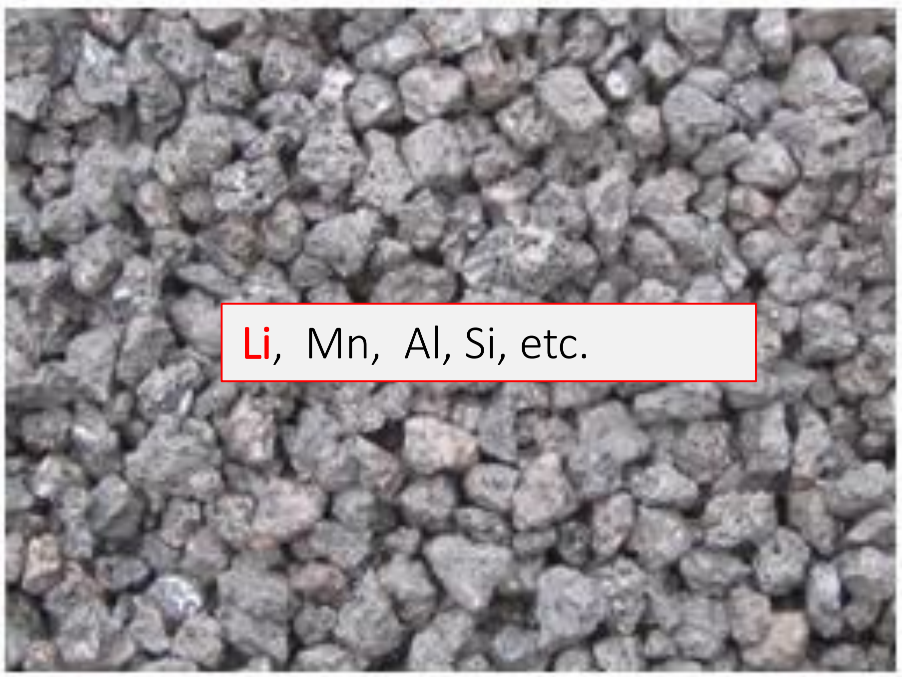
Many other chemicals in the battery are lost. From a lifecycle perspective, this is sub-optimal, and for batteries without Ni or Co, the economics are not nearly as good, leaving an open question as to suitability for future batteries. Because energy recovery does not count, the recovered mass is right on the boundary of the EU Battery Directive target (50%).

i. Pyrolysis

Lost materials and pyrolysis

There is an open question as to the potential to recover metals such as Lithium from pyrolysis slag. At present, the slag is used as a concrete additive, where it does possess some beneficial properties, but will result in the permanent scattering of its constituent materials.

If the feed for pyrolysis is pure lithium batteries (as opposed to mixed with NiMH, other types of batteries), then the slag could theoretically contain up to 1% lithium by mass. Such a concentration is roughly equivalent to marginal Spudomene mines for lithium, indicating that it may not be impossible to recover it. Such a process is unlikely to be viable with low volumes of slag however, and compared to simply selling the slag as additive would likely be very unattractive to a company considering it.



Li, Mn, Al, Si, etc.

ii. Hydrothermal Recycling

Hydrothermal processes use in-solution chemistry to isolate component chemical compounds from battery waste

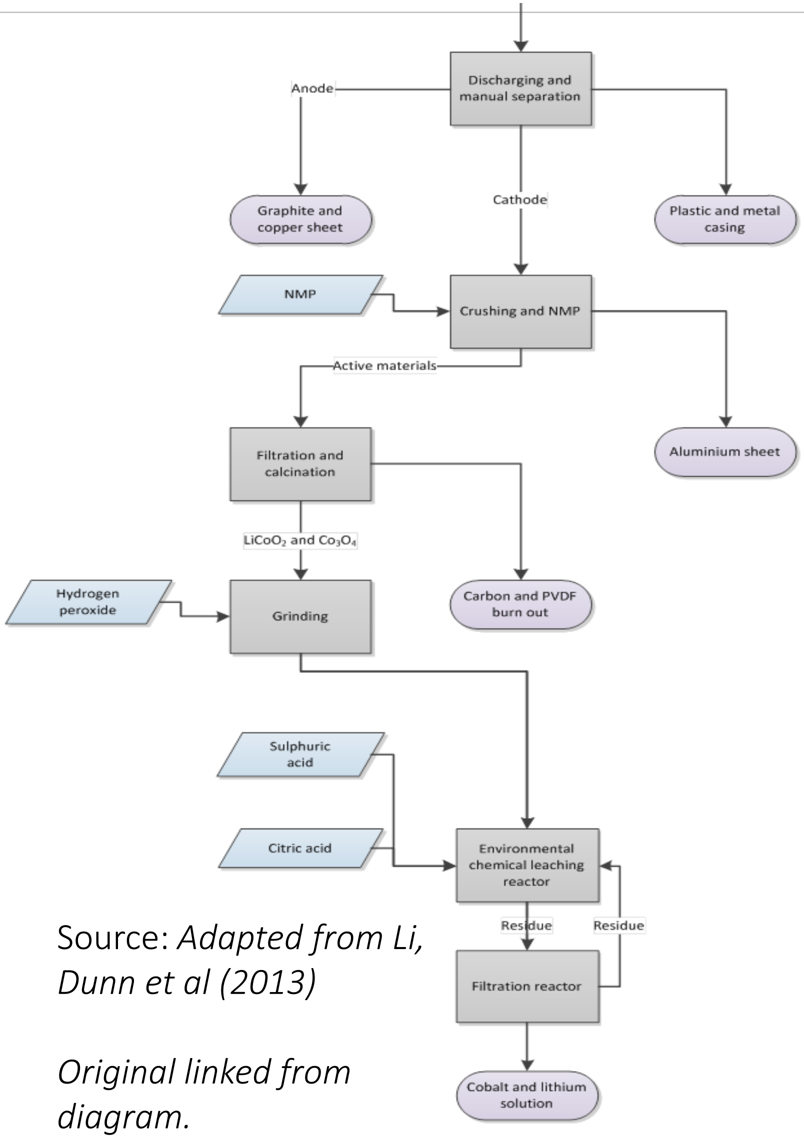
The defining aspect of hydrothermal approaches is ultimately the use of acid reactions to precipitate the salts as metals

ii. Hydrothermal Recycling

For hydrothermal processes, batteries are typically mechanically separated and the cathode materials are crushed and added to some form of solvent, such as NMP, which dissolves the binder from the cathode, and leaves the aluminium foil to be recovered with the metal oxide suspended in solution.

The NMP/water liquid is then filtered and the NMP can be recovered and reused at approximately 80% efficiency if the process is done at large enough scale to afford a recovery unit.

After isolating and drying the cathode powder residue, the metals in it can be leached out with an acid, often a strong one such as Nitric acid, but this can also be done with more ‘eco-friendly’ acids such as citric acid (*Li, Dunn et al 2013*). The metal can then be precipitated as a pure salt.



Source: *Adapted from Li, Dunn et al (2013)*

Original linked from diagram.

ii. Hydrothermal Recycling

Advantages

Hydrothermal methods of recycling are actually a collection of tailorable processes that resemble mining extraction. Through a combination of physical and chemical means, many of the constituents of a cell can be recovered in a form that facilitates easy recycling or simplified procedures to reuse as battery material.

Virtually any material can be recovered at high efficiency.

The chemistry and procedures are fairly mature due to their heritage in the mining industry, and could scale up given financial incentive.

Disadvantages

Many of the possible environmental and revenue gains from recovering more material are offset by large scale use of hot water, acids, and solvents, all of which are fairly energy intensive and bring the potential for issues with runoff without tight control of the process.

The source material needs to be known (e.g. battery chemistry) in order to tailor an efficient process. This implies that batteries must be sorted by chemistry.

The potential revenue and costs that make hydrothermal approaches promising are highly dependent on scale. Scaling is thus a chicken and egg problem.

iii. Direct Physical Recycling

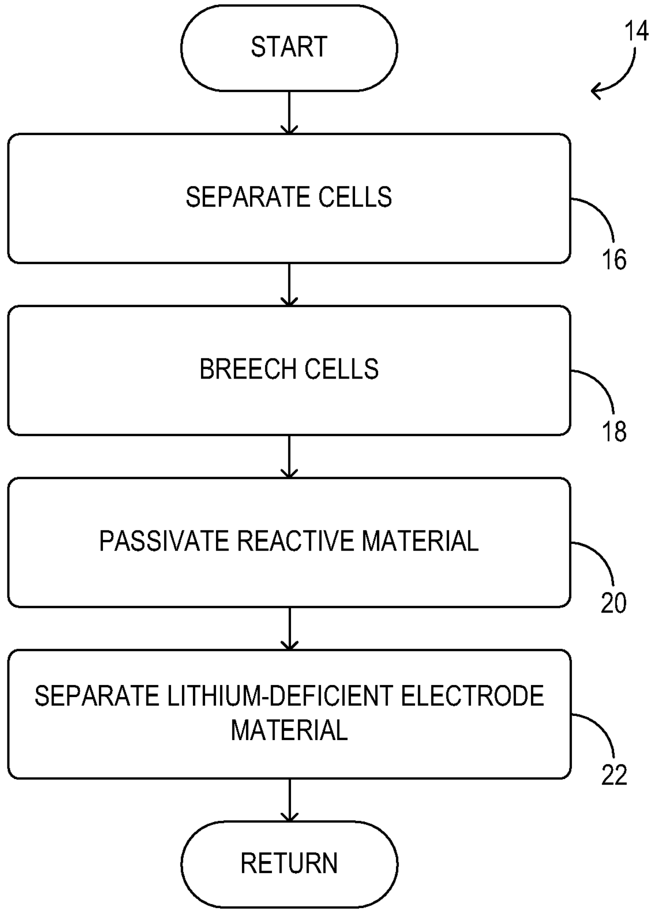
Direct recycling of battery materials means removing and refurbishing them, allowing reuse without changing their chemical form. Only demonstrated recently, has the potential to be environmentally and economically superior.

iii. Direct Physical Recycling

In the envisioned direct physical recycling process, the cells are separated from each other, breached (punctured), passivated and have the material separated. The passivation is required to make chemistries such as LCO-G safe from fire risk, and can be carried out through methods such as a controlled injection of oxidizer in solution.

Separation of the cathode material can occur physically or through transport with a solvent such as supercritical CO_2.

The recovered cathode material can then be re-baked or re-sintered with a lithium compound to restore the original properties. 100% recovery of original performance has been demonstrated as of 2015 (Sloop, 2015 : Link).



Source: US PATENT 8,846,225 *(2015).Original linked from diagram.*

iii. Direct Physical Recycling

Advantages

Direct physical recycling potentially recovers battery materials in a reusable form: this means higher revenues and lower environmental impacts.

The worst case scenario is more or less equivalent to hydrothermal recycling.

The process is not as dependent on scale as pyrolysis or hydrothermal approaches, which could have radical implications for end of life logistics; recycling may be possible in large cities, rather than having a few large sites for the whole EU.

Disadvantages

Direct physical recycling has only recently been demonstrated at a workable scale and quality.

The process depends on knowing the battery composition, meaning that battery chemistry must be known and cells sorted appropriately.

The ‘manual’ approach to breaching the cell and extracting its contents may be difficult to scale.

The process itself has no theoretical downsides, providing that the previous points can be addressed.

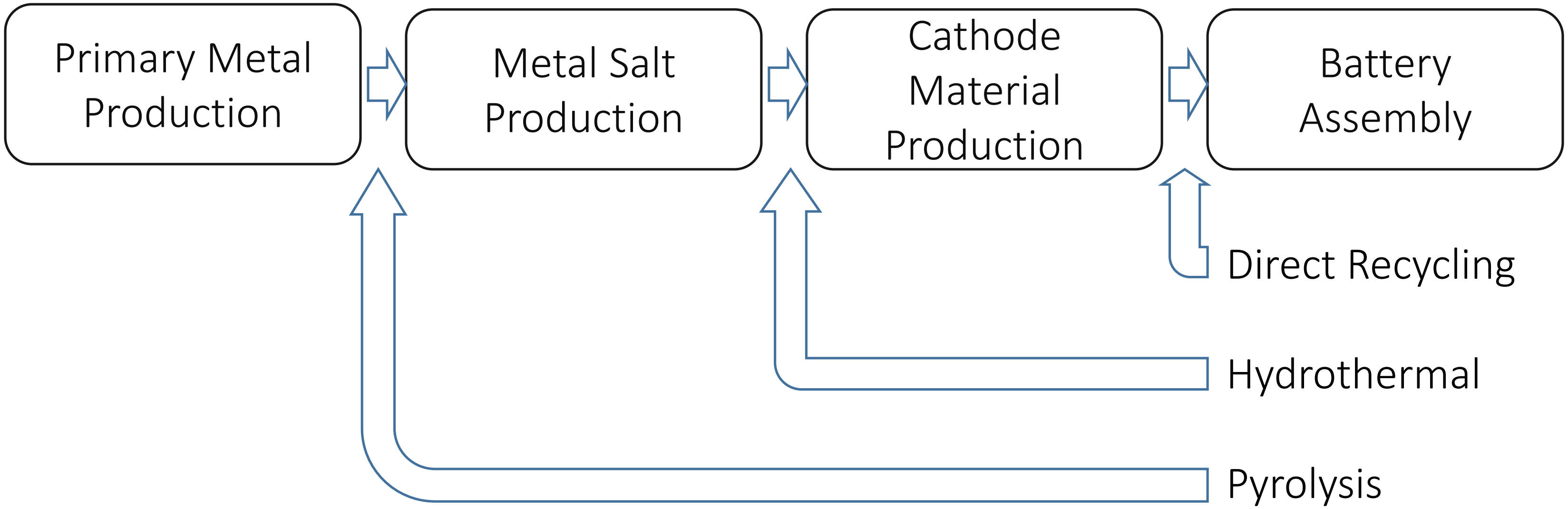
iv. Process Comparisons

There are some steps that recycling processes have in common

Discharging –	modules and battery packs can carry dangerous voltages, and the potential for adverse chemical reactions is higher with charged batteries
Passivation –	not needed for pyrolysis, passivation is removing the chemical activity of the battery contents. Can be done in many ways, e.g. cryogenic freezing or controlled oxidation
Disassembly –	once passivated and opened, the contents can be removed through disassembling the cell, or through shredding it

iv. Process Comparisons

In theory, skipping more life cycle stages should result in superior environmental performance



Primary Metal Production

Metal Salt Production

Cathode Material Production

Battery Assembly

Direct Recycling

Hydrothermal

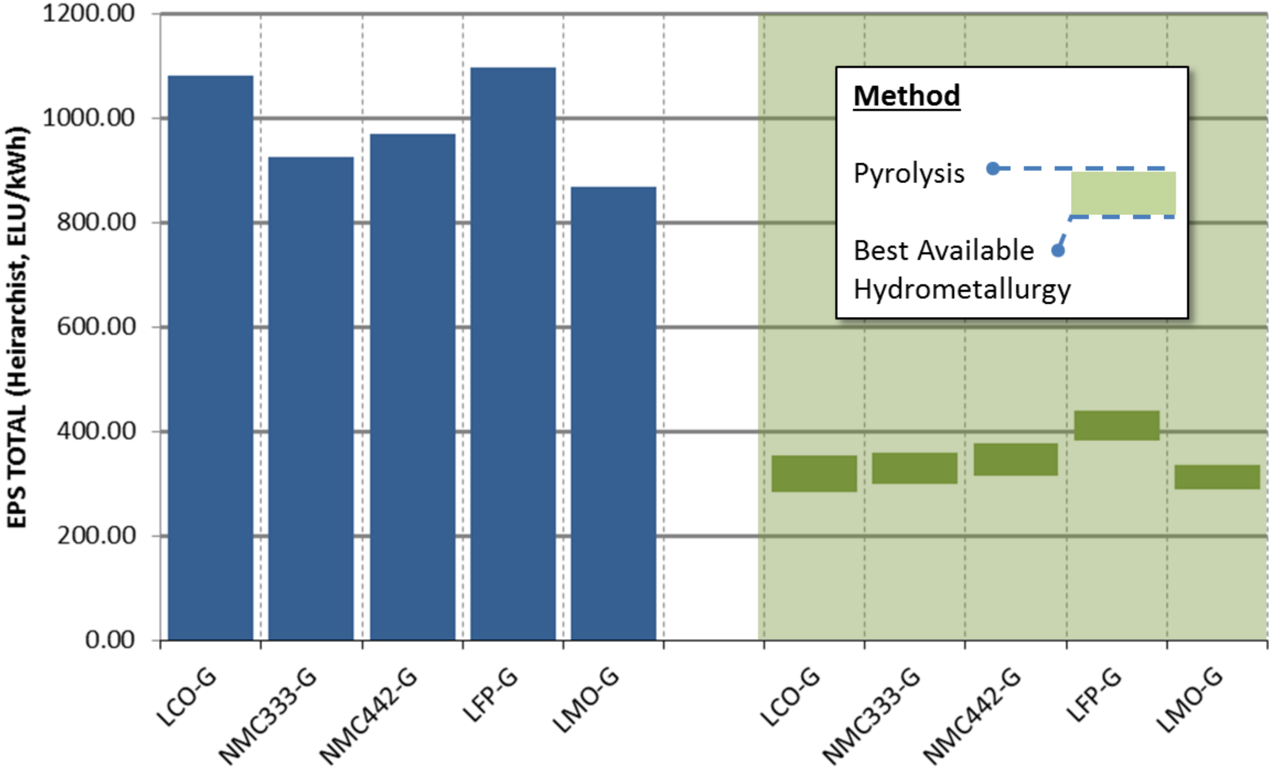
Pyrolysis

All recycling methods will result in considerable environmental improvement of battery lifecycles

The results for hydrothermal recycling indicate a superior recovery of materials, tempered by the use of large quantities of hot water and solvents and acids that are energy intensive to produce.

Direct recycling is anticipated to be a fairly major improvement over existing methods.

Source: *Realize modelling, previous industrial project*. Can be compared with the GREET model



iv. Process Comparisons

Comparison of material fates for the most constrained metals

	Ni, Co fate	Li fate	Other notes
'Pyro-'	Recoverable from molten alloy, 90%+	Lost in slag Max recovery approx. 50-60% (expensive)	Cu in alloy, All else lost to slag or burned for energy
'Hydro-'	Recoverable as salts, 95%+	Can be precipitated, 90%+ recovery	Most things recoverable to 80%+
'Direct '	Recoverable as battery materials	Partially reused, partially recovered	Other materials recoverable as fractions, similar to hydro

Technology status and prospects

This section describes the current development status of recycling technology, including actors involved in the system, and an analysis of the economic prospects of recycling lithium ion batteries.

i. Current actors and facilities

ii. Technological status and assessment of prospects

Companies with some capacity to recycle LIBs in Europe, 2015

Company	Location	Recycling process	Materials recovered
Accurec	Germany	Pyrolysis and hydrometallurgy.	Aluminium, copper, iron scrap, iron/magnesium, nickel/cobalt, future: LiCO3.
Recupyl	France	Mechanical separation, hydrometallurgical leaching and refining.	Aluminium, cobalt, stainless steel, lithium products.
SNAM	France	Crushing, pyrolysis, distillation, pyro-metallurgy.	Ca, ferro nickel alloys, ferro cobalt alloys
Umicore	Belgium (Sweden)	Pyrometallurgical smelting followed by hydrometallurgical refining.	Cobalt, nickel
Batrec	Switzerland	Pyrolysis, pyrometallurgy.	Ferromanganese, Zn, mercury.
G & P Batteries	UK	Pyrometallurgical or hydrometallurgical.	
Pilagest	Spain	Mechanical separation, chemical treatment.	Plastic, paper, ferro compounds, ferric components, metals, zinc sulphate, manganese salts/dioxide/graphite.
Eurodieuze	France	Hydrometallurgy	Nickel, cadmium, steel
GRS Batterien	Germany	Pyrometallurgy	Cobalt, nickel, copper

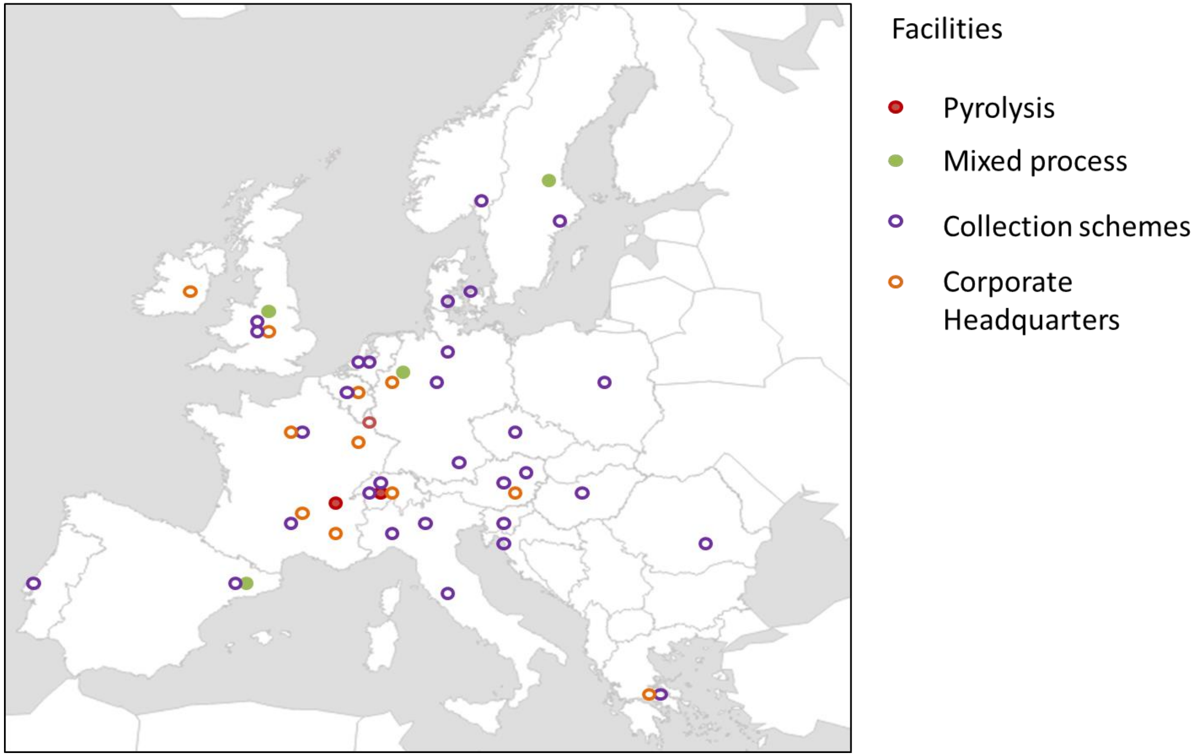
i. Current Actors and Facilities

Location of facilities in EU

Pyro approaches exist at industrial scale – enough capacity for 2020 already in EU.

Hydro approaches at pilot scale, some companies developing in EU and industrially in N.A. (e.g. Toxco)

Direct approach proven at proof of concept, developed by two companies in N.A. (OnTo, Retreiv)



Source: previous table, company websites

ii. Status and assessment of prospects

Technology status, end of 2015

At the end of 2015, the only recycling technology available on an industrial scale in Europe is pyrolysis. Hydrometallurgical facilities in Europe are still at a prototype stage, and while larger hydrometallurgy plants operate in North America (e.g. Toxco), they are not yet at a level where the capacity exists to handle more than a small fraction of future battery flows.

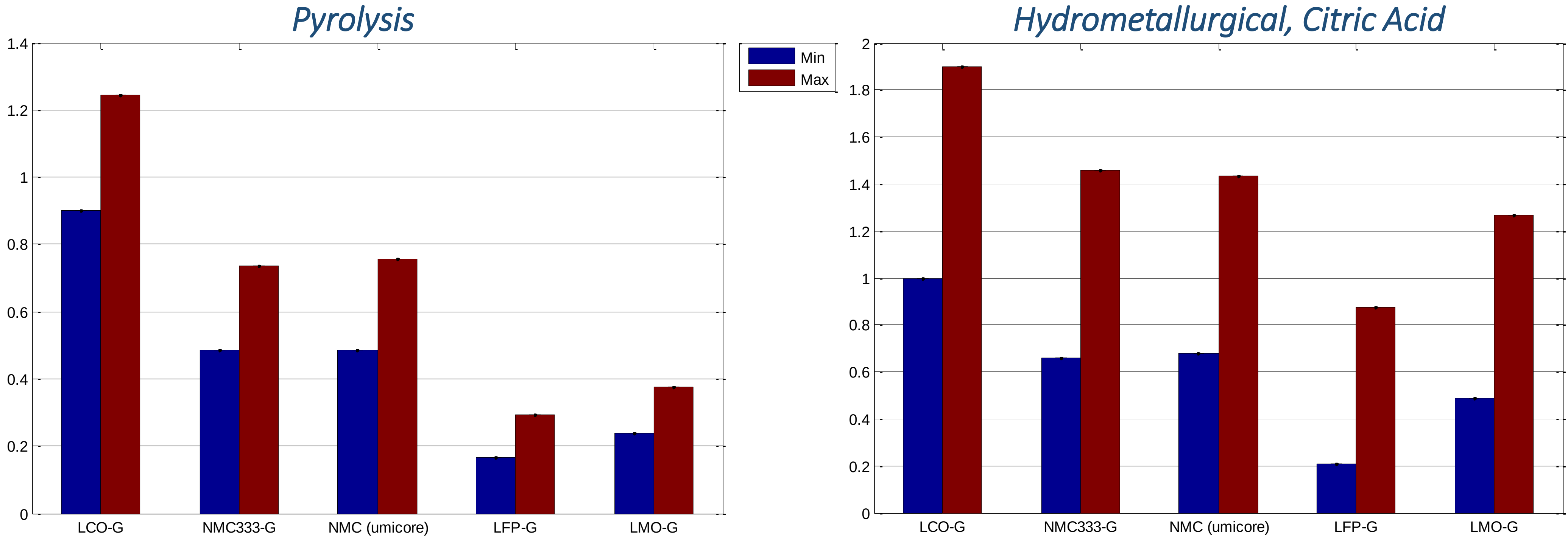
In contrast, direct physical recycling is being developed by two North American companies, but is still at the laboratory stage. 2015 saw successful rebuilding of a 'like-new' battery from recycled materials.

As batteries may not be landfilled, this means that existing recyclers can (and do) charge a premium gate fee to recycle used batteries.

This fee is anecdotally roughly 4€/kg ($5 USD/kg)

ii. Status and assessment of prospects

Estimated gross process margins (€/kg)



Source: models from process section, using current pricing for all inputs and outputs. Reflects an optimistic vision of large scale purchases, and all outputs being saleable at market prices. Capital, Labour, IP, Rent, Disassembly not included.

Hydrometallurgy has better economic prospects at scale, but both processes may struggle with LFP batteries. Current gate fees are by far a larger source of revenue than the materials.

ii. Status and assessment of prospects

> “profits from selling recovered metals are not major driver of [our] recycling operation”
>
> Maarten Quix, Head of Battery Recycling, Umicore
> as quoted in: Nature 526, (29 October 2015) doi:10.1038/526S100a (linked)

- Existing industrial scale recyclers understand that the main factor for the decision to recycle is currently legislation.
- Gate fees are integral to their business model.
- Developers of direct recycling (and new hydrothermal) approaches also understand this.

ii. Status and assessment of prospects

A shift to direct physical recycling could provide a large revenue boost for Ni/Co materials, and represents a radical improvement for other cathode materials

Cathode	Price of raw materials (€/kg)	Price of cathode material (€/kg)
$LiCoO_2$	16.1	24-31
$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	9.8	20-26
$LiMnO_2$	3.3	9
$LiFePO_4$	1.4	18

Source: Adapted from Gaines et al, 2013 (linked)

ii. Status and assessment of prospects

Can hydrothermal methods or direct physical recycling scale to compete with existing pyrolysis facilities?

This is the 64 000€ question. Gate fees at present represent a market inefficiency, but are also a massive incentive for new entrants to the market as they make all processes very profitable. It is easy to note that they are often referenced in pitch decks for new technologies and companies. As new facilities come on line, gate fees should drop and will eventually result in selection pressure.

Conclusions and Discussion

i. The need for recycling

ii. Prospects for recycling and outlook for recovery of scarce metals

iii. Implications for battery producers/users

i. The need for recycling

Many reasons to recycle batteries are cited

Direct motivations for actors:

1. Comply with legislation (most important for producers, owners)
2. Economic Reasons (most important for recyclers)

Societal motivations:

3. Minimize environmental harm potential from battery lifecycles
4. Circular flows of strategic metals
5. Make electromobility possible!

i. The need for recycling

Are circular flows of battery materials necessary?

It is fairly certain that large scale adoption of lithium batteries will stress cobalt supplies (Gaines et al 2013), but not all batteries need cobalt. Lithium is a longer term concern (Kushnir and Sandén 2013), and some argue that it may not be a concern at all (Yaksic and Tilton 2009, Gaines et al. 2014). Given that available pyrolysis recycling can recover cobalt, is there are pressing need for change?

Access to materials may be an important policy driver.

The EU is 100% import dependent on all potentially scarce battery materials, a fact which is recognized in the initiatives for a circular economy (EU COM 2011/21), and commission directives on strategic materials. Even without an immediate need to recycle for scarcity reasons, the very concentrated supply chains in cobalt and lithium may represent a risk for European industry. This risk is considered sufficient at the EU level to justify research and development of recycling capacity (EU COM 2014).

i. The need for recycling

Current gate fees will hinder reaching EV competitiveness targets

Various long run targets for battery prices have been proposed in order to ensure the cost competitiveness of electrified transport. These range from $150-200/kWh for the Advanced Battery Consortium to <$250/kWh from the International Energy Agency.

In either case, $5/kg translates to some $35-50/kWh, which could push out achieving the cost targets by a decade, or prevent it entirely. On a purely life cycle cost basis, higher competitiveness in the recycling market will be a critical part of achieving cost effective and sustainable electrified transport.

ii. Prospects for recycling

Legislation coupled with lack of choice produces gate fees

Although end of life batteries are still a fairly small waste flow in mass terms, there are not very many options for recycling them. The choice is essentially to pay whatever it takes to recycle the battery or ‘remove it from the system’ via export or even simple warehousing. Gate fees will likely be a fact of life for the near and medium term.

Gate fees are a potent incentive for new firms to enter market

Gate fees are much higher than the potential revenue from materials, and all of the processes for recycling should be able to operate at a profit (very slim for LFP type chemistries). Competition for gate fees should be the result, hopefully reducing them significantly in the future.

ii. Prospects for recycling

There will be no issue with recycling cobalt or nickel, but recycling lithium will require new processes

Recovery of lithium from pyrolysis slag is not likely to be cost effective, and thus circular flows of lithium will require alternative recycling processes. Both hydrothermal and direct physical recycling can achieve this goal.

The good news is that innovation is occurring, and that new processes can be cost effective at scale, indicating every technical possibility for circular flows of battery materials in the future.

iii. Implications for battery producers / users

Design for recycling is simple for batteries, but should be considered now.

Batteries all need to be disassembled. Bolts are preferred over glue, and electronic modules and copper connectors should be simple to separate.

Direct and Hydrothermal approaches require chemistry-specific handling. This means that capability to sort batteries by content is a prerequisite for future recycling.

Direct physical recycling may require further adaptations, such as the ability to unroll/unpack cell interior, to enable efficient removal of materials for processing.

References and Appendices

i. References

ii. Appendices

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ii. Appendix A – Mass fraction and hotspots of cell production

Aspect	**LCO-G**	**NMC333-G**	**NMC442-G**	**LFP-G**	**LMO-G**
Final Cell Capacity (Wh/kg)	135	140	140	90	135
Mass	**LCO-G**	**NMC333-G**	**NMC442-G**	**LFP-G**	**LMO-G**
Cathode	25%	27%	34%	24%	25%
Al Foil	14%	15%	13%	16%	14%
Anode	16%	16%	14%	14%	10%
Cu Foil	21%	18%	16%	22%	27%
Binders	4%	4%	4%	4%	4%
Electrolyte, Salt and separator	11%	11%	10%	11%	11%
Case and terminals	9%	9%	8%	9%	9%
Environmental Impact /kg	**Energy (CED/kg)**	**ReCiPE Ecosystem (Points/kg)**	**Recipe Total (Points/kg)**	**EPS Abiotic (ELU/kg)**	**EPS Total (ELU/kg)**
Al Foil	194.00	0.24	1.14	3.82	11.87
Copper Foil	60.30	0.13	6.90	308.37	320.01
Steel (Case)	22.00	0.00	0.00	0.00	0.00
LiPF6	340.00	0.61	3.13	45.50	50.60
EC/DMC	39.00	0.03	0.19	1.16	1.37
PVDF	366.00	0.43	2.07	10.20	13.50
Separator	112.00	0.11	0.60	10.20	13.50
Carbon Black	89.00	0.05	0.38	1.01	1.10
Graphite	67.00	0.06	1.31	93.20	96.58
LiCoO2	170.00	0.20	2.45	226.88	232.49
LiNMC 424	123.00	0.15	2.10	182.00	190.00
LiNMC 333	123.00	0.15	2.10	186.00	195.00
LiFePO4	50.00	0.06	0.19	43.00	50.00
LiMn2O4	40.00	0.06	0.19	65.00	71.00

ii. Appendix B – Material breakdown and value of cells by chemistry

Materials		**LCO-G**		**NMC333-G**		**LFP-G**		**LMO-G**		
	Price [€/kg]	**Mass [kg /tonne]**	**Value [€]**	**Mass [kg /tonne]**	**Value [€]**	**Mass [kg /tonne]**	**Value [€]**	**Mass [kg /tonne]**	**Value [€]**	**Reference**
Aluminium	0,7	122,2	86,7	122,2	86,7	122,2	86,7	122,2	86,7	(Subito)
Aluminium - Foil	0,7	92,2	65,5	98,8	70,1	105,4	74,8	92,2	65,5	(Subito)
Carbon - Activated	0,3	11,2	0,33	12,0	0,36	10,8	0,32	11,3	0,34	Alibaba
Carbon - Graphite	1,0	103,0	103,0	103,4	103,4	93,2	93,2	64,8	64,8	Alibaba
Cobalt	20,0	99,9	1998	36,0	720,0	0,0	0,0	0,0	0,0	(London Metal Exchange)
Copper	2,3	40,0	90,8	40,0	90,8	40,0	90,8	40,0	90,8	(London Metal Exchange)
Copper - Foil	2,3	140,6	319,1	119,3	270,9	144,4	327,7	176,5	400,8	(London Metal Exchange)
EC	1,2	29,6	34,7	29,6	34,7	29,6	34,7	29,6	34,7	(Shenzhen Hongye Tiancheng Technology Co. Ltd.)
DMC	1,2	29,6	34,7	29,6	34,7	29,6	34,7	29,6	34,7	(Shenzhen Hongye Tiancheng Technology Co. Ltd.)
Electronics	-	90,0	-	90,0	-	90,0	-	90,0	-	-
Iron	0,3	0,0	0,0	0,0	0,0	58,6	17,6	0,0	0,0	(Eurofer the European Steel Association 2013)
Lithium - cathode	7,9	11,8	92,9	12,9	101,5	6,9	54,5	12,4	97,5	(Hubei Baijierui Advanced Materials Co.)
Lithium - salt	7,9	0,3	2,4	0,3	2,4	0,3	2,4	0,3	2,4	(Hubei Baijierui Advanced Materials Co.)
Manganese	0,6	0,0	0,0	33,6	18,8	0,0	0,0	97,8	54,8	(Hunan Centre Machinery Co.)
Nickel	10,0	0,0	0,0	35,9	329,0	0,0	0,0	0,0	0,0	London Metal Exchange
Plastic - Binder	8,4	14,7	124,5	15,4	130,2	13,9	117,3	12,8	108,1	(Moore Recycling Associates 2009)
Plastic - Separator	8,4	6,6	55,6	6,6	55,6	6,6	55,6	6,6	55,6	(Moore Recycling Associates 2009)
Steel	0,3	80,0	24,0	80,0	24,0	80,0	24,0	80,0	24,0	(Eurofer the European Steel Association 2013)
Total scrap value [€/tonne cells]		**3905**		**2003**		**921**		**1056**		