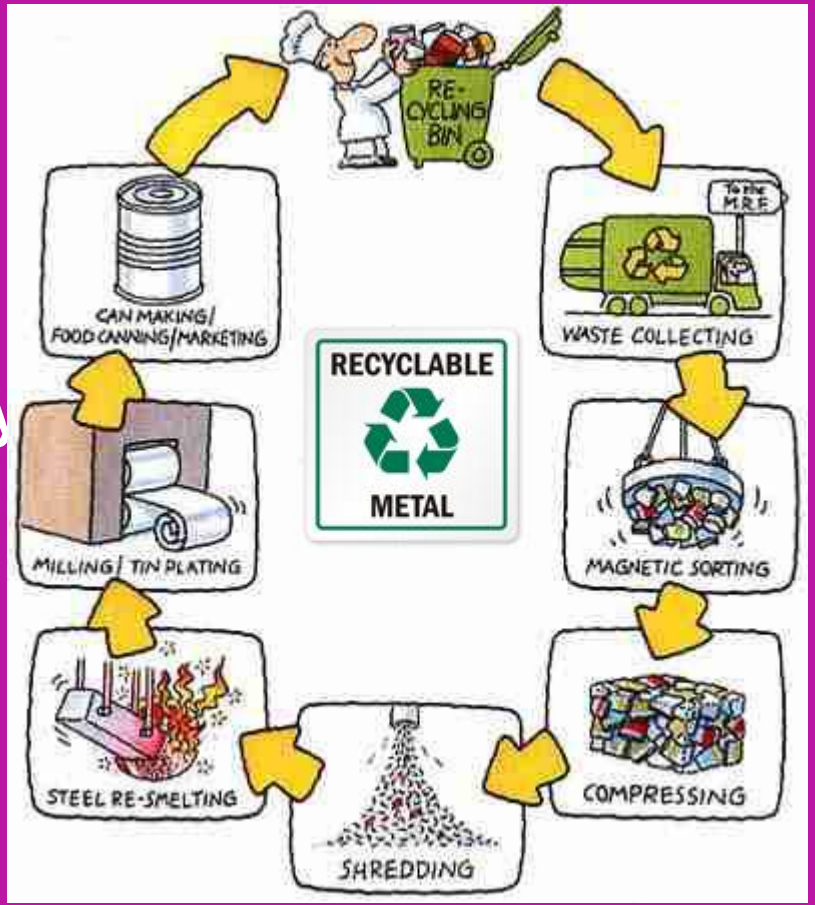
Module A2: Recycling challenge for energy systems

AAE-E3120 Circular Economy for Energy Storage

Prof. Annukka Santasalo-Aarnio



https://twitter.com/AlcoMetals/status/1313947235600785409

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Learning outcomes

- **Identify circular economy concepts and the role of energy in recycling**
  - Introduction to recycling processes
  - Mechanical, pyrometallurgy and hydrometallurgy

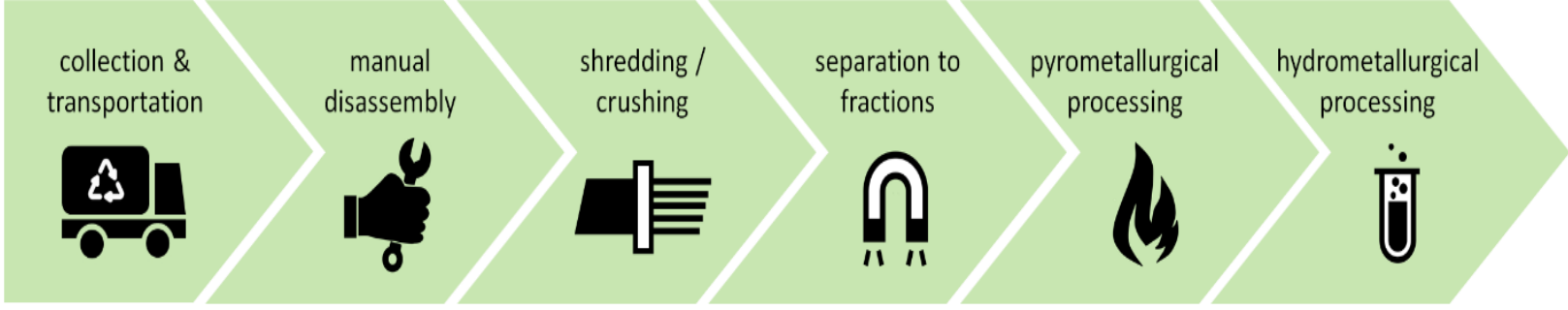
- **Recognition of the challenge in recycling of multicomponent materials**

Metal Recycling

Mechanical separation

Waste sorting at WtERT:
https://www.wtert.net/news/457/New-Transfer-Station-and-Sorting-Plant-Azcapotzalco-Mexico-City.html

Metal recycling processes



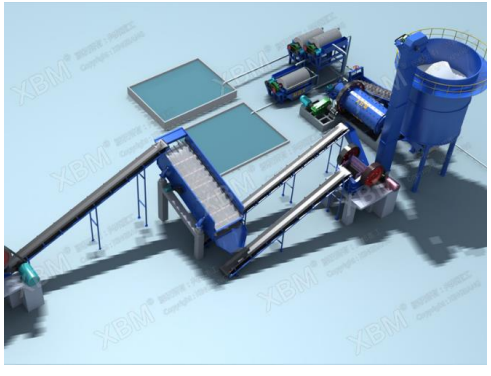
Current experience on WEEE recycling

WEEE = Waste electrical and electronic equipment

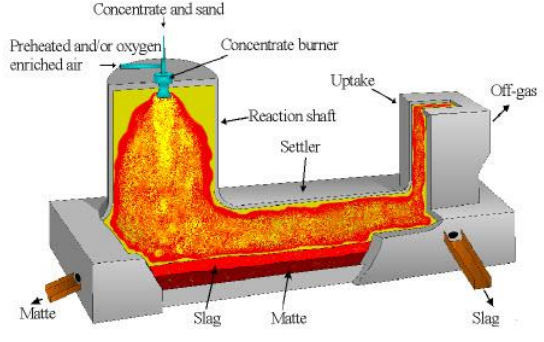
K. Miettunen, A. Santasalo-Aarnio, “Eco-design for dye solar cells: from hazardous waste to profitable recovery” J. Cleaner Production, 320 (2021) 128743. https://doi.org/10.1016/j.jclepro.2021.128743

Metal recycling processes

Mechanical separation



Hydrometallurgy



www.totalmateria.com

Pyrometallurgy

Mechanical recycling

Aiming for material liberation

The traditional approach -> crushing/shredding

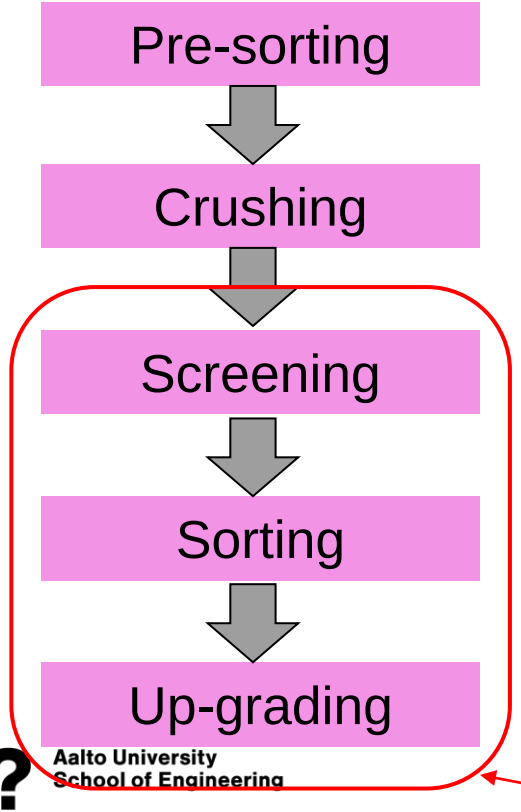
- -> To decrease the particle size

From as small particles as possible -> separate different materials from each other with different methods

- Depending on the material properties (magnetic; particle size…)
- These are called: **“Unit operations”**

Mechanical recycling

Aiming for material liberation



Prepare materials-specific batches for crushing

Selecting parts for reuse (if possible)

Decrease the size of the batch, Liberation

Fraction materials to ease further process steps

Generate element-based fractions

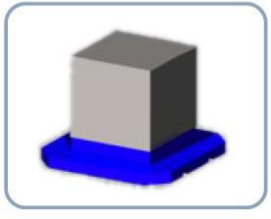
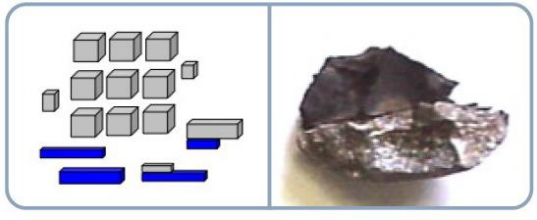
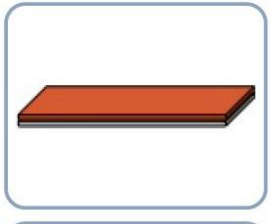
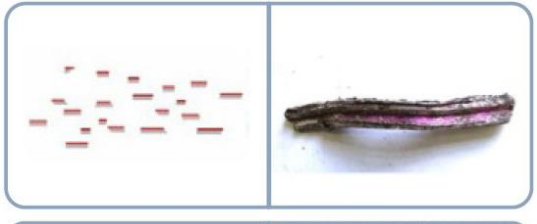
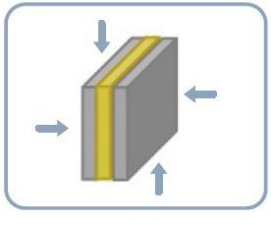
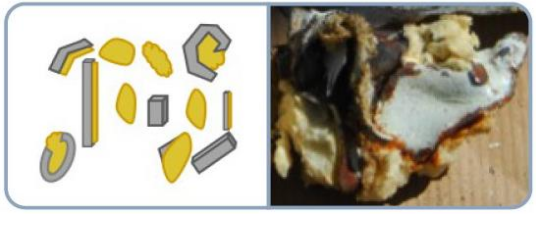
Increase commercial value of the product

Recycling process

Material liberation

Reflect to your lecture journal

Which of these material connection types are easy to liberate?

Connection types	Before shredding	After shredding	Liberation behaviour
Bolting/ Reveting			
Gluing			
Coating/ Painting			
Foaming			

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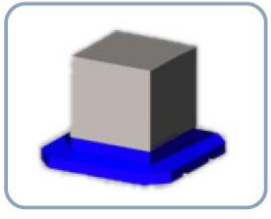
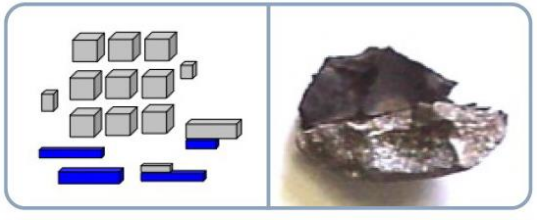
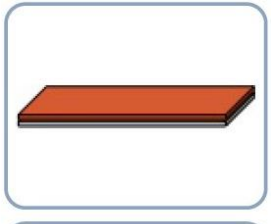
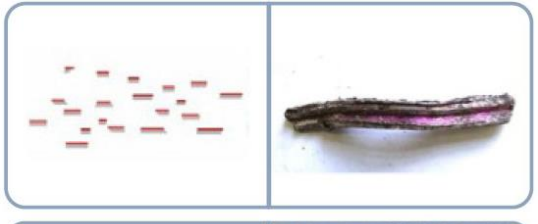
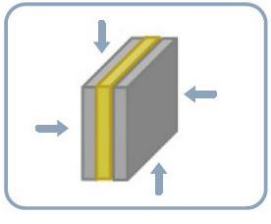
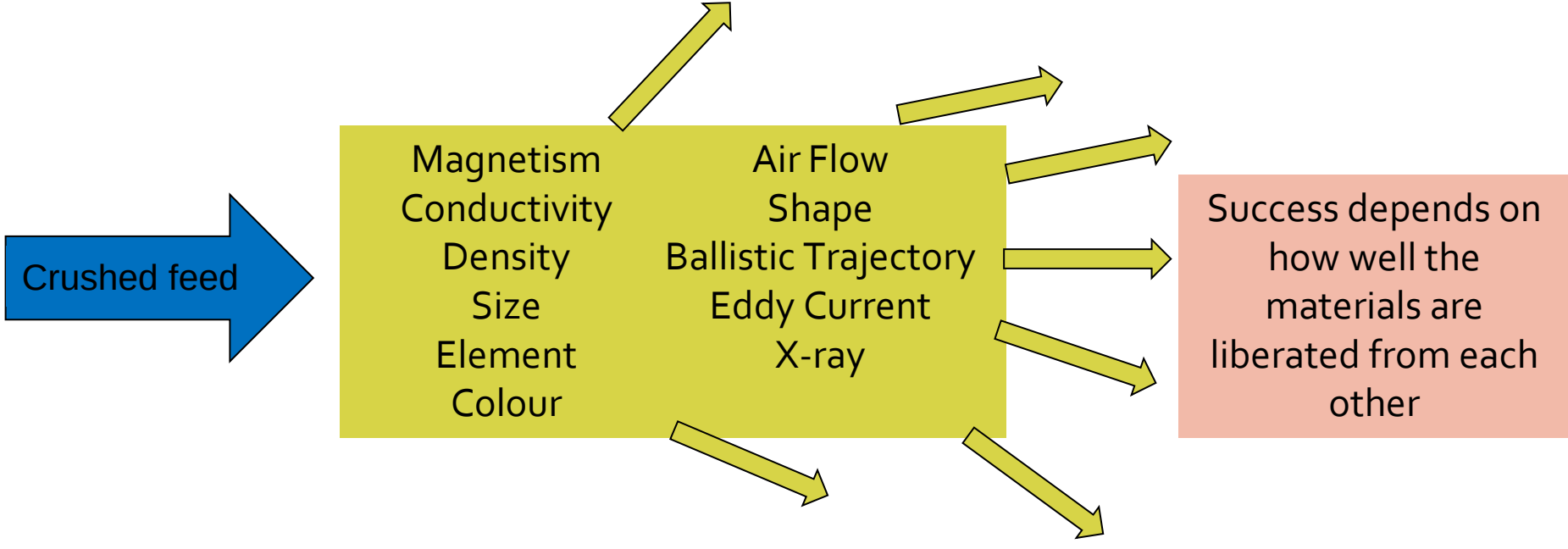
Material liberation

Connection types	Before shredding	After shredding	Liberation behaviour
Bolting/ Riveting			High liberation High randomness
Gluing			Medium liberation Medium randomness
Coating/ Painting			Low liberation
Foaming			Medium liberation Medium randomness

Sorting of materials



Robotic and AI methods will be applied

Sorting of materials

Hand sorting	-> Valuable, toxic or difficult components
Low density magnets	-> Ferrous
High density magnets	-> Stainless steel
Cyclone	-> Light fragments
Eddy current	-> Non-ferrous metals (Al, Cu…)
Inductive	-> Metals/Non-metal separation
Flotation	-> Different density materials

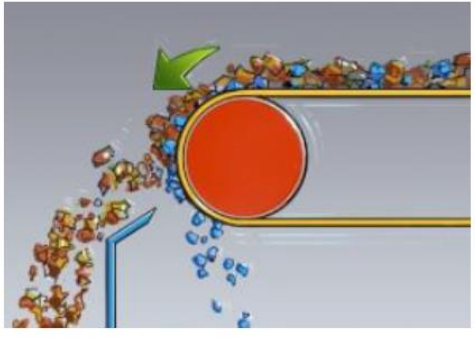
Unit operations - magnets

Electromagnetism & Electrical Conductivity - Magnets

Overbelt magnet

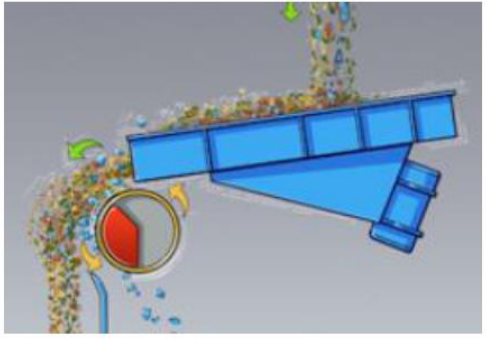
Fe removal & protection

Head roll magnet



Fe removal

Drum magnet



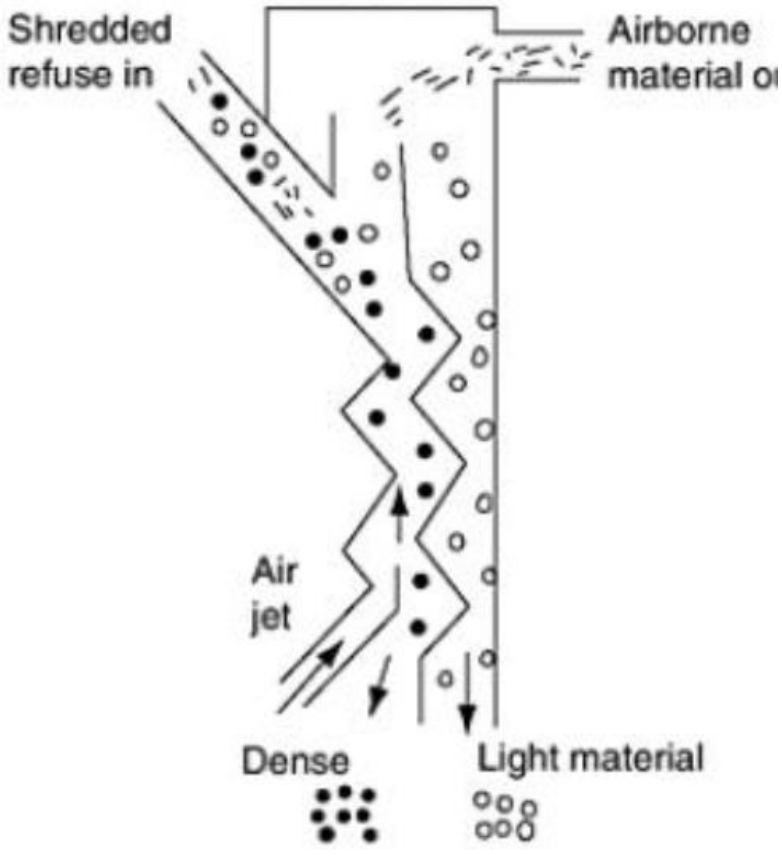
Fe removal

Unit operations - Cyclons

Specific gravity

Separation of:

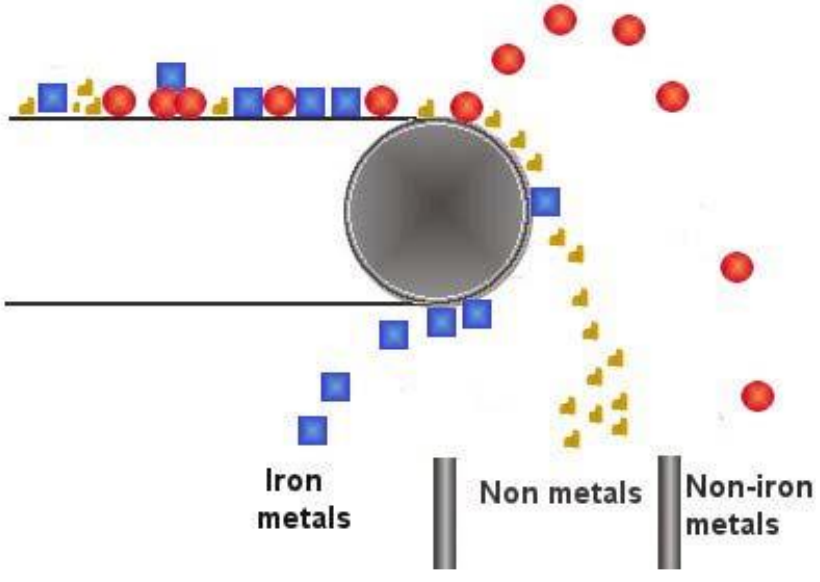
Light fragments (polymers/fabric)
heavy fragments



Unit operations – Eddy current

Electromagnetism & Electrical Conductivity – Eddy Current -

When a Non-Iron Metal crosses the induced magnetic field, it undergoes an **repulsion effect** and jumps a certain distance ahead of the Foucault drum



Sorting – by Hand

WEEE waste fractions

Ferrous metals

To further treatment (contains metals)

Cables

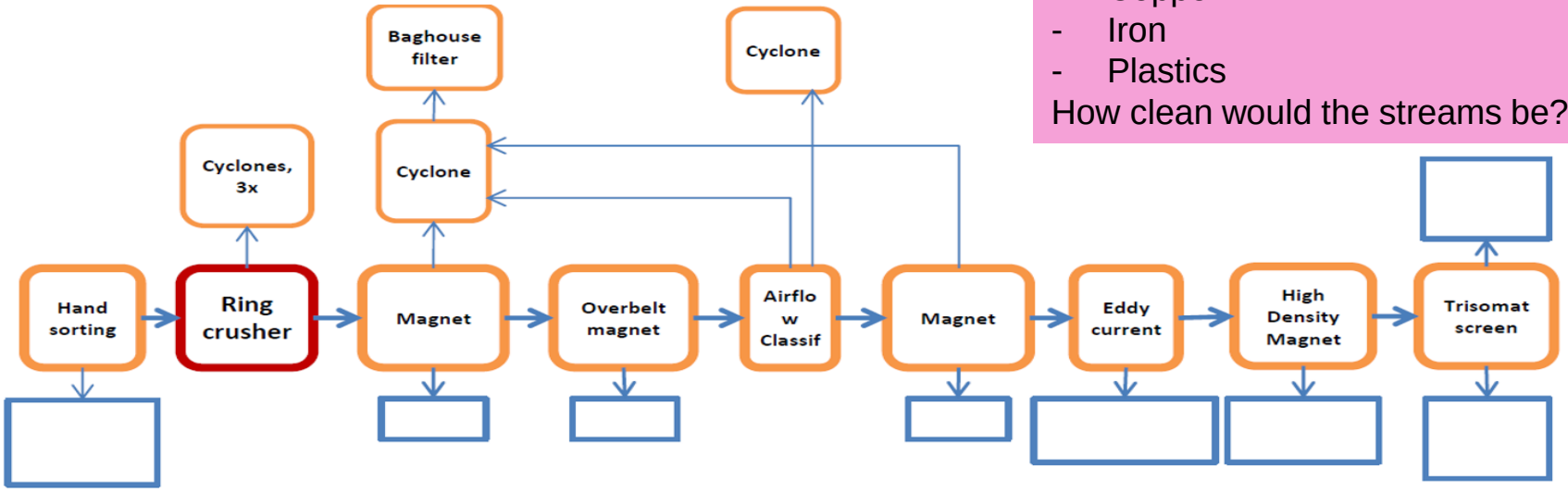
PCB

Aluminum

Example: WEEE recycling

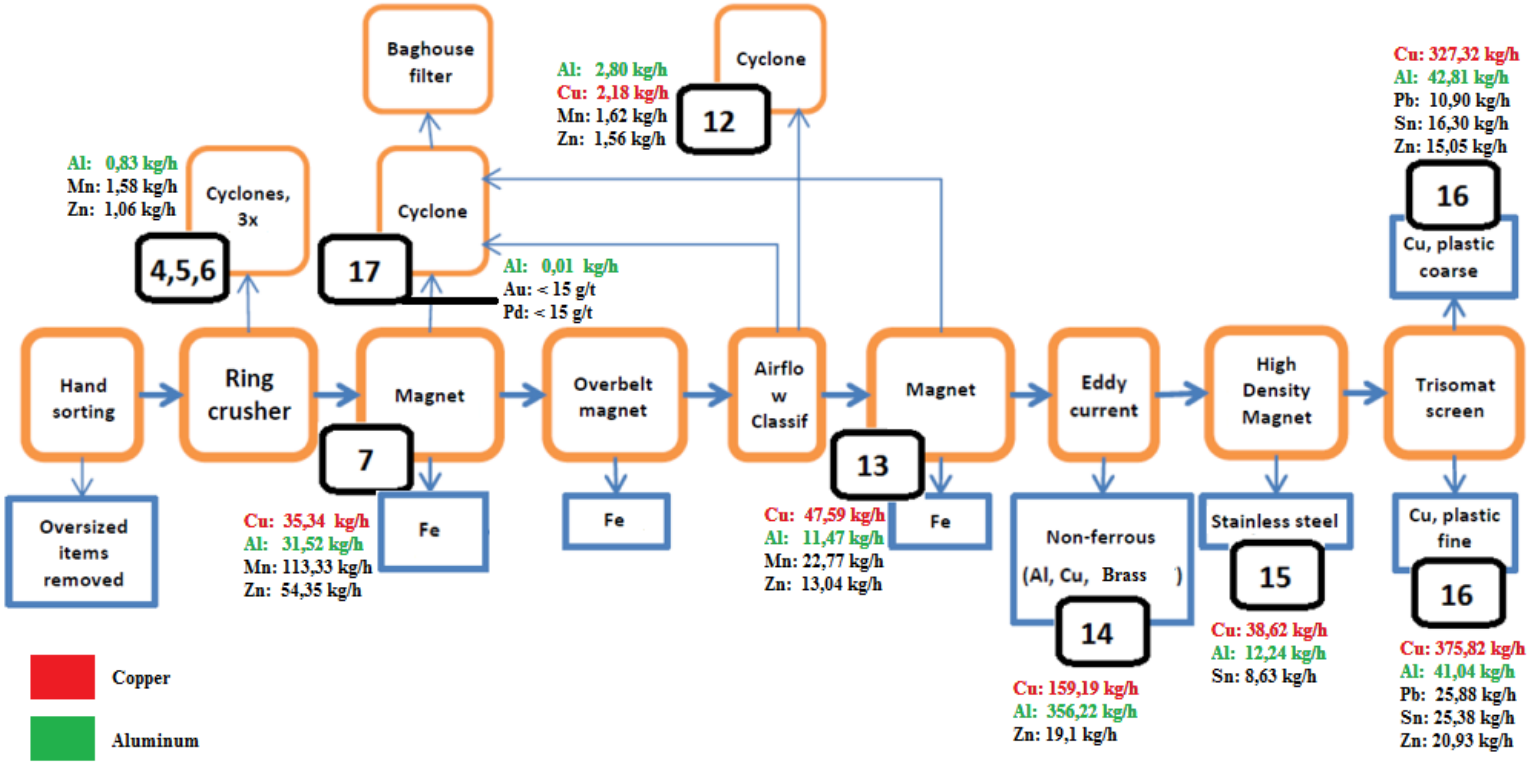
Where do you expect to find the majority of these elements?
- Copper
- Iron
- Plastics

How clean would the streams be?



Tatu Karlström, BEHAVIOR OF SELECTED WEEE MATERIALS IN A RING CRUSHER, Master's thesis, (2016)
https://aaltodoc.aalto.fi/handle/123456789/23638

Example: WEEE recycling



Tatu Karlström, BEHAVIOR OF SELECTED WEEE MATERIALS IN A RING CRUSHER, Master's thesis, (2016)
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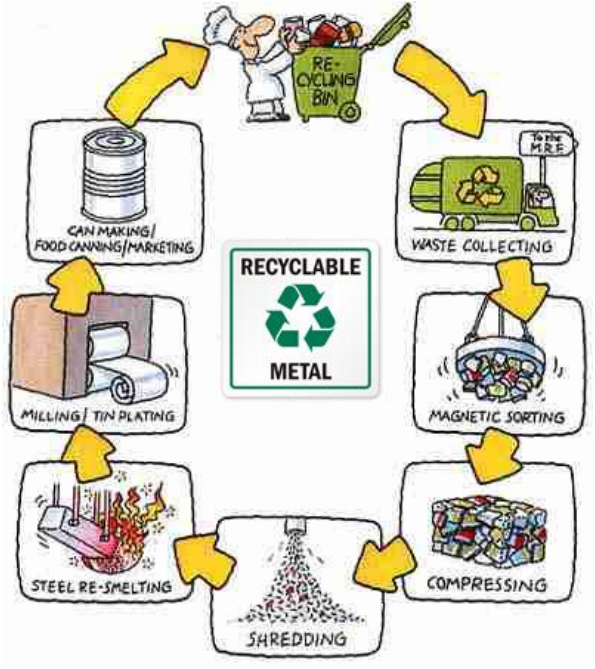
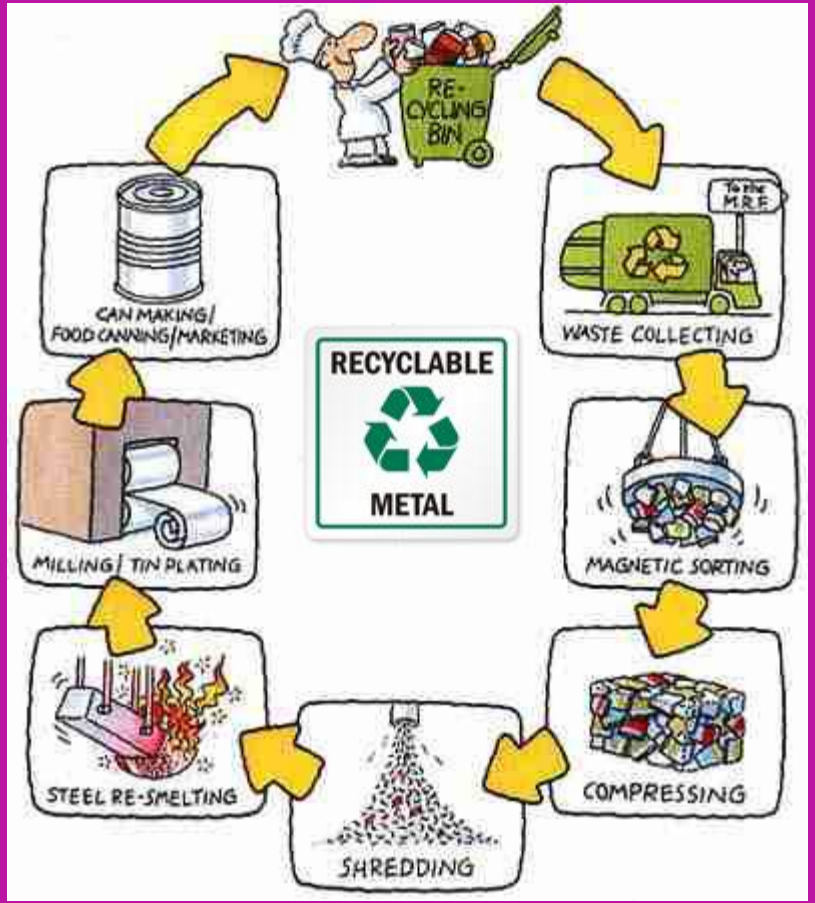
Is recycling a “clean process”



Pure metal stream

Metal Recycling

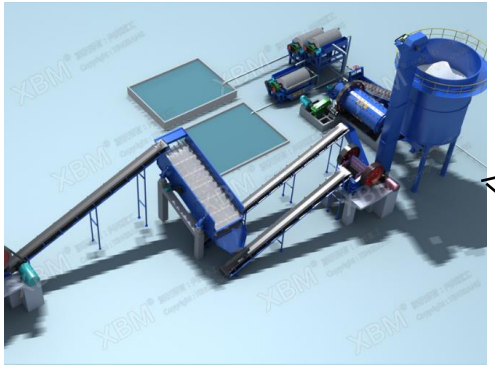
Pyrometallurgy
Hydrometallurgy



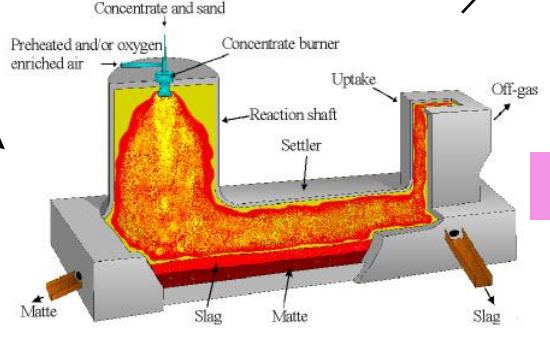
https://twitter.com/AlcoMetals/status/1313947235600785409

Recycling processes

Mechanical separation



Hydrometallurgy



Pyrometallurgy

www.totalmateria.com

Example: Lead Acid battery recycling

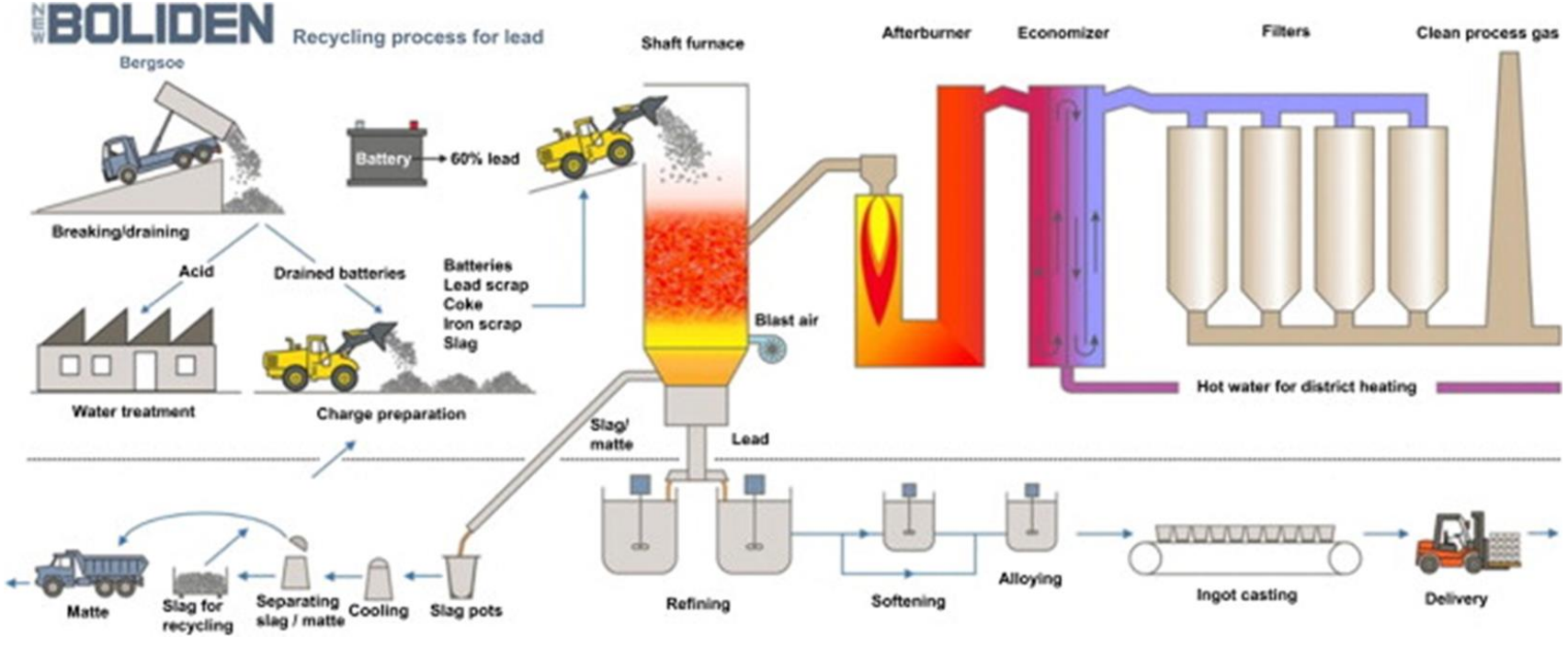
- Efficient recycling system
- Commercially feasible process

- **Simple energy system**:
  1. Lead electrodes
  2. Sulphuric acid electrolyte
  3. Plastic casing

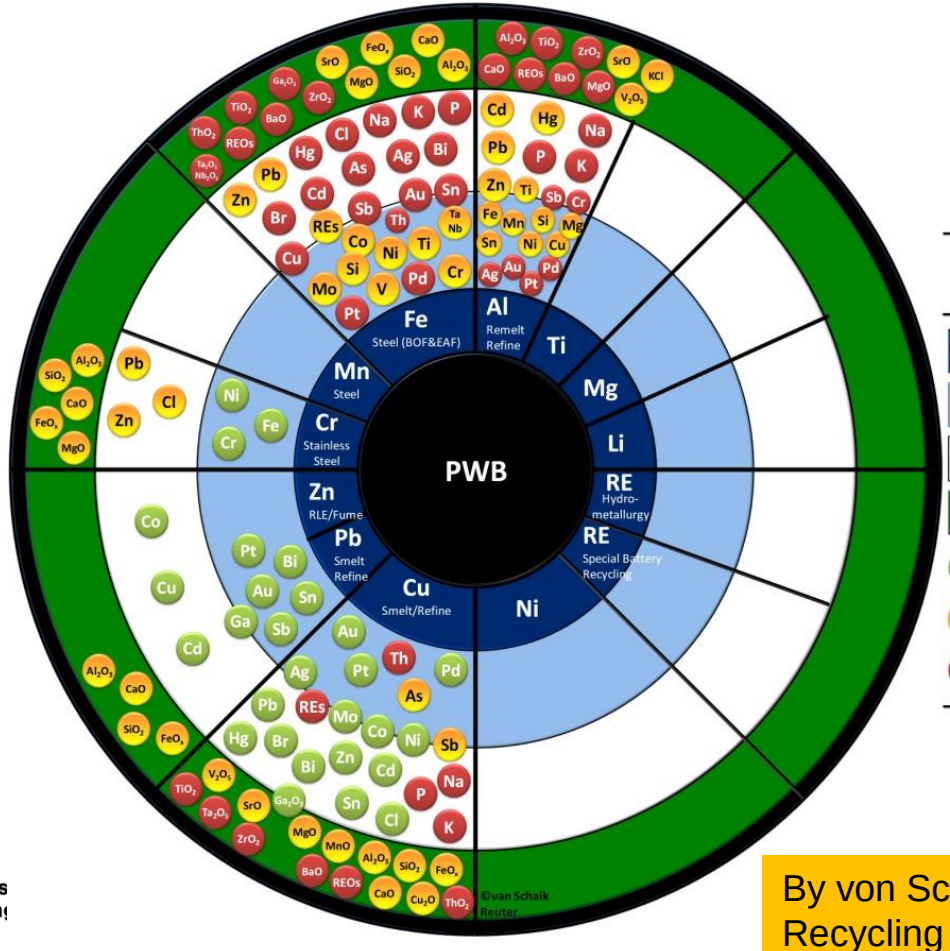
Indiamart.com

Pyrometallurgy:

Lead Acid battery recycling



Pyrometallurgy: The metal wheel



The Main Thermodynamic and Economic Destination of Metals, their Alloys and Compounds from EoL Products for the Best Available Technology Processing Routes (Segments in Figure)

Society's Essential Carrier Metals: Primary Product
Extractive Metallurgy's Backbone (primary and recycling metallurgy)
The metallurgy infrastructure makes a "closed" loop society and recycling possible.

Dissolves mainly in Carrier Metal if Metallic (Mainly to Pyrometallurgy)
Valuable elements recovered from these or lost (metallic, speiss, compounds or alloy in EoL also determines destination as also the metallurgical conditions in reactor).

Compounds Mainly to Dust, Slime, Speiss, Slag (Mainly to Hydrometallurgy)
Collector of valuable minor elements as oxides/sulphates etc. and mainly recovered in appropriate metallurgical infrastructure if economic (EoL material and reactor conditions also affect this).

Mainly to Benign Low Value Products
Low value but inevitable part of society and materials processing. A sink for metals and loss from system as oxides and other compounds. Comply with strict environmental legislation.

El **Mainly Recovered Element**
Compatible with Carrier Metal as alloying Element or that can be recovered in subsequent Processing.

El **Mainly Element in Alloy or Compound in Oxidic Product, probably Lost**
With possible functionality, not detrimental to Carrier Metal or product (if refractory metals as oxidic in EoL product then to slag / slag also intermediate product for cement etc.).

El **Mainly Element Lost, not always compatible with Carrier Metal or Product**
Detrimental to properties and cannot be economically recovered from e.g. slag unless e.g. iron is a collector and goes to further processing.

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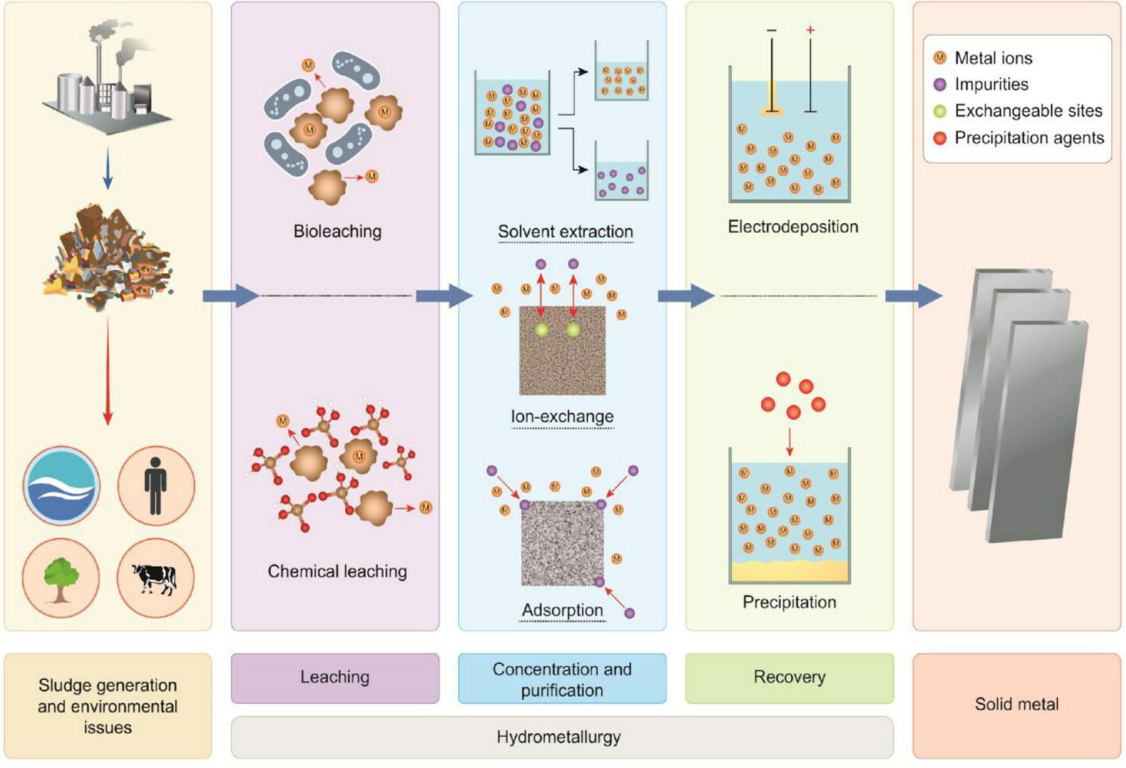
By von Schaik and M.A. Reuter, 2013. Metal Recycling Opportunities.

Hydrometallurgical processes

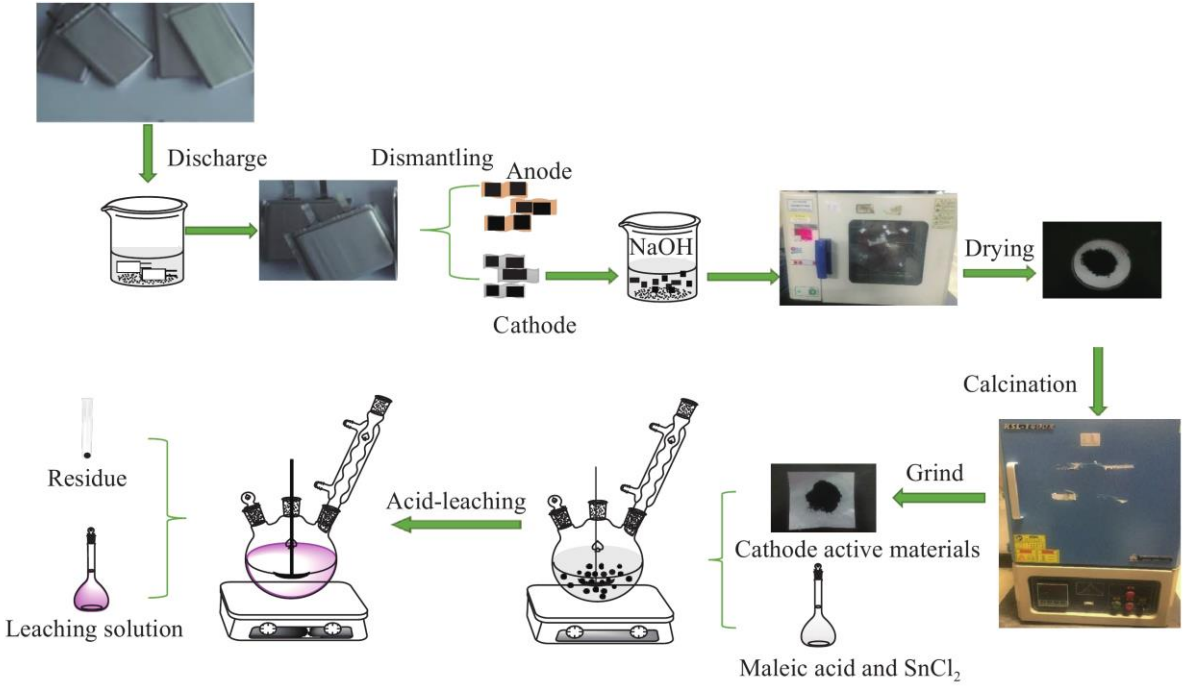
- Utilization of chemical processes to recover the metals
- Use of temperature, chemicals, pressure, solvents…



V. Gunarathne et al. (2022) Hydrometallurgical processes for heavy metals recovery from industrial sludges, Critical Reviews in Environmental Science and Technology, 52:6, 1022-1062, DOI: 10.1080/10643389.2020.1847949

Hydrometallurgical processes

- Dissolved into chemicals
  - Reduced in metal form
- Difficult if many metals in the solution
- Can be prepared in large scale
- Traditionally used for recovery of metals in ore processing

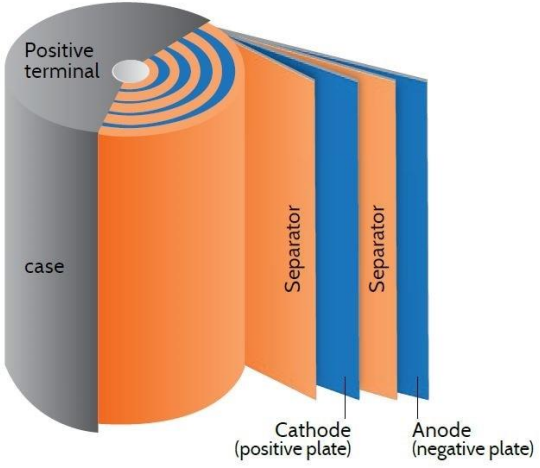


Liu-ye Sun et. al. Hydrometallurgical recycling of valuable metals from spent lithium-ion batteries by reductive leaching with stannous chloride, Int. J. Miner. Metall. Mater., 28(2021). https://doi.org/10.1007/s12613-020-2115-z

Li-ion battery recycling - materials

Table 1. Lithium-Ion Battery (LiB) Constructive Components and Materials.

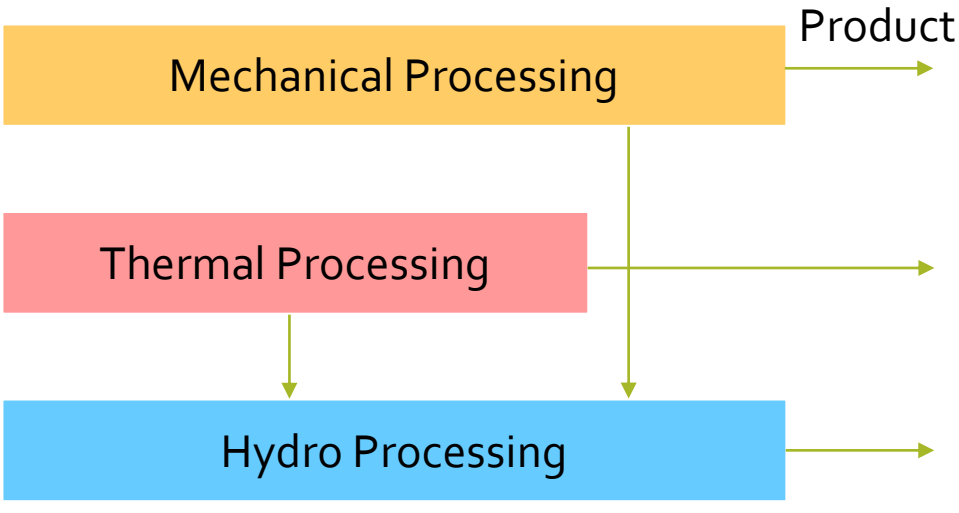
Battery Component	%w/w	Most Commonly Used Material
Case	~25%	Steel/plastics
Cathode	~27%	$LiCoO_2$, $LiNi_xMn_yCo_zO_2$, $LiMn_2O_4$, $LiNiO_2$, $LiFePO_4$
Anode	~17%	Graphite/$Li_4Ti_5O_{12}$
Copper and aluminium foils and current collectors	~13%	Cu/Al
Electrolyte	~10%	Solution of $LiPF_6$, $LiBF_4$, $LiClO_4$, and $LiSO_2$ dissolved in propylene carbonate, ethylene carbonate, or dimethyl sulfoxide
Separator	~4%	Microporous polypropylene



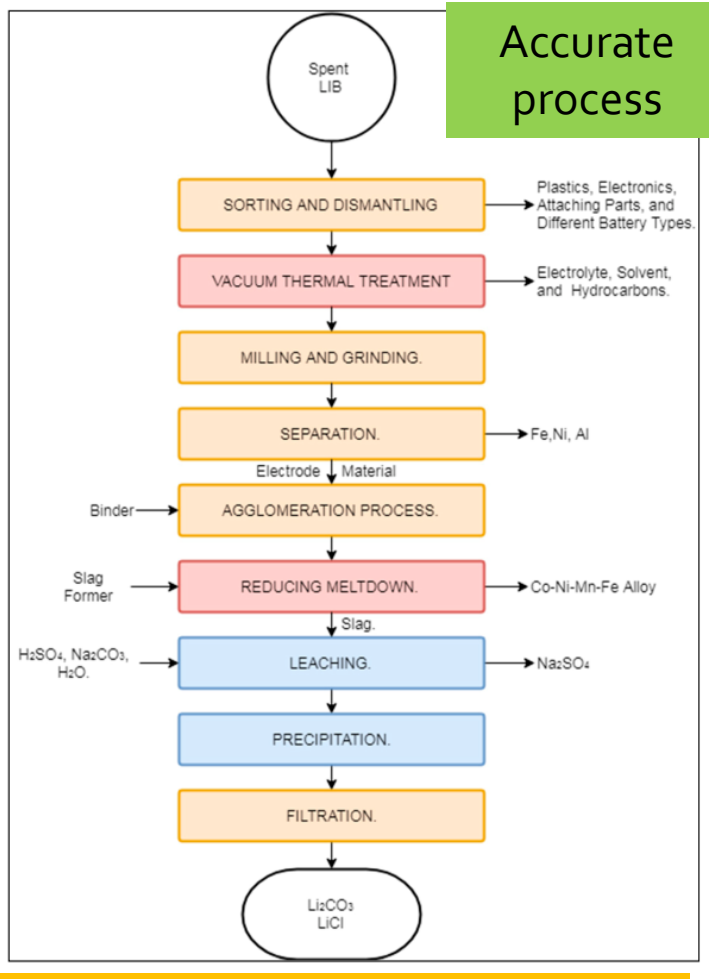
https://galusaustralis.com

O. Velázquez-Martínez et al., “A Critical Review of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective “ *Batteries* 2019, 5, 68; doi:10.3390/batteries5040068

Li-ion battery recycling



Accurate process



O. Velázquez-Martínez et al., “A Critical Review of Lithium-Ion Battery Recycling Processes from a Circular Economy Perspective “ *Batteries* 2019, 5, 68; doi:10.3390/batteries5040068

Hydrometallurgical most effective for valuable materials recovery and used by leading Asian players

Recovery rates by approach[1]

Chemical component	Li	Ni	Co	Cu	C
Pyrolysis	0%	40 – 60%	40 – 60%	n.c.	0%
Pyrolysis - Hydrometallurgical	50 – 60%	> 95%	> 95%	> 95%	0%
Mechanical - Pyrolysis (slag)	0%	40 – 60%	40 – 60%	n.c.	0%
Mechanical - Hydrometallurgical (black-mass)	> 90%	> 99%	> 99%	> 99%	0%

Source Roland Berger research; selected companies

[1] All recovery rates measured at end of recycling process

Roland Berger

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W. Bernhart (2019) Battery manufacturers and OEMs need a clear framework to work within – at European and national level. https://www.rolandberger.com/en/Insights/Publications/Battery-recycling-is-a-key-market-of-the-future-Is-it-also-an-opportunity-for.html

Hydrometallurgical most effective for valuable materials recovery and used by leading Asian players

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Source Roland Berger research; selected companies

[1] All recovery rates measured at end of recycling process

Roland Berger

Reflect to your lecture journal

What recovery rates are enough to make the batteries sustainable?

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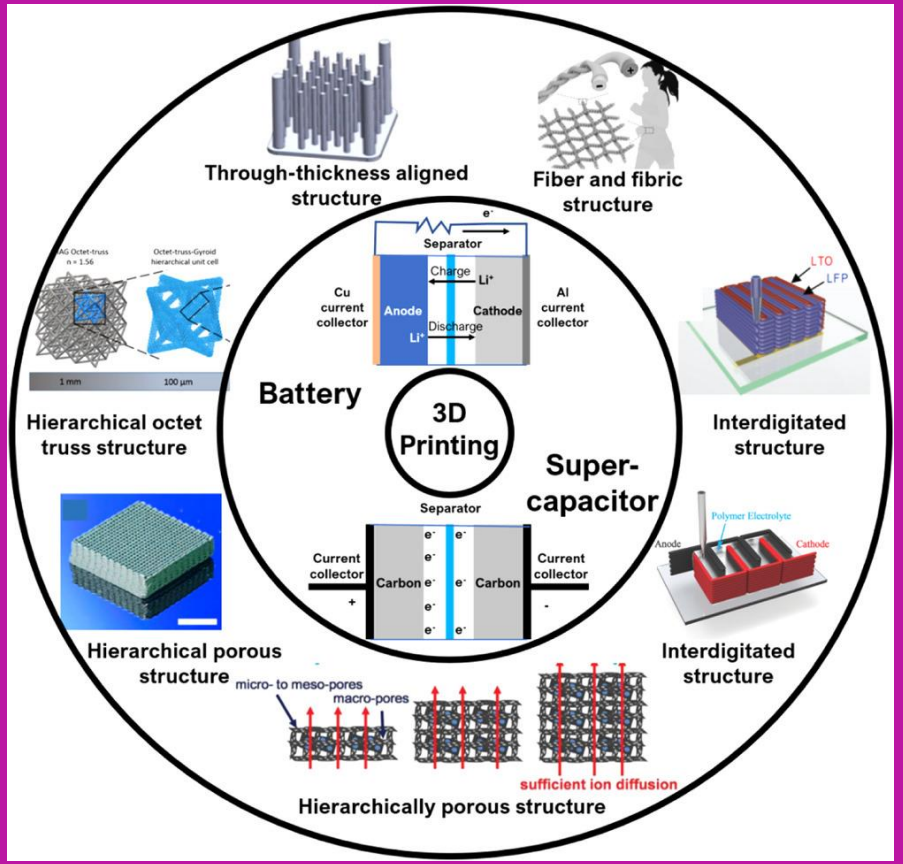
W. Bernhart (2019) Battery manufacturers and OEMs need a clear framework to work within – at European and national level. https://www.rolandberger.com/en/Insights/Publications/Battery-recycling-is-a-key-market-of-the-future-Is-it-also-an-opportunity-for.html

Challenges with Energy System Recycling



T. Chu et al. (2021) 3D printing-enabled advanced electrode architecturedesign, Carbon Energy, 424-439
DOI: 10.1002/cey2.114

Challenge in recycling

- We discuss End of Life conditions
- Must be economically viable (business/legislation)
- Needs large volumes

Photos of Severi Ojanen at MeTYK-project 2017

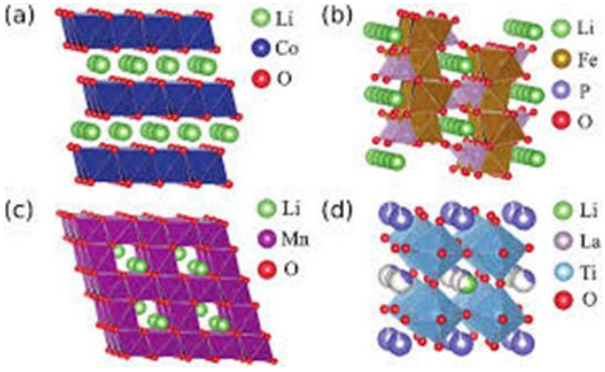
Challenges in multicomponent Recycling

- Cup
- Spoon
- Coffee
- Water
- Milk
- Sugar

How would you separate these components?

Example by Prof. Markus Reuter, Helmholtz institute

Energy Systems – complex materials



Nanomaterials for positive and negative electrodes

How do we separate these?

M. Saitoh *et al*., “Systematic analysis of electron energy-loss near-edge structures in Li-ion battery materials “Phys. Chem. Chem. Phys., 2018, 20, 25052—25061; DOI: 10.1039/c8cp03390k

Linear vs. Circular design aim

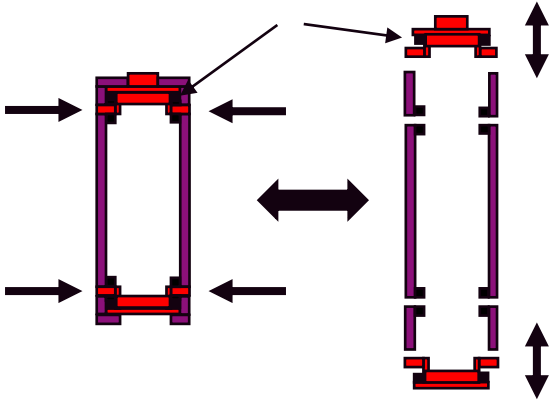
www.futuristgerd.com

Eco-Design

How do we address the challenges of Recycling multimaterial systems

-> This needs to be done at the **Design stage – not end of life**

This we address during this course!



Eco-design Li-ion battery
Innovation at
Materials for Renewable Energy
course by students 2017

Take-home message

“Multimaterial component system recycling is challenging IF this was not taken into account at the design phase.”